NASA/TP—2020–5008734

State-of-the-Art
Small Spacecraft Technology

Small Spacecraft Systems Virtual Institute

Ames Research Center, Moffett Field, California

October 2020

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Space Administration

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Small Spacecraft Technology
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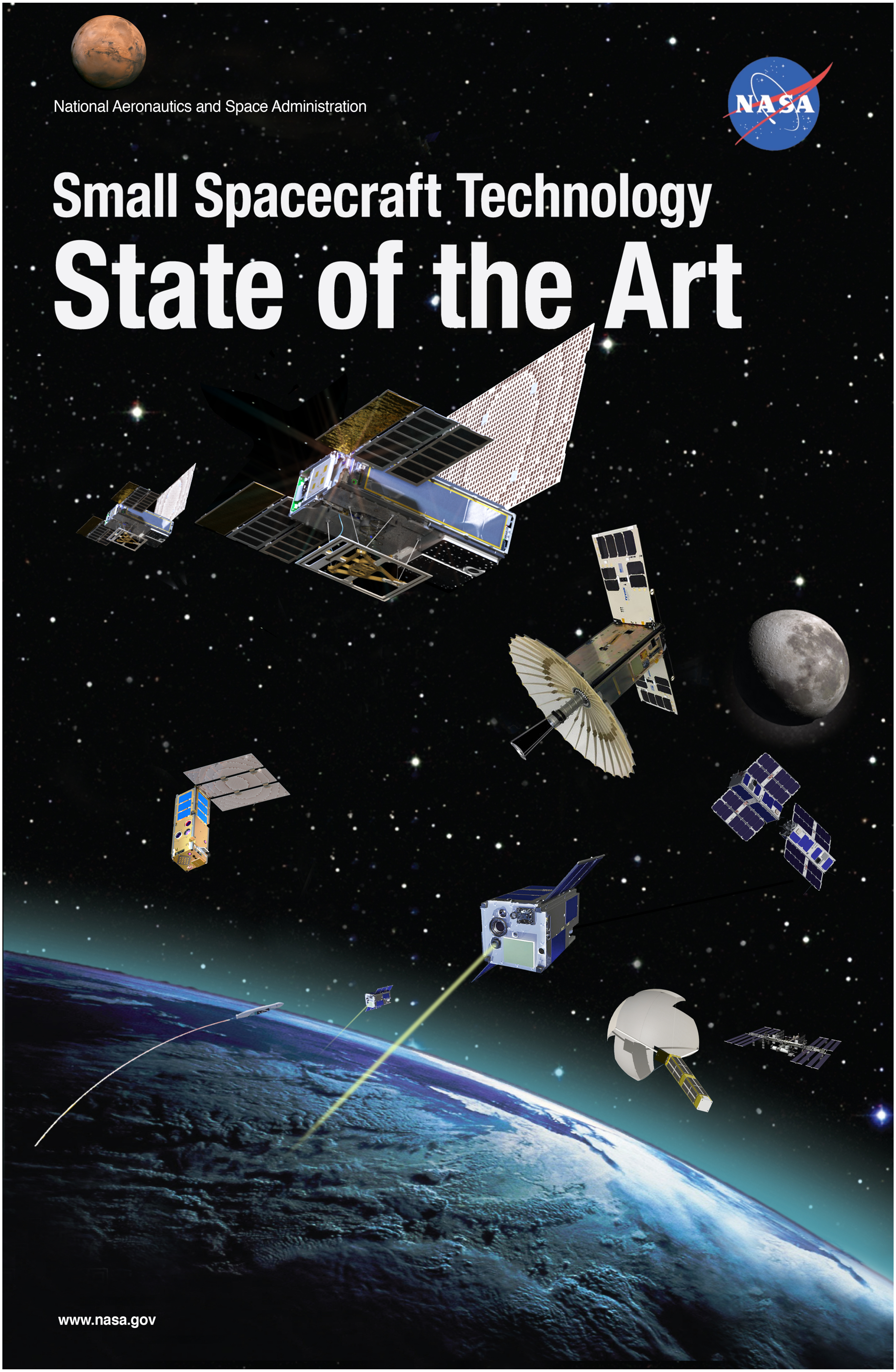

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Division Chief:
Bruce Yost

Editor:
Sasha Weston

Contributors and Reviewers:

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Contents

Preface

When the first edition of NASA's *Small Spacecraft Technology State-of-the-art* report was published in 2013, 247 CubeSats and 105 other non-CubeSat small spacecraft under 50 kilograms (kg) had been launched, and these represented less than 2% of launched mass into orbit. By 2019, small spacecraft with mass less than 180 kg made up almost 7% of all mass launched into orbit. Additionally, 63% of spacecraft under 600 kg had mass less than 180 kg and of those 47% were CubeSats (1). Since 2013, flight heritage for small spacecraft, primarily CubeSats, has nearly doubled and with dedicated smallsat launch capabilities readily available and expanding, opportunities to demonstrate new technologies and systems are expected to increase.

The 2020 edition of this report captures and distills the wealth of new information available on small spacecraft systems from NASA and other publicly available sources. Overall, this report is a survey of small spacecraft technologies sourced from open literature; it does not endeavor to be an original source, and only considers literature in the public domain to identify and classify devices. Commonly used sources for data include manufacturer datasheets, press releases, conference papers, journal papers, public filings with government agencies, news articles, presentations, and Small Spacecraft Systems Virtual Institute Federated Search. Data not appropriate for public dissemination, such as proprietary, export controlled, or otherwise restricted data, are not considered. As a result, this report includes many dedicated hours of desk research performed by subject matter experts reviewing resources noted above.

The organizational approach for each chapter is relatively consistent with previous editions with the introduction of the technology, current development status of the technology's procurable systems, and a summary of surveyed technologies. For each edition, chapters are updated with new and maturating technologies and reference missions. Tables in each section provide a convenient summary of the technologies discussed, with explanations and references in the body text. We have attempted to isolate trends in the small spacecraft industry to point out which technologies have been adopted as a result of successful demonstration missions.

The reports' original layout has changed to reflect the adaptation to the growth in the small spacecraft market, and information has been added and removed. An added chapter on Flight Software lists resources on the programs that make a spacecraft function; the inclusion of Identification and Tracking Systems chapter details the current development status of technologies used to track SmallSats in orbit; additionally, Space Situation Awareness will provide information on the expanding need for space traffic control systems. Several chapters underwent a complete rewrite to better display useful information. The Launch, Integration, and Deployment chapter focus is now on the different launch integration roles, paradigms, deployment methods, and ISS services, and no longer lists the various launch vehicles and deployers. In order to reduce confusion surrounding the true readiness of propulsive technologies for mission infusion, the Propulsion chapter follows a more detailed definition of NASA TRL scale based on propulsion devices and now includes prevailing technology types for each propulsive category. Lastly, the Ground Data Systems and Mission Operations chapter is an elaborate breakdown of the process spacecraft designers are faced with for obtaining data from the spacecraft and several new factors involving ground segment designs.

A central element of the report is to list state-of-the-art technologies by NASA Standard Technology Readiness Level (TRL) as defined by the 2020 NASA Engineering Handbook, found in NASA NPR 7123.1C. The authors of this report have endeavored to independently verify the TRL value of each technology by citing published test results or publicly available data to the best of their capability and committed time. Where test results and data disagree with vendors' own advertised TRL, the authors have attempted to engage the vendors to discuss the discrepancy.

Readers are strongly encouraged to follow the references cited to the literature describing full performance range and capabilities of each technology. Further, readers may reach out to individual companies for further information. It is important to note that this report takes a broad system-level view. To attain a high TRL, the subsystem must be in a flight-ready configuration with all supporting infrastructure—such as mounting points, power conversion, and control algorithms—in an integrated unit.

The TRL is based purely on NASA TRL guidelines unless otherwise noted, regardless of specific mission requirements. The TRL value could vary depending on the design factors for a specific technology. For the purposes of this document, a technology simply having functioned in the relevant environment is sufficient to achieve a given TRL. Furthermore, if a technology has flown on a mission without success, or without providing valid confirmation to the operator, that “flight heritage” is discounted.

An accurate TRL assessment requires a high degree of technical knowledge on a subject device as well as an understanding of intended spacecraft bus and target environment. Although the authors strongly encourage a TMA well-supported with technical data prior to infusing new technologies into programs, the authors believe TRLs are most accurately determined when assessed by a program within the context of the program’s unique requirements

While the overall capability of small spacecraft has matured since the 2018 edition of this report, technologies are still being developed to make deep space smallsat missions more routine. This has led to intense scrutiny over the radiation protection in small spacecraft, especially given their tendency to use low-cost, commercial off-the-shelf (COTS) components. Consequently, this report also includes radiation mitigation strategies for small spacecraft missions.

Future editions of this report may include content dedicated to the rapidly growing fields of assembly integration and testing services, and mission modeling and simulation–all of which are now extensively represented at small spacecraft conferences. These fields are still in their infancy, and as these subsystems and services evolve and reliable conventions and standards emerge, the next iteration of this report may also evolve to include additional chapters.

References

(1) C. B. Bok, A. Comeau, A. Dolgopolov, T. Halt, C. Juang, P. Smith, "SmallSats by the Numbers." 2020. Bryce and Space Technology (https://brycetech.com/downloads/Bryce_Smallsats_2020.pdf).

1.0 Introduction

1.1 Objective

The objective of this report is to assess and provide an overview of the state-of-the-art in small spacecraft technologies. This report focuses on the spacecraft system as a whole, with current best practices for integration, and then presents the state-of-the-art for spacecraft subsystems. Certain chapters have a particular emphasis on CubeSat platforms as nanosatellite applications have expanded due to their high market growth in recent years. This report was first commissioned by NASA's Small Spacecraft Technology (SST) program in mid-2013 in response to the rapid growth in interest in using small spacecraft for missions beyond low-Earth orbit, and was updated in 2015 and 2018. In addition to reporting currently available technologies that have achieved TRL 5 or above, a prognosis is provided describing technologies "on the horizon," those technologies that are considered future efforts. This work is funded by NASA's Space Technology Mission Directorate (STMD) and Science Mission Directorate (SMD).

1.2 Scope

The SmallSat mission timeline began at NASA Ames Research Center with the launch of Pioneer 10 and 11 that launched in March 1972 and April 1973, respectively, and both weighed < 600 kg. Ames' SmallSat program then focused on lunar exploration with Lunar Prospector (< 700 kg) in 1998, Lunar Crater Observation and Sensing Satellite or LCROSS (< 630 kg) in 2009, and Lunar Atmosphere and Dust Environment Explorer or LADEE, which weighed around 380 kg and launched in September 2013. Before LADEE in late 2010, NASA's first minisatellite called Fast, Affordable, Science and Technology Satellite (FASTSAT) had a launch mass <400 lbs that provided an upper mass limit of small spacecraft classification of 500 kg. This decrease in spacecraft mass and increased science capabilities has ignited the miniaturization and maturity of aerospace technologies that has shown to be capable for less cost. Since 2013 with the exponential growth of CubeSats, the classification of SmallSats has been reduced further to a launch mass of under 180 kg to accommodate the EELV Secondary Payload Adapter (ESPA) payloads.

Originally developed in 1999 by California Polytechnic State University at San Luis Obispo (Cal Poly) and Stanford University, a small educational platform called a CubeSat was designed for space exploration and research for academic purposes. CubeSats are now a common category of small spacecraft weighing only a few kilograms based on a form factor of a 10 centimeters (cm) square cube (2). CubeSats can be composed of a single cube (a "1-unit [1U]" CubeSat) or several cubes combined to form, for instance, 3U or 6U units as shown in figure 1.1. On the lower mass

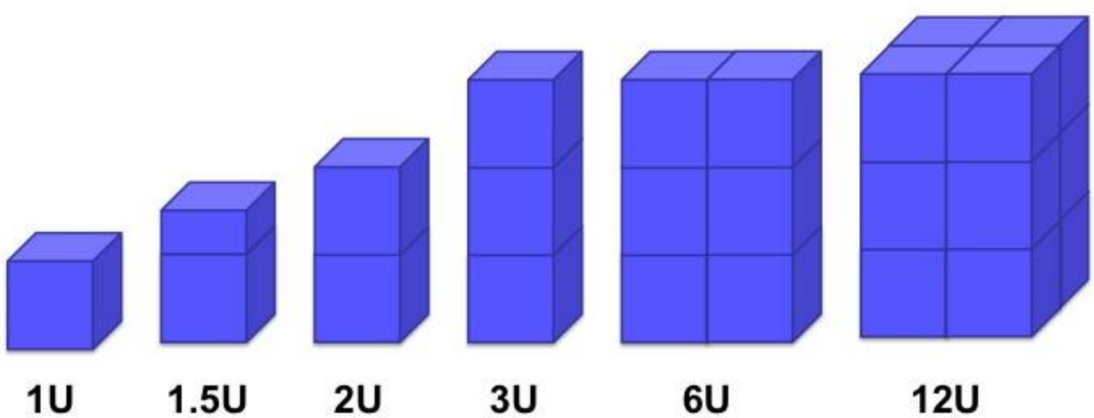


Figure 1.1: CubeSats are a class of nanosatellites that use a standard size and form factor. Credit: NASA.

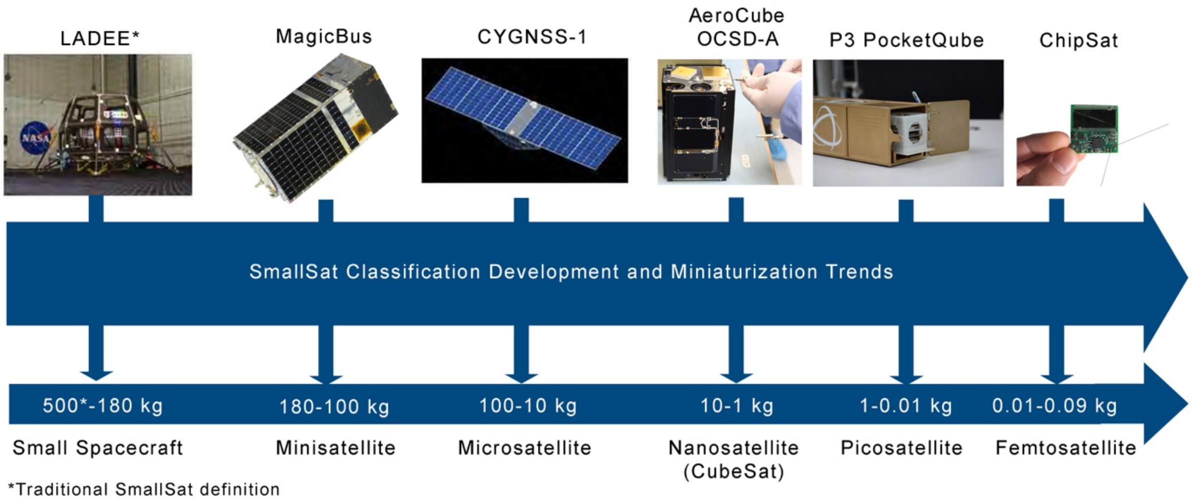


Figure 1.2: Overview of the variety of spacecraft that fall into the small spacecraft category. Credit: NASA and Adcole Space.

end, there are projects such as KickSat-2, which deployed 100 cm-scale “ChipSat” spacecraft, or Sprites, from a 2U femtosatellite deployer in March 2019. These femtosatellite ChipSats are the size of a large postage stamp and have a mass below 10 grams.

Spacecraft are generally grouped according to their mass. NASA’s SST Program now defines small spacecraft (2) as follows: the term “small spacecraft” applies to any spacecraft with a wet mass at or below 180 kg; minisatellites are those with a mass of 100 – 180 kg; microsatellites have a mass of 10-100 kg; nanosatellites have a mass of 1 – 10 kg; picosatellites have a mass of 1 – 0.01 kg, and femtosatellites have a mass 0.01 – 0.09 kg. Figure 1.2 gives an example of the variety of spacecraft that fall into the small spacecraft category.

1.3 Assessment

The state-of-the-art assessment of a technology is performed using NASA’s TRL scale (figure 1.3). For this report, a technology is deemed state-of-the-art whenever its TRL is larger than or equal to 5. A TRL of 5 indicates that the component and/or brassboard with realistic support elements is built and operated for validation in a relevant environment so as to demonstrate overall performance in critical areas. Success criteria include documented test performance demonstrating agreement with analytical predictions

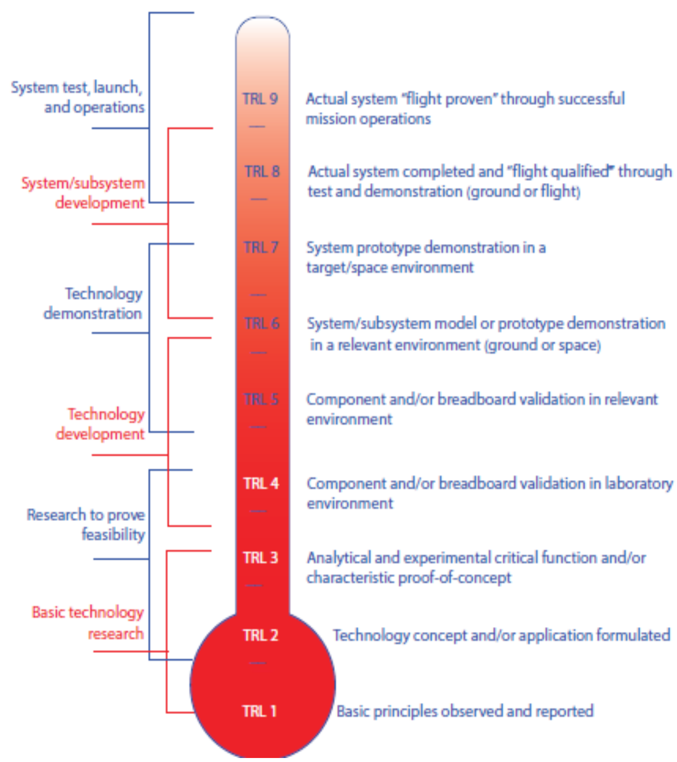


Figure 1.3: NASA’s standard Technology Readiness Level (TRL) scale. Credit: NASA.

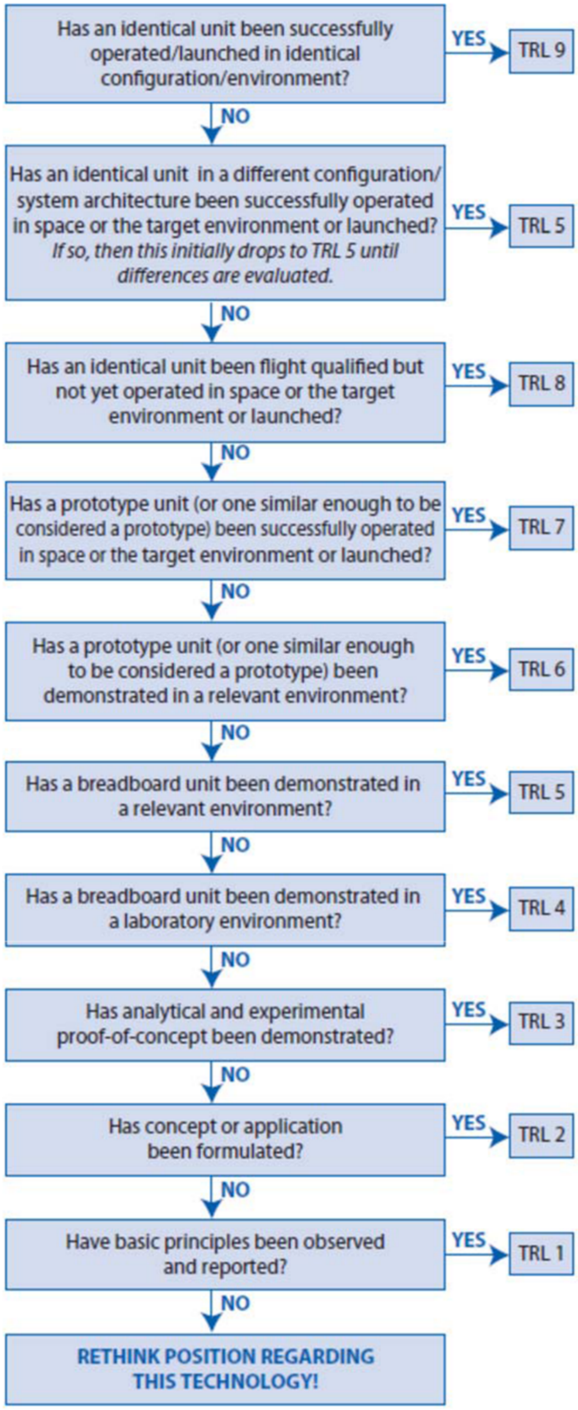


Figure 1.4: Technology Maturity Assessment (TMA) thought process. Credit: NASA.

and documented definition of scaling requirements. Performance predictions are made for subsequent development phases (3).

A technology is considered not state-of-the-art whenever its TRL is lower than or equal to 4. In this category, the technology is considered to be “on the horizon.” A TRL of 4 is defined as a component and/or breadboard validated in a laboratory environment with documented test performance demonstrating agreement with analytical predictions and a documented definition of the relevant environment.

NASA standard TRL requirements for this report version are stated in the NPR 7123.1C, which is effective through February 14, 2025, and the criteria for selection of appropriate TRL are described in the NASA Systems Engineering Handbook 6105 Rev 2 Appendix G. Please refer to the NASA Online Directives Information System (NODIS) website

https://nodis3.gsfc.nasa.gov/ for NPR documentation. The following paragraphs are excerpts from the NASA Engineering Handbook 6105 Rev 2 (pp. 252 – 254) to highlight important aspects of NASA TRL guidelines in hopes of eliminating confusion on terminology and heritage systems.

1.3.1 Terminology

“At first glance, the TRL descriptions in figure 1.3 appear to be straightforward. It is in the process of trying to assign levels that problems arise. A primary cause of difficulty is in terminology; e.g., everyone knows what a breadboard is, but not everyone has the same definition. Also, what is a “relevant environment?” What is relevant to one application may or may not be relevant to another. Many of these terms originated in various branches of engineering and had, at the time, very specific meanings to that particular field. They have since become commonly used throughout the engineering field and often acquire differences in meaning from discipline to discipline, some differences subtle, some not so subtle. “Breadboard,” for example, comes from electrical engineering where the original use referred to checking out the functional design of an electrical circuit by populating a "breadboard" with components to verify that the design operated as anticipated. Other terms come from mechanical engineering, referring primarily to units that are subjected to different levels of stress under testing, e.g., qualification, protoflight, and flight units. The first step in developing a uniform TRL assessment (see figure 1.4) is to define the terms used. It is extremely important to develop and use a consistent set of definitions over the course of the program/project."

1.3.2 Heritage Systems

"Note the second box particularly refers to heritage systems. If the architecture and the environment have changed, then the TRL drops to TRL 5—at least initially. Additional testing may need to be done for heritage systems for the new use or new environment. If in subsequent analysis the new environment is sufficiently close to the old environment or the new architecture is sufficiently close to the old architecture, then the resulting evaluation could be TRL 6 or 7, but the most important thing to realize is that it is no longer at TRL 9. Applying this process at the system level and then proceeding to lower levels of subsystems and components identifies those elements that require development and sets the stage for the subsequent phase, determining the new TRL."

References

(1) NASA Systems Engineering Handbook. NASA/SP-2016 6105 Rev. 2. https://www.nasa.gov/feature/release-of-revision-to-the-nasa-systems-engineering-handbook-sp-2016-6105-rev-2
(2) NASA. What are SmallSats and CubeSats? February 26, 2015. Revised August 6, 2017. https://www.nasa.gov/content/what-are-smallsats-and-cubesats
(3) NASA Online Directives Information System (NODIS). https://nodis3.gsfc.nasa.gov/

2.0 Complete Spacecraft Platforms

2.1 Introduction

The capability of combining subsystems into a compact spacecraft platform has advanced considerably since the 2018 edition of this report. Commercial-off-the-shelf (COTS) assembled spacecraft buses enable secondary payloads on larger launch vehicles or via dedicated rideshare opportunities on a small spacecraft launcher, thus expanding the small spacecraft market. These buses provide modular platforms upon which a payload can be hosted and ready to fly in a comparatively short amount of time. Integrated platforms can be used for a wide variety of missions, and the integrated subsystems are operable in a range of environmental and mission conditions.

Two trends have emerged in the nanosatellite bus market: CubeSat component developers with a sufficiently diverse portfolio of subsystems offering package deals, and companies traditionally offering engineering services for larger bespoke platforms miniaturizing their subsystems. This chapter is divided into minisatellite (100 – 180 kg), microsatellite (10 – 100 kg), nanosatellite (1 – 10 kg), and picosatellite (<1 kg) classifications, differentiated by manufacturer. The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

2.2 State-of-the-Art

2.2.1 Minisatellite (100 – 180 kg)

Table 2-1 lists available or in development integrated small spacecraft platforms and their specifications.

Adcole Space

The MagicBus platform (figure 2.1) is equipped with communications encryption, propulsive orbit maintenance capability, and an electro-optical imaging configuration featuring a 24 – 50 cm aperture telescope. The dimensions go up to 965 x 660 x 610 mm with a total system mass of 50 – 220 kg (1). The scalable payload dimensions are 221 x 190 x 99 mm to 210 x 221 x 190 mm with a total system mass of 50 – 220 kg. In collaboration with the U.S. Army Space, Missile Defense Command, and the U.S. Army Forces Strategic Command, the Kestrel Eye 1 spacecraft was based on the MagicBus platform that flew in 2017 for ten months.

Figure 2.1: Kestrel Eye IIM spacecraft on a MagicBus platform. Credit: Adcole Space.

University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS SFL)

The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies has extensive experience building integrated small spacecraft platforms and collecting on-orbit data for their various small satellites

Table 2-1: Integrated Minisatellite Platform Specifications

Product	Vehicle Size (mm)	Payload Mass (kg)	Payload Power (W)	Point Control (arcsec)	Pointing Knowledge (arcsec)	TRL in LEO Environment
Dauntless	1000 x 1000 x 1000	Up to 500	Up to 1000	Unk	Unk	6
Nemo-150	600 x 600 x 600	Up to 70	>50	Unk	Unk	9
MagicBus	965 x 660 x 610	50 – 220	Up to 150, option for 780	±0.15° 3σ	0.01° 3σ	9

missions.

The Nautilus (Nemo-150) bus offers up to 70 kg in payload mass and has an envelope of 600 x 600 x 600 mm. This bus also offers a separation service that provides propulsive capabilities of cold gas, resistojet, monopropulsion, and Hall Effect thrusters (2). This platform will be demonstrated on the nanosatellite for Earth Monitoring and Observation–High Definition (NEMO-HD) mission that is scheduled for launch with Arianespace in August 2020 (3).

2.2.2 Microsatellites (10 – 100 kg)

Table 2-2 is a list of the integrated microsatellite platforms and their specifications

AAC Clyde Space

AAC Clyde Space EPIC spacecraft platforms leverage decades of flight heritage. Available from 1U to 12U, the EPIC platform offers up to 9U in payload volume and a range of configurations. The 6U standard platforms have VHF/UHF transceiver with an in-house whip antenna, transceiver from CPUT/ETSE and a high-speed S-band transmitter with patch antenna for payload communications.

Figure 2.3: EPIC 12U Platform. Credit: AAC Clyde Space.

The payload volumes of the EPIC 12U (figure 2.3) and 12U PLUS are respectively 8U and 9U, a default data storage of 4GB, and 100 Mbps / 9.6 kbps data downlink and 8 Mbps / 6 kbps of uplink capability (4). The 6U platform was demonstrated as part of the NSLSat1 mission, which launched July 2019, and achieved mission success (5). The other platforms have also been flight proven.

Adcole Space

The 12U platform shown in figure 2.4 has two standard configurations that offer varying options for propulsive orbit maintenance capability (up to 138 m s^{-1} with green monopropellant system, and 38 m/s with a water and alcohol bipropellant system), solar array geometries, and S- and L-Band uplink and downlink capabilities. The scalable payload accommodations are 4U (221 × 195 x 960 mm) or 8U (221 × 195 x 192 mm).

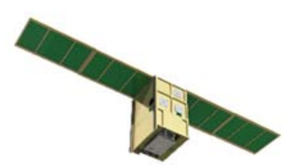


Figure 2.4: 12U platform. Credit: Adcole Space.

Berlin Space Technologies

Berlin Space Technologies manufacturers a series of small spacecraft platforms named the LEOS-30, LEOS-50 and LEOS-100. The LEOS platforms are based on designs flown for multiple TUBSAT and LAPAN missions (6).

The vehicle dimensions range from 300 x 300 x 500 mm to 600 x 600 x 825 mm, with 8 – 30 kg payload mass, and have a built-in transmitter capable of 2 to 100 Mbps downlink (7). BST has supported several flight demonstration missions with their complete spacecraft and Attitude Determination and Control System (ADCS) components.

Blue Canyon Technologies

The full line of Blue Canyon buses provides flexibility for payloads in LEO to Geosynchronous Earth orbits, with kilowatt solar arrays on the X-SAT Saturn, and a range of propulsion options. Blue Canyon's X-SAT Venus ESPA-class microsatellite platform has launched seven times carrying payloads from 10 to 90 kg. The X-SAT Venus carries 400 W solar arrays and optional electric propulsion for maneuvering and momentum management beyond LEO. Blue Canyon's XB6 and XB12 platforms have a maximum allocated payload volume of 4U and 10U respectively, and 4 kg and 8 kg payload mass. These larger CubeSats and X-SAT MicroSats can be equipped with electric and chemical propulsion systems, have downlink capability up to 100 Mbps with in-house X-band and S-band SDR and antennas. Their platforms are compatible with UHF, S-band and X-band equipment, and have been integrated with several commercial as well as in-house radios. The XB6 has extensive flight heritage on several microsatellite missions since 2016 including Asteria, CubeRRT, HaloSat, and TEMPEST-D. The XB12 bus (Figure 2.5) will be provided for two upcoming demonstrations, Link XVI and ASCENT, that are scheduled for launch in 2021.

Figure 2.5: XB12. Credit: Blue Canyon Technologies.

GomSpace

The larger 6U and 12U standard platform (see figure 2.6 for their 6U bus) is capable of a variety space applications and science missions such as radio communication, air track or sea vessel monitoring, and Internet of Things (IoT) data communications constellations. Depending on the chosen system elements, these platforms have a variety of configurations that can be implemented. A more advanced setup utilizes two Sun Tracking Solar Panels (2.6 kg) for high power payloads that can generate up to 70 W of average orbit power for the 6U and up to 75 W for the 12U, and two cold gas thrusters (0.9 kg). The available payload mass for the 6U has a maximum of 8 kg and the 12U can allow up to 16 kg. The downlink capability using a high-speed X-band radio is 225 Mbps and 6 Mbps with a highspeed S-band radio. Two 6U buses flew as part of the GOMX-4 mission and have operated successfully since 2018.

Millennium Space Systems (MSS)

Millennium Space Systems has completed a demonstration of the Altair 1, or Altair Pathfinder, a 6U CubeSat that scales-down the original Altair 27U small spacecraft avionics and architecture. The Altair 1 CubeSat (14 kg) was deployed May 2017 and has operated nominally (8).

NanoAvionics

NanoAvionics offers a series of minisatellite platforms ranging from 6U to 16U: M6P, M12P, and M16P. The standard configuration of the platforms has a vast selection of ADCS operational modes and is optimized for a variety of science missions: IoT, M2M, ADS-B, AIS and other commercial and emergency communication applications, and Earth Observation (EO) missions.

The largest platform is the M16P that provides up to 15U payload volume and contains an in-house, green enabling propulsion system for small satellites (EPSS). The standard configuration of the multifunctional 6U platform M6P was the first preconfigured bus designed to support mission requirements for IoT communications, Earth observation and commercial applications (9). This bus (figure 2.7) has a 7.5 kg payload allocation and includes the EPSS propulsion systems. In April 2019, a demonstration mission was launched using the M6P bus for Lacuna Space LoRa –based Space Gateway that supports an Internet of Things (IoT) communications network comprised of 32 spacecraft. (10)

In June 2020, NanoAvionics was in contract with Thales Alenia Space to build two satellite M12P buses (figure 2.7) for Omnispace's satellite-based Internet of Things (IoT) infrastructure. The payload is being developed by prime contractor Thales Alenia Space, in partnership with Syrlinks (11).

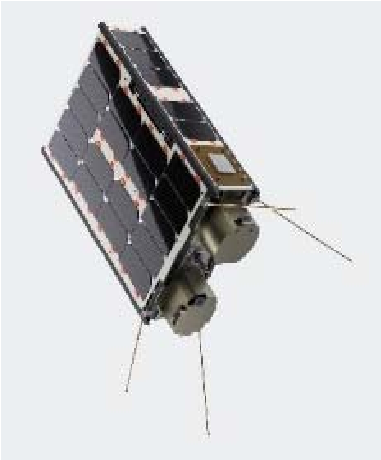


Figure 2.7: (top) M12P platform and (bottom) M6P platform. Credit: NanoAvionics.

Open Cosmos

The 6U and 12U and Microsatellite platforms offer 6 and 12 kg payload mass and are equipped with UHF/VHF, S and X-band radios and transmitters with up to 50 Mbps data downlink rate. Both buses have cold gas propulsive capabilities and provide a redundant data storage of 8 GB and 12 GB respectively. The 6U platform has flown and operated in space multiple times. The 12U platform will be used for the upcoming demonstration mission by Lift Me Off (LMO) in 2021 (12).

SITAEL

Figure 2.8: S-75 platform. Credit: SITAEL S.P.A.

The S-50 and S-75 are the two Microsatellite platforms offered by SITAEL: the S-50 is the smaller platform with 320 x 320 x 400 mm dimensions and up to 20 kg payload mass. The S-75 platform measures 340 x 340 x 660 mm also with a 20 kg payload mass, however this platform has the added capability for Hall Effect electric propulsion, deployable solar arrays, and fine attitude control (13). There are two upcoming missions planned to validate the S-75 platform (figure 2.8) in space and both are a collaborative project between Sitael, ESA and the Italian Space Agency (ASI). The μHETSat mission and the STRIVING project that will launch its maiden spacecraft, are based on the S-75 platform, and both are slated to launch on LauncherOne in 2021. The S-50 platform was released from the SSO-A rideshare mission in December 2018, although there are no details about the specific mission.

Tyvak Nano-Satellite Technology, Inc.

Figure 2.9: Mavericks MicroSat platform. Credit: Tyvak Nano-Satellite Technology, Inc.

There are three microsatellite options that Tyvak offers: the TRESTLES 6U, TRESTLES 12U, and the Mavericks MicroSat platform (figure 2.9). These platforms use the in-house MRK2 avionics platform to support a wider range of mission specifications. The 6U and 12U integrated platforms are equipped with UHF, S-Band, and X-Band antennas with 9.6 kbps to 2 Mbps data downlink capabilities, and have allocated payload volumes from 3U to 9U, respectively. The Mavericks platform provides the option to use a Ka-Band antenna and has a mission dependent payload volume. Tyvak is also involved with six Technology Pathfinder Demonstration missions based on their 6U platform. The first dubbed Tyvak-0129 was launched December 2019, and successfully demonstrated the platform's capabilities (14).

University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS SFL)

The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies has a variety of microsatellite platform buses with flight heritage in low-Earth orbit. The smallest MicroSat platform, Spartan, is a 6U bus that has a 6 kg payload allocation (up to 4U volume). The Jaeger 12U/16U platform offers up to 15 kg payload mass (10U volume). The Nemo bus provides up to 12 kg payload mass. All three buses have radios that offer 50 Mbps downlink capability. Defiant platform is a scalable bus that provides up to 30 kg of payload mass and up to 120 Mbps downlink. All UTIAS SFL integrated buses are equipped with a cold gas propulsion system option (15).

The Grey Jay Pathfinder R&D microsatellite project is a formation flying constellation of three spacecraft that will support the Arctic surveillance technology demonstration. The Grey Jay spacecraft is based on SFL's DEFIANT minisatellite with an envelope of 300 x 300 x 400 mm and up to 30 kg of payload mass (16).

Table 2-2: Integrated Microsatellite Platform Specifications							
Manufacturer	**Product**	**Vehicle Size (mm)**	**Payload Mass (kg)**	**Payload Power (W)**	**Point Control**	**Pointing Knowledge**	**TRL in LEO Environment**
AAC Clyde Space *(Sweden)*	EPIC 6U	Unk	Unk	180 peak	<0.05°	0.002°/s	9
	EPIC 12 U	Unk	Unk	240	Up to 0.05	0.002°	6
	EPIC 12 U Plus	Unk	Unk	300	Up to 0.05	0.002°	6
Adcole Space *(USA)*	12U	Up to 221 × 195 x 192	4U – 7U	84.3 (EOL)	±0.1° 3σ	<10 m	9
Argotech (*Italy*)	Hawk-6	365 x 239 x 109	2.5	Up to 50	0.007 deg 1-sigma	0.011 deg 1-sigma	6
	Hawk-12	365 x 239 x 219	7	Up to 50	0.007 deg 1-sigma	0.011 deg 1-sigma	6
Berlin Space Technologies *(Germany)*	LEOS-30	Unk	20	Unk	Unk	Unk	9
	LEOS-50	600 x 600 x 300	50	20	1	10 arcsec	9
	LEOS-100	600 x 600 x 800	65	60	1	2.5 arcsec	9
Blue Canyon Technologies *(USA)*	XB6	335 x 238 x 115	4	< 140	±0.002°	±0.002°	9
	XB12	335 x 238 x 228	8	< 140	±0.002°	±0.002°	9
	X-SAT Venus	470 x 470 x 230	90	350	±0.002°	±0.002°	9
EnduroSat *(Bulgaria)*	6U	970 x 197 x 223	7.2 – 7.8	10 – 30	< 0.1°	Unk	6
GomSpace *(Denmark)*	6U	Unk	Up to 8	12	Unk	Unk	9
	12U	Unk	Up to 16	Unk	Unk	Unk	6
IMT *(Italy)*	Nadir Platform	320 x 320 x 460 mm	10	15 (EOL)	1°	0.5°	Unk
ISIS *(The Netherlands)*	6U Bus	Unk	6	10	< 0.05°	< 0.05°	9
MSS *(USA)*	Altair	100 x 100 x 600	14 (total)	Unk	Unk	Unk	9
NanoAvionics	Multifunctional 6U	380 x 189 x 236	7.5	32	< 0.2°	< 0.05°	9

(Lithuania)	platform "M6P"						
	Multifunctional 12U platform "M12P"	226 x 226 x 381	17.5	30	< 0.1°	< 0.05°	6
	Multifunctional 16U platform "M16P"	226.3 x 226.3 x 494	16.5	40	< 0.1°	< 0.05°	6
Open Cosmos *(United Kingdom)*	6U	Unk	6	50	Up to 0.01°	40 arcsec 10°s slew rate	9
	12U	Unk	12	100	Up to 0.01°	40 arcsec 10°/s slew rate	6
Sitael *(Italy)*	S-50	340 x 340 x 660	20	26	Up to 0.1	<0.01 arcsec	7
	S-75	320 x 320 x 400	20	< 30	Up to 0.1	<0.006 arcsec	9
	NANOsky I 6U	226 x 100 x 366	6	<150	Unk	Unk	Unk
SkyLabs	NANOsky I 20U	200 x 200 x 500	10-20	<300	Unk	Unk	Unk
Spire Global *(USA)*	LEMUR 6U	100 x 200 x 345	5.0	5 – 12W ave, 45W peak	+/- 3° (pitch & roll), +/- 5° (yaw)	1000 arcsec, 3-sigma	6
Sputnix (Russia)	SXC6 6U	100 x 226.3 x 366	6	35	< 0.1 °	Unk	6
Tyvak NanoSatellite Technology *(USA)*	TRESTLES 6U	Unk	3	180	Unk	Unk	7
	TRESTLES 12U	Unk	13	180	Unk	Unk	7
	MARVERICKS MICROSAT	Unk	Mission Dependent	> 2kW	Unk	Unk	9
UTIAS SFL *(Canada)*	SPARTAN	100 x 200 x 360	6	160	< 2 °	< 2 °	9
	DEFIANT	300 x 300 x 400	5 – 10	< 65	< 2 °	< 2 °	9
	JAEGER 12U	200 x 200 x 360	12	< 76W h/orbit, 215 W peak	2°	10 arcsec/ 1 arcsec	9
	JAEGER 16U	200 x 200 x 450	24	< 76W h/n orbit, 215 W peak	2°	10 arcsec/ 1 arcsec	9

2.2.3 Nanosatellites (1 – 10 kg)

Table 2-3 is a list of the integrated nanosatellite platform specifications.

AAC Clyde Space

The 1U and 3U EPIC nanosatellite platforms have payload volumes ranging from 0.2U – 4.5U and peak payload power from 15 W to 180 W. A 'PLUS' configuration for each platform is also offered that allows for more payload power and volume. The EPIC 3U bus has a VHF/UHF transceiver with an in-house whip antenna and a high-speed S-band transmitter with patch antenna; standard downlink capability is 2 Mbps and high-speed is up to 10 Mbps (17).

Blue Canyon Technologies

Blue Canyon's XB3 Cubesat is its longest operating platform, continuing to provide data from the first XB3 which launched in 2016. The XB3 has continued to gain successful flight heritage on several nanosatellite missions since 2016 (e.g., RAVAN Mission, figure 2.10). The allocated payload mass is 2 kg in ~1.7U volume, and it uses in-house S-band SDR and antennas as the standard communications solution.

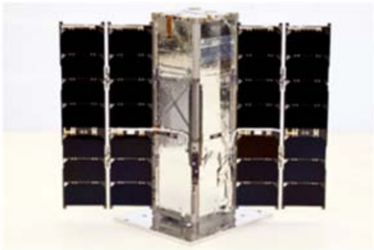


Figure 2.10: BCT XB3 spacecraft bus for the APL RAVAN mission. Credit: NASA.

EnduroSat

EnduroSat currently has a total of 150 systems flying in space and provides 1U – 6U CubeSat platforms. The 1U - 3U have flown in low-Earth orbit. These integrated buses allow for 0.5 kg – 1.5 kg of payload mass and all are customizable. The platforms include an EnduroSat UHF Antenna and UHF Transceiver Type II for 19.2 Kbps data downlink, and can be paired with EnduroSat S-Band and X-Band transmitter and receiver. For each platform, the available mass and power are orbit, mission, and configuration dependent within the range defined by EnduroSat (18). The EnduroSat-1 spacecraft is based on the 1U platform (shown in figure 2.11) and flew successfully in space in May 2018, and the 6U platform is planned for space validation in June 2021 (19).

Figure 2.11: EnduroSat 1U and 3U spacecraft. Credit: EnduroSat.

German Orbital Systems

German Orbital Systems offers a wide range of nanosatellite platforms from 3U to 16U form factor. The 3U spacecraft enables ADS-B signal monitoring, remote sensing in different spectral regions, and IoT applications. For missions using laser terminals or precise orbit control maneuvers, the platforms can be equipped with active ADSC based on reaction wheels or jitter free active ADCS based on fluid-dynamic actuators. With over nine space demonstrations using the standard 3U platform, several space applications have been identified and an advanced 3U platform called the RAVEN has been developed based on previous in-orbit findings (20).

GomSpace

Figure 2.12: GomSpace GOMX 3U bus. Credit: GomSpace.

The GOMX bus has a series of CubeSats under the moniker GOMX that have 1U, 2U, and 3U configurations. The 1U/2U standard platform is designed for signal reception and Earth observation experiments and can be equipped with a GomSpace RGB camera (21). The 1U and 3U buses have operated in low-Earth orbit, and the 3U is shown in figure 2.12.

Gumush Aerospace & Defense

There are modular 1U, 2U and 3U platforms offered at Gumush Aerospace and Defense. The n-ART Basic bus has a 2.2 kg payload mass allocation, and a payload volume of 100 x 100 x 345 mm. The second configuration, n-ART Extreme, has a 1.6 kg payload mass allocation and 100 x 100 x 155 mm payload volume. Both configurations offer UHF/VHF deployable antennas with downlink capability of 1200, and the Extreme platform has S-Band transmitter and Patch Antenna capabilities (100 kbps) (22).

The n-ART bus has been demonstrated in space in support of the QB50 project. BeEagleSat and HAVELSAT are 2U CubeSats that have an in-house X-ray detector and Software Defined Radio (respectively). Both launched in April 2017, and operated nominally.

Ingegneria Marketing Tecnologia (IMT)

The IMT 3U platform has capabilities to support several types of science missions such as atmospheric science, Earth science, and biological experiments. It has a payload allocation of 2.2 kg (1.5U volume), comes with VHF/UHF transmitter and antenna, and 8 GB of data storage capability (23).

Innovative Solutions In Space (ISIS)

ISIS provides platforms ranged from 1U to 6U. The 2U bus can accommodate a payload of 1 kg with 1.5 W average power, and <10° pointing accuracy. The 3U platform offers a scalable payload volume (1.5 – 2U), and has a payload mass of up to 2 kg. The 6U platform offers 6 kg payload mass, and is equipped with the option for a propulsion module (Innovations Solutions in Space 2020). These platforms have been demonstrated in space.

NanoAvionics

Figure 2.13: M3P platform. Credit: NanoAvionics.

Figure 2.13 shows the M3P, a 3U platform that has an optional propulsion system in addition to a 3 kg payload mass allocation. All platforms are pre-integrated mechanically, electrically and functionally tested, and are pre-qualified for easy payload integration. They all use NanoAvionics ADCS sensors and actuators (sun sensors, reaction wheels, and magnetorquers), and are 3-axis stabilized; the M3P has 0.1° attitude pointing and 0.05 of knowledge in default configuration (24).

Satrevolution

The Uni-Bus and Pre-Uni-Bus are scalable platforms respectively from 1.5U, 2U, and 3U and 1U, 1.5U, and 2U. The differences between the Uni- and Pre-Uni buses is fundamental; the Uni-Bus is more powerful and advanced with greater communications capability. The Uni-Bus 3U platform has two UHF radios and S-Band transmitter with downlink capability of 9.6 kbps, and has a maximum available payload volume of 2U. The Pre-Uni platforms are equipped with UHF/VHF transceivers. The 3U Uni-Bus platform will be flown on the SW1FT and STORK missions in 2021 with an additional optical payload (25), shown in

Figure 2.14: SW1FT (right) and STORK (left). Credit: Satrevolution.

Figure 2.14. The 6U and 12U are currently being developed with a S-Band communication system for downlink.

Sputnix

NanoSatellite platforms OrbiCraft-Pro SXC1, SXC3, and SXC6 (1U, 3U, and 6U) are offered with different modifications and a variety of options for each integrated subsystem. The educational modification is a basic CubeSat kit that requires assembly. The experimental platform is assembled ready for payload integration. The Flight modified platform is ready for payload integration and has passed qualification testing. The Profi modified platform comes fully tested with an installed and calibrated ADCS system and solar panels. The available payload mass is 0.43, 2.6, and up to 8 kg, respectively, and all three standard platforms include a default UHF transceiver (9600 bps default downlink capability); the 3U and 6U have the option to use a high speed X-band radio (26).

University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS SFL)

The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies has a 3U nanosatellite platform bus with flight heritage in low-Earth orbit. The smallest platform, Thunder, is a 3U bus that has 3 kg payload allocation (up to 2U volume), offers 2 Mbps downlink capability, and is equipped with a cold gas propulsion system (15). This bus has extensive flight heritage with CanX-7 and -2, and NTS.

Table 2-3: Integrated Nanosatellite Platform Specifications							
Manufacturer	**Product**	**Vehicle Size (mm)**	**Payload Mass (kg)**	**Payload Power (W)**	**Point Control**	**Pointing Knowledge**	**TRL in LEO**
AAC Clyde Space (*Sweden*)	EPIC 1U	Unk	Unk	30 W peak	< 5°	0.020°/s	7
	EPIC 3U	Unk	Unk	120 W peak	< 0.1°	0.005°/s	9
Blue Canyon Technologies *(USA)*	XB3	335 x 115 x 112	2	Up to 60	±0.002°	±0.002°	9
EnduroSat (Bulgaria)	3U	970 x 970 x 150	Up to 1.5	10 – 15 W	< 0.1 – 1°	9	9
	1U	970 x 970 x 108	0.950	900 mW	Up to 3°	9	9
GomSpace (Denmark)	GomS-1U	Unk	1	3.4 W peak	Unk	Unk	9
	GomS-3U	Unk	2	8 W peak power	Unk	Unk	9
Gumush (Turkey)	n-ART Extreme	100 x 100 x 340.5	1.6	4 W Continuous	2°	Unk	9
	n-ART	100 x 100 x 340.5	2.2	Up to 40 W	Unk	Unk	9
IMT (Italy)	1U	970 x 970 x 530	0.5	700 mW	Up to 3°	9	9
	3U	3U Compliant	< 6	3	10°	5°	6
ISIS	1U Bus	Unk	0.7	400 mW	Unk	Unk	9

(The Netherlands)	3U Bus	Unk	Up to 4	10	10° (in sunlight)	Unk	9
MSS *(USA)*	Altair1	100 x 100 x 600	14 (total)	Unk	Unk	Unk	9
NanoAvionics *(Lithuania)*	Multifunctional 3U platform "M3P"	Unk	3	20	up to 0.1°	0.05°	9
OpenCosmos *(Spain)*	3U	Unk	2	25	1º	Unk	9
SatRevolution *(Poland)*	Uni-Bus	Unk	< 2	50 (Peak)	< 0.2°	Unk	9
	Pre-Uni	Unk	< 2	25 (Peak)	< 0.1°	Unk	7
SkyLabs	NANOSky I 3U	100 x 100 x 341	2.5	25	Unk	Unk	Unk
Spacemanic *(Slovakia)*	1U	100 x 100 x 113.5	0.52	0.4	Unk	1° and better (up to 0.1°)	6
	3U	100 x 340 x 100	2.11	0.6	+/- 3º	1° and better (up to 0.1°)	6
Spire Global *(USA)*	LEMUR 3U	100 x 100 x 345	1.5	5 – 12 W ave, 35 W peak	+/- 3º (pitch & roll), +/- 5º (yaw)	1000 arcsec, 3-sigma	9
Sputnix (Russia)	SXC1 1U	108 x 108 x 113.5	0.43	200 mW	Unk	Unk	Unk
	SXC3 3U	108 x 108 x 340.5	3.6	600 mW	Unk	Unk	Unk
UTIAS SFL *(Canada)*	THUNDER 3U	100 x 100 x 340	< 3	Up to 31 Wh/orbit, 62 W peak	2°	10 arcsec	9

2.2.4 Picosatellites

As described in the Introduction, picosatellites, also known as picosats or FemtoSats, are defined as spacecraft with a total mass of 0.1 – 1 kg. In this classification, the PocketQube has been defined as half the size of a 1U CubeSat in 5 cm^3 dimensions, or 1P, where P = 1 PocketQube unit, one-eighth the volume of a CubeSat (27). The mass of these spacecraft vary from 0.15 – 0.28 kg and have been categorized as “1P,” “2P,” and “3P.” Table 2-4 describes the current specifications for PocketQube platforms that are in accordance with the first issue of the PocketQube Standard. Table 2-5 is a list of the integrated PocketQube platforms.

Table 2-4: PocketQube Platform Specifications

Units (P)	Dimensions (mm)	Mass (kg)	Payload Mass (kg)	Power (W)	Payload Power (W)
1P	50 x 50 x 50	0.15 – 0.28	0.1	0.25	Unk
2P	50 x 50 x 114	<0.5	0.3	1	0.5
3P	50 x 50 x 178	<0.75	Unk	5	<5

Professor Twiggs proposed the first PocketQube in 2009 for an academic evaluation of a cost-effective method for engaging students in space sciences. The first PocketQubes launched in November 2013, on a Dnepr rocket via the Morehead Rome Femto Orbital Deployer attached to the UniSat-5 microsatellite (28). Since 2013, several companies and universities have shown an interest in PocketQube design, and by the end of 2019, eleven PocketQubes successfully completed in-space demonstration. The cost for a single 1P PocketQube spacecraft is around $20k, based on a 1P PocketQube being one-eighth of a 1U CubeSat volume and thus one-eighth the cost; a 2P picosatellite is estimated to be 50% the cost of a 3U CubeSat mission (29). Due to this reduced cost, they have become popular for kick-starter companies, and amateur radio satellite designers.

Besides educational purposes, it is difficult to apply these small form factors for Earth observation and telecommunications missions, as these types of missions require high power for heavy data transmission and a fine ADCS for strict pointing requirements; a clear obstacle for this class of spacecraft to fully overcome. However, the low cost of these small spacecraft is a benefit, and the constrained microelectromechanical system (MEMS) components that can be customized and tested are within the budget of a typical CubeSat mission.

Table 2-5: Integrated PocketQube Platforms

Manufacturer	Product	TRL in LEO Environment
Alba Orbital	2P (modular) Unicorn-1	7
Alba Orbital	3P (integrated) Unicorn-2	9
Delft University of Technology	Delfi-PG	6
Picosat Systems	OzQube-1 platform	6

Budapest University of Technology and Economics	SMOG-P, 1P & 3P	9

Alba Orbital

Alba Orbital provides COTS PocketQube platforms. The Unicorn-2 platform (figure 2.15) is based on Alba Orbital's flight demonstrated modular 3P platforms that carried an in-house S-band InterSatellite Link radio as the payload and demonstrated PocketQube ADCS: 2-axis sun sensors, four light dependent resistors, three brushless motors with reaction wheels and three axis magnetometer and magnetorquers, all designed at Alba Orbital. Their UHF and S-band modules can downlink up to 200 kbps.

Figure 2.15: P3 PocketQube with camera. Credit: Alba Orbital.

Delft University of Technology

Delft University of Technology has developed several small spacecraft missions, and has recently established a PocketQube bus called the Delfi PocketQube (Delfi-PQ) that is slated for launch by the end of 2020. This spacecraft will demonstrate a PocketQube-sized ADCS system built at TU Delft; TU Delft plans to demonstrate a PocketQube-sized propulsion system in the near future as well.

Picosat Systems

Picosat Systems provides small spacecraft solutions and has developed the OzQube-1 bus that is based on a 1P modular platform with separate subsystems connected together via a common backplane of a PocketQube (PQ-60 'standard'). This bus went through a trial deployment from a hand-held deployer on a zero-G flight above France and is scheduled for launch by the end of 2020. The power supply for the payload allows up to 1.32 W, however the actual payload will draw <1.25 W during image capturing (37).

2.3 On the Horizon

As spacecraft buses are combinations of the subsystems described in later chapters, it is unlikely there will be any revolutionary changes in this chapter that are not preceded by revolutionary changes in some other chapter. As launch services become cheaper and more commonplace the market will expand, allowing universities and researchers interested in science missions to purchase an entire spacecraft platform as an alternative to developing and integrating it themselves. As subsystems mature, they will be included in future platforms offered by vendors, which will continue to gain flight heritage and improve their platforms with increased performance as newer vendors emerge into the market. This is demonstrated in the use of PocketQubes and their requirement to satisfy ultra-low mass and volume constraints, while simultaneously enabling high-performance capabilities. These smaller form factors have performed in relevant environment and radiation testing, and are more commonly equipped with propulsive capabilities.

As the industry matures, we will likely see key advancements in radiation tolerance and radiation hardening, especially as small spacecraft start venturing into deep space. Subsystems described later in this report include details on radiation testing (see Structures chapter), but a subsystems' mean time between failures (MTBF) and overall system reliability will become key design criterion as the sample groups become large enough to be statistically significant.

2.4 Summary

A number of vendors have pre-designed, fully integrated small spacecraft buses that are space rated and available for purchase. Due to the small but growing market they will of course cooperate with customers to customize the platform. This archetype is continued in the CubeSat form factor, but a new design concept has also emerged: due to the CubeSat standard interfaces, many interchangeable standardized components are available, leveraging consumer electronics standards to approach the plug-and-play philosophy available for terrestrial PCs and computer servers. In particular, CubeSat communications and guidance, navigation and control subsystems have matured significantly. Small spacecraft vendors are building preconfigured platforms with smaller and larger variants to meet the majority of potential smallsat needs. Since the 2018 edition of this report there are more buses available that offer scalability, propulsion integration, and proven avionics. The maturity of these subsystems will facilitate high TRL COTS CubeSats for lunar or deep space environments.

Since the 2018 edition of the report, there have been developments in smaller form factors such as Pico/FemtoSats, although the constraints are still too great for heavy data driven missions. There is a small collection of flight heritage for PocketQubes, which all demonstrated their technology capability, but the desire to have these ultra-small spacecraft perform Earth observation and telecommunications missions is a little daunting. By the end of 2020, there will have been a great leap towards exposing these <1 kg form factors in low-Earth to GEO.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

References

(1) Adcole Maryland Aerospace. MAGICBus 50 kg - 180 kg Satellite Platform, Express Class Satellite - Low Mission Cost, Accelerated Production. [Online] 2018. https://www.adcolemai.com/small-satellites/.

(2) University of Toronto Institute for Aerospace Studies Space Flight Laborator. Products & Services: Satellite Platforms. [Online] 2018. https://www.utias-sfl.net/?page_id=89.

(3) Clark, Stephen. Spaceflight now: After weather delays, Arianespace delays Vega launch to recharge batteries. [Online] 07 2020. https://spaceflightnow.com/2020/07/01/after-weather-delays-arianespace-pauses-vega-launch-operations-to-recharge-batteries/.

(4) AAC Clyde Space. EPIC 12U. [Online] 2020. https://www.aac-clyde.space/epic-spacecraft/epic-12.

(5) AAC-Clyde Space. AAC Clyde Space confirms successful launch of NSLSat-1. [Online] 07 14, 2019. https://www.aac-clyde.space/latest/6-successful-launch-of-nslsat-1.

(6) European Space Agency. LAPAN-A2 - eoPortal Directory - Satellite Missions. *eoPortal Directory - Satellite Missions.* [Online] 2015. https://directory.eoportal.org/web/eoportal/satellite-missions/l/lapan-a2.

(7) Berlin Space Technologies. Berlin Space Tech. [Online] 2020. https://www.berlin-space-tech.com/products/small-satellite-systems/.

(8) Millenium Space Systems, Inc. Altair. *Millenium Space Systems Platforms.* [Online] 2015. http://www.millennium-space.com/platforms.html#altair.

(9) NanoAvionics. 6U CubeSat Platform "M6P" CubeSat Platforms. *NanoAvionics.* [Online] 2018. https://n-avionics.com/cubesat-components/platforms/cubesat-6u-platform-m6p/.

(10) Nanoavionics. Lacuna Space Signs Second Contract With NanoAvionics to Support its Growing IoT Satellite Constellation. [Online] 07 17, 2019. https://nanoavionics.com/press-releases/lacuna-space-signs-second-contract-with-nanoavionics-to-support-its-growing-iot-satellite-constellation/.

(11) NanoAvionics. NanoAvionics Selected by Thales Alenia Space to Build the First Two Satellite Buses for Omnispace Constellation. *NanoAvionics.* [Online] 06 18, 2020. https://nanoavionics.com/press-releases/nanoavionics-selected-by-thales-alenia-space-to-build-the-first-two-satellite-buses-for-omnispace-constellation/.

(12) Open Cosmos. Lift Me Off winner in the Open Cosmos, ESA Space Solutions & ESA Business Applications Call to Orbit. [Online] 01 2020. https://www.open-cosmos.com/news/lift-me-off-winner-in-the-open-cosmos-esa-space-solutions-amp-esa-business-applications-call-to-orbit.

(13) SITAEL. S-200 Platform datasheet. [Online] 2020. http://www.sitael-hellas.com/wp-content/uploads/2015/10/S-200.pdf.

(14) Tyvak NanoSatellite Technology, Inc. Platforms. [Online] 2020. [Cited: Juin 10, 2020.] https://www.tyvak.com/platforms/.

(15) UTIAS SFL. Satellite Platforms. [Online] 2020. [Cited: July 9, 2020.] https://www.utias-sfl.net/?page_id=89.

(16) Boucher, Marc. DND Project Grey Jay will use the SFL Defiant Platform and Other new Details. [Online] 02 25, 2019. https://spaceq.ca/dnd-project-grey-jay-will-use-the-sfl-defiant-platform-and-other-new-details/.

(17) AAC-Clyde. EPIC Spacecraft. *AAC Clyde Space.* [Online] 2020. https://www.aac-clyde.space/epic-spacecraft.

(18) EnduroSat. 6U Cubesat Platform. [Online] 2020. [Cited: June 30, 2020.] https://www.endurosat.com/cubesat-store/all-cubesat-modules/6u-cubesat-platform/.

(19) Spacewatch. Momentus and EnduroSat Announce Two Service Agreements. [Online] 2020. https://spacewatch.global/2020/06/momentus-and-endurosat-announce-two-service-agreements/.

(20) German Orbital Systems. Cubesat Misions. [Online] 2020. https://www.orbitalsystems.de/cubesat-missions/.

(21) GomSpace. U/2U Platform. [Online] 2020. http://gomspace.com/1u-2u-platform.aspx.

(22) Gumush Aerospace & Defense. N-ART BUS. [Online] 2020. [Cited: June 30, 2020.] https://gumush.com.tr/product/n-art-bus/.

(23) Ingegneria Marketing Tecnologia. Cubesat Platform. [Online] 2020. [Cited: June 30, 2020.] http://www.imtsrl.it/cubesat-3u.html.

(24) NanoAvionics. Nanosatellite Buses. [Online] 2020. https://nanoavionics.com/nanosatellite-buses/.

(25) Satrevolution. CubeSat Store. [Online] 2020. [Cited: July 1, 2020.]

(26) Sputnix. Cubesat platforms. [Online] 2020. [Cited: July 1, 2020.] https://sputnix.ru/en/satellites/cubesat-platforms/.

(27) Twiggs, R. and Deepak, R. "*Thinking Out of the Box: Space Science Beyond the CubeSat."* 2012. JoSS, Vol 1.

(28) Wikipedia. PocketQubue. [Online] July 24, 2018. [Cited: August 28, 2018.] https://en.wikipedia.org/wiki/PocketQube.

(29) R J Twiggs, J G Jernigan, L R Cominsky, B K Malphrus, BS Silverman, K Zack, S McNeil, W Roach-Barrett, and T-LogoQube Team. "*The PocketQube Concept."* California State Polytechnic University: s.n., 2014. CubeSat Workshop.

(30) Surrey Satellite Technology Ltd. SSTL Micro. [Online] 2020. https://www.sstl.co.uk/getmedia/78c3ae88-0f17-40a1-9448-8c3c7e9f6944/SSTL-MICRO.pdf.

(31) German Orbital Systems. CUBESAT MISSIONS. [Online] 2020. [Cited: July 8, 2020.] https://www.orbitalsystems.de/cubesat-missions/.

(32) Open Cosmos. 3u, 6u, 12u and small-satellite platforms. [Online] 2020. [Cited: June 30, 2020.] https://www.open-cosmos.com/satellites.

(33) Sequoia Space. NANU-K SATELLITES. [Online] 2020. [Cited: July 8, 2020.] https://www.sequoiaspace.com.co/.

(34) Spacemanic. Cubesat Platforms. [Online] 2020. [Cited: July 8, 2020.] https://spacemanic.com/cubesat-platforms/.

(35) Sputnix. Cubesat nanosatellite platform line Sputnix LLC. [Online] 2020. [Cited: July 9, 2020.] https://sputnix.ru/tpl/docs/SPUTNIX-Cubesat%20platforms-eng.pdf.

(36) Kestrel Eye. *ePortal Directory.* [Online] 2018. https://directory.eoportal.org/web/eoportal/satellite-missions/k/kestrel-eye.

(37) McAndrew, S. " Development of OzQube-1". 1st Asian PocketQube Workshop. November 5, 2018.

3.0 Power

3.1 Introduction

The electrical power system (EPS) encompasses electrical power generation, storage, and distribution. The EPS is a major, fundamental subsystem, and commonly comprises up to one-third of total spacecraft mass and volume. Power generation technologies include photovoltaic cells, panels and arrays, and radioisotope or other thermonuclear power generators. Power storage typically occurs in batteries; either single-use primary batteries, or rechargeable secondary batteries. Power management and distribution (PMAD) systems facilitate power control to spacecraft loads. PMAD takes a variety of forms and is often custom-designed to meet specific mission requirements. EPS engineers often target a high specific power or power-to-mass ratio (W h kg^{-1}) when selecting power generation and storage technologies to minimize system mass impact. The volume is more likely to be the constraining factor for nanosatellites.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

3.2 State-of-the-Art – Power Generation

3.2.1 Solar Cells

Solar power generation is the predominant method of power generation on small spacecraft. As of 2020, approximately 85% of all nanosatellite form factor spacecraft were equipped with solar panels and rechargeable batteries. Limitations to solar cell use include diminished efficacy in deep-space applications, no generation during eclipse periods, degradation over mission lifetime (due to aging and radiation), high surface area, mass, and cost. In order to pack more solar cells into limited volume in SmallSats and NanoSats, mechanical deployment mechanisms can be added, which may increase spacecraft design complexity, reliability, as well as risks. Photovoltaic cells, or solar cells, are made from thin semiconductor wafers that produce electric current when exposed to light. The light available to a spacecraft solar array, also called solar intensity, varies as the inverse square of the distance from the Sun. The projected surface area of the panels exposed to the Sun also affects generation, and varies as a cosine of the angle between said panel and the Sun.

While single junction cells are cheap to manufacture, they carry a relatively low efficiency, usually less than 20%, and are not included in this report. Modern spacecraft designers favor multi-junction solar cells made from multiple layers of light-absorbing materials that efficiently convert specific wavelength regions of the solar spectrum into energy, thereby using a wider spectrum of solar radiation (1).

The theoretical efficiency limit for an infinite-junction cell is 86.6% in concentrated sunlight (2). However, in the aerospace industry, triple-junction cells are commonly used due to their high efficiency-to-cost ratio compared to other cells. Figure 3.1 illustrates the available technologies plotted by energy efficiency. This section individually covers small spacecraft targeted cells, fully-integrated panels, and arrays. Table 3-1 itemizes small spacecraft solar panel efficiency per the available manufacturers. Note the efficiency may vary depending on the solar cells chosen.

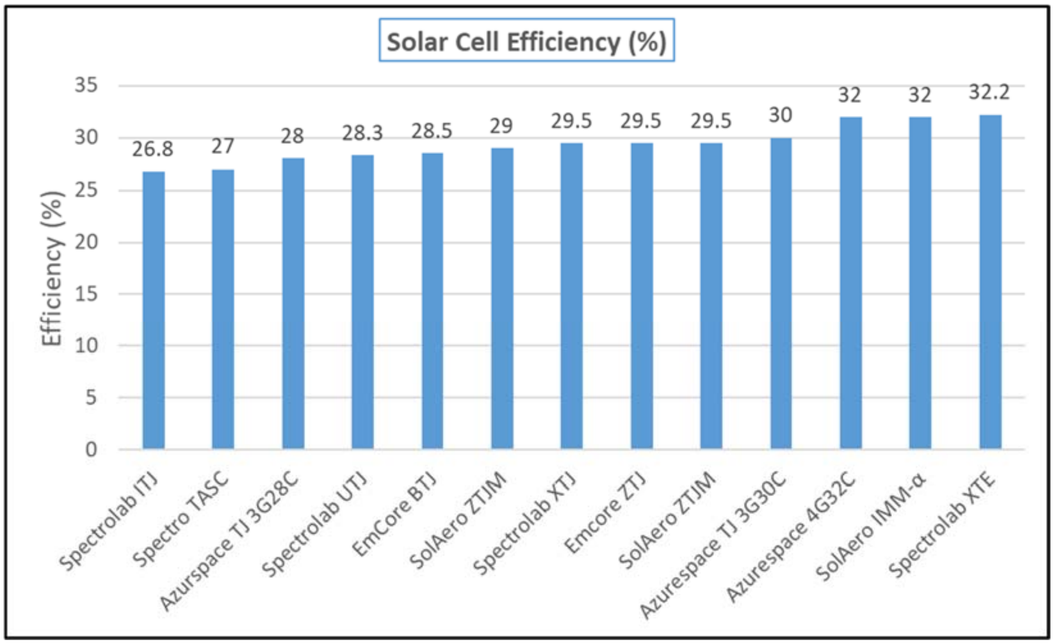


Figure 3.1: Solar cell efficiency. Credit: NASA.

AzurSpace

AzurSpace offers multi-junction solar cells with efficiencies ranging from 28 – 32%. Cells are built from layered GaInP/GaAs/Ge materials, and several dimensional options exist. These cells are used quite often with other solar arrays for space applications. Their 32% efficiency-class, quadruple-junction cells have a thickness of 80μm and measure 40 x 80 mm ± 0.1 mm with a typical operational voltage of 2900 mV (3).

Emcore Corporation

Emcore produces two triple-junction solar cells with 28.5% and 29.5% average efficiency that are available in standard and custom sizes. These second and third generation cells have rich flight heritage; ZTJ cells were flown on NASA's CYGNUS mission (4). The 27.7% triple-junction solar cells with a 0.9 W maximum power point were selected for the 3U Phoenix CubeSat, part of the QB50 mission initiative launched in Spring 2017 (5).

Spectrolab

SpectroLab offers several solar cells in the 28.3 – 32.2% average efficiency range (Ultra Triple Junction (UTJ), NeXt Triple Junction (XTJ), XTJ-Prime and XTE series). The most efficient XTE cells are 32.2% and are available in 27 cm^2 to > 80 cm^2 (6). The XTJ Prime cell energy conversion efficiency is 30.7% and can be delivered in scalable sizes (27 cm^2 through 84 cm^2). The XTJ Prime is built on a heritage upright lattice matched XTJ structure (7). The 29.5% XJT solar cells have been geostationary orbit (GEO) qualified; wafers are 140 μm thick. The Ultra Triple Junction cells range from 27.7 – 28.3% efficiency, and are low-Earth orbit and GEO qualified with performance validated in orbit to 1% of ground test results. The UTJ devices are rated at TRL 9 for small spacecraft applications (8).

SolAero Technologies

Solar cells manufactured by SolAero range from 28 – 32% average efficiency and have extensive flight heritage on both large and small spacecraft. SolAero also manufactures 27% - 29.5% efficiency solar cells (BJT, ATJ, and ZTJ) that are fully space qualified for small spacecraft missions (9).

A collaboration between the Air Force Research Laboratory (AFRL) and SolAero has developed Metamorphic Multi-Junction (IMM-α) solar cells that have been shown to be less costly with increased power efficiency for military space applications (1). The process for developing IMM-α cells involves growing them upside down, where reversing the growth substrate and the semiconductor materials allows the materials to bond to the mechanical handle, resulting in more effective use of the solar spectrum (1). A single cell can leverage up to 32% of captured sunlight into available energy. This also results in a lighter, more flexible product. These cells had their first successful orbit in low-Earth orbit in 2018, and since then they have operated in low-Earth orbit on other CubeSat missions.

Table 3-1: Solar Array/Panel Products

Product	Manufacturer	Solar Cells Used	TRL
Solar Panel (0.5-12U); Deployable Solar Panel (1U, 3U)	AAC Clyde Space	SpectroLab UTJ	9
Solar Panel (0.5-12U); Deployable Solar Panel (1U, 3U)	AAC Clyde Space	SpectroLab XTJ	9
Solar Panel (0.5-12U); Deployable Solar Panel (1U, 3U)	AAC Clyde Space	AzurSpace 3G30A	9
Sparkwing Solar Panel	Airbus Defense and Space	AzurSpace 3G30A	6
DSA/1A	CubeSatshop	AzurSpace 3G30A	9
Solar Panel (5 x 5 cm, 1U, 2U 3U, 6U, 12U)	DHV Technology	AzurSpace 3G30C Advanced, Solaero ZTJ-Ω	9
Solar Panel	EnduroSat	CESI CTJ30 & AzurSpace 3G30	9
NanoPower (CubeSat and custom)	GomSpace	AzurSpace 3G30A	9
CubeSat Solar Panels	ISIS	AzurSpace 3G30x	9
GaAs Solar Arrays	NanoAvionics	N/A	N/A
Varies	Pumpkin	SpectroLab XTJ Prime	9
HaWK	MMA	SpectroLab XTJ	9
eHaWK	MMA	SpectroLab XTJ & Prime	9
Space Solar Panel	SpectroLab	SolAero ITJ	9
Space Solar Panel	SpectroLab	SolAero UTJ	9
Space Solar Panel	SpectroLab	SolAero XTJ	9
Space Solar Panel	SpectroLab	SolAero XTJ Prime	9

3.2.2 Solar Panels & Arrays

AAC Clyde Space

AAC Clyde Space solar panels use 28.3% efficient, Spectrolab UTJ cells, mounted to printed circuit boards (PCB) of a carbon fiber-reinforced plastic (CFRP) substrate, nominally fitting a 7S1P and 9S2P cell configuration per 3U and 6U panel face, respectively (figure 3.2). Their spring-loaded hinges and hold-down/release mechanism have been proven on numerous SmallSat missions (10).

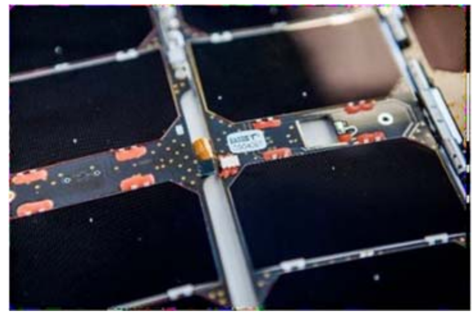


Figure 3.2: AAC Clyde Space solar arrays. Credit: AAC Clyde Space.

Airbus Defense and Space Netherlands

Sparkwing is a commercial-off-the-shelf (COTS) solar array for SmallSats (figure 3.3) that includes mechanical and electrical interfacing designed for plug & play integration to the spacecraft. More than 30 different panel dimensions are available, which can be configured into deployable wings with one, two or three panels per wing. The solar arrays are made with Azur 3G30A cells that have beginning-of-life (BOL) average efficiency of 29.5% and are offered in 19 or 26 cells in series and in a variety of dimensions. The power output range in low-Earth orbit per wing is from 66 W BOL for the smallest variant (1 panel of 440 x 700 mm) to 1077 W BOL for the largest variant (3 panels of 1070 x 1100 mm). Each wing includes one central hold-down and release mechanism, one hinge line and 4 snubbers as the mechanical interface to the spacecraft. The Sparkwing design is based on the solar array products for large satellites that have extensive flight heritage in low-Earth orbit, medium Earth orbit (MEO), GEO and interplanetary missions, and these arrays will undergo an extensive final test program starting September 2020.

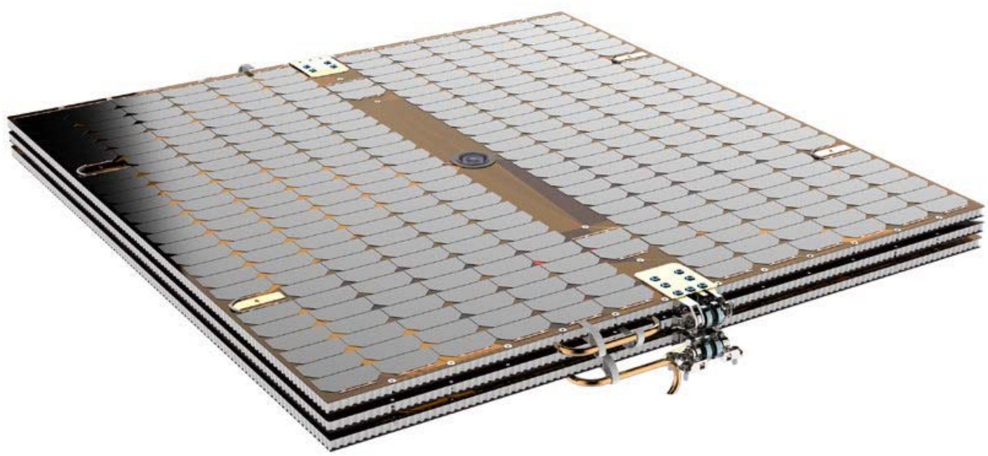


Figure 3.3: Sparkwing solar panel. Credit: Airbus Defense and Space Netherlands.

Astro- und Feinwerktechnik

Astro- und Feinwerktechnik have developed an adaptable solar array for minisatellites that is approximately 120 W with a mass of 4.19 kg. The startup-configuration dimensions are 546 x 548 x 620 mm. These arrays successfully flew on the 120 kg microsatellite TET-1 in 2012.

DHV Technology

DHV Technology manufactures a wide range of solar panels sizes (figure 3.4), from 1U to 12U CubeSats and custom sized CFRP solar panels. The 1U solar panels weigh <0.040 kg and produce 2.24 W, and several deployable CubeSats, 3U-Triple deployable (<0.35 kg) that generate 22.2 W and 12-Doble Deployable (<0.6 kg) that generate 40 W. The CFRP Panels are manufactured for different power buses as 28V or 50V and customizing the mechanical and electrical interface when needed.

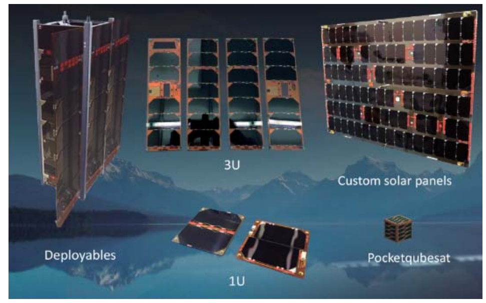


Figure 3.4: DHV's range of small satellite solar panels. Credit: DHV Technology.

DHV Technology is also working with the design and manufacture of multi-deployable solar arrays for larger SmallSat platforms that can reach per system up to 1200W. Currently in TRL 7 but TRL 9 is estimated by end of 2020.

EnduroSat

EnduroSat sells a variety of space-qualified solar panels with triple junction (InGaP/GaAs/Ge) cells rated to 29.5% efficiency. Cell thickness is 150 μm ± 20 μm. They offer 1U/1.5U/3U/6U and customized 3U and 6U solar panels, as well as deployable arrays (figure 3.5). The 1U and 3U overall panel masses are 0.04 kg and 0.155 kg, respectively. Maximum cell voltages are 2.33 V per cell (11). They also offer 5 configurations (X/Y, X/Y with Magnetorquer, Z, Z with Magnetorquer, X/Y with RBF) that have a mass range of 0.058 – 0.043 kg. The 1U configuration flew on EnduroSat-1 launched in May 2018.

Figure 3.5: 3U deployable solar array. Credit: EnduroSat.

GomSpace

GomSpace produces two NanoPower power systems for CubeSats, both use 30% efficient cells and include Sun sensors and gyroscopes. The customizable panels have a maximum output of 6.2 W and 7.1 W and include a magnetorquer. The CubeSat panel weighs 0.026 – 0.029 kg without an integrated magnetorquer, or 0.056 – 0.065 kg with one, and produces 2.3 – 2.4 W (12).

Innovative Solutions In Space (ISIS)

ISIS provides high-performance, CubeSat compatible solar panels that come in 1 – 6U sizes, for use on applications up to 24U. Custom sizes are also available and figure 3.6 shows 3U panels integrated on a CubeSat. These solar arrays are compatible with Pumpkin structures and the GomSpace NanoPower EPS. ISIS solar panels have flight heritage since 2013. ISIS solar panels use Azur Space solar cells that offer up to 30% efficiency (13). The 3U MIniature Student saTellite (MIST) CubeSat will fly with two ISIS 3U solar panels, expected to launch in 2021 (14).

Another solar array product for standard 1U ~ 6U configuration. The EXA DSA series shown in figure 3.6 use a titanium scaffold for the deployment mechanism which provides a thin (0.25 mm) and sturdy structure while reducing mass. The arrays are composed of five panels, three on the top and two on the bottom, that attached to the CubeSat structure. AzureSpace 30G-30 solar cells are used to provide high power efficiency (29.6%) while maintaining low cost due to the maturity of the cells.

NanoAvionics

Figure 3.6: (right) 3U solar panels and (left) EXA DSA solar arrays. Credit: ISIS.

This manufacturer provides 1U – 12U and custom-size GaAs (Triple junction GaInP/GaInAs/Ge epitaxial structure) solar arrays rated up to 29.5 % efficiency. These solar arrays have 36.85 mW cm^{-2} power-generation capacity in LEO and a PCB thickness of <1.7 mm (15). Figure 3.7 shows their CubeSat GaAs solar panel.

Figure 3.7: CubeSat GaAs solar panel. Credit: NanoAvionics.

MMA Design, LLC

MMA Design's HaWK (High Watts per Kilogram) solar array designed for 3U – 12U platform spacecraft is deployable and gimbaled. The original HaWK peak power is 36 W with a voltage of 14.2 V (16). The eHaWK solar array is a modular, scalable system designed for 6U CubeSats and larger buses. The eHaWK starts at 72 W, uses Spectrolab UTJ 28.3% or XTJ-Prime 30.7% cells, and weighs approximately 0.6 kg (17). The HaWK is scheduled to launch on NASA's BioSentinel mission in 2020, and eHaWK (figure 3.8) is already in deep space onboard the MarCO mission since 2018.

MMA also has zHaWK and rHaWK solar arrays that are based on HaWK series. The zHaWK consists of two array wings that are mounted on opposite 1U x 3U faces that consist of 6 panels (42 cells total), similarly to the HaWK configuration. The estimated mass of this array is 0.35 kg. The rHaWK produces 90+ kW m^{-3} and 150+ W kg^{-1} at 28^{o}C. The RHaWK leverages scaled, proven TRL 7 – 8 solar array technologies that has been in development under multiple Air Force Research Laboratory (AFRL) and NASA Small Business Innovation Research (SBIR) (18).

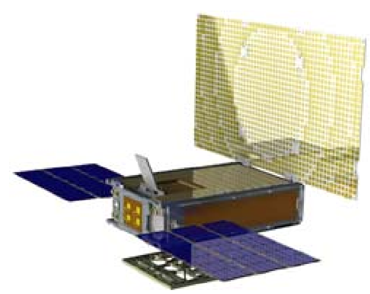


Figure 3.8: MMA's eHaWK solar array on the Mars Cube One (MarCO) CubeSat. Credit: NASA.

Pumpkin, Inc.

Pumpkin is one of the most commonly used CubeSat buses. It offers a large selection of standardized 1U – 6U solar array panels as well as custom designed solar array power products.

The SUPERNOVA series (figure 3.9) for example, offers 64 W off power at 6U configuration. Pumpkin mainly uses SpectroLab XTJ Prime cells (30.7% efficiency) although other alternative cells can be used. Pumpkin's Modular Deployable Solar Array System (PMDSAS) technology combines materials, processes, design innovations and technologies to manufacture both fixed and deployable solar panels for nanosatellites. Standard, COTS panels are available, as well as custom designs. Pumpkin solar arrays have achieved TRL 9 with various spaceflight missions.

Figure 3.9: Pumpkin SUPERNOVA 64 W 6U configuration. Credit: Pumpkin, Inc.

SpectroLab

SpectroLab's space solar panels have flown on multiple spacecraft in low-Earth orbit and GEO. They are available in small sizes (30 cm^2) and use SpectroLab's Improved Triple Junction (ITJ), UTJ, or XTJ cells (19). Their solar panels were also used on the Juno spacecraft, which reached Jupiter in the Summer of 2016.

3.3 Power Storage

Solar energy is not always available during spacecraft operations; the orbit, mission duration, distance from the Sun, or peak loads may necessitate stored, on-board energy. Primary and secondary batteries are used for power storage and are classified according to their different electrochemistries. As primary-type batteries are not rechargeable, they are used only for short mission durations (around 1 day, up to 1 week). Silver-zinc are typically used as they are easier to handle and discharge at a higher rate, however there are also a variety of lithium-based primary batteries that have a higher energy density, including: lithium Sulfur dioxide ($LiSO_2$), lithium carbon monofluoride ($LiCF_x$) and lithium thionyl chloride ($LiSOCl_2$) (20).

Secondary-type batteries include nickel-cadmium (NiCd), nickel-hydrogen (NiH_2), lithium-ion (Li-ion) and lithium polymer (LiPo), which have been used extensively in the past on small spacecraft. Lithium-based secondary batteries are commonly used in portable electronic devices because of their rechargeability, low weight, and high energy, and have become ubiquitous on spacecraft missions. They are generally connected to a primary energy source (e.g. a solar array) and are able to provide rechargeable power on-demand. Each battery type is associated with certain applications that depend on performance parameters, including energy density, cycle life and reliability (20). A comparison of energy densities can be seen in figure 3.10, and a list of battery energy densities per manufacturer is given in table 3-2.

This section will discuss the individual chemical cells as well as pre-assembled batteries of multiple connected cells offered from multiple manufacturers. Due to small spacecraft mass and volume requirements, the batteries and cells in this section will be arranged according to specific energy, or energy per unit mass. There are, however, a number of other factors worth considering, some of which will be discussed below (21).

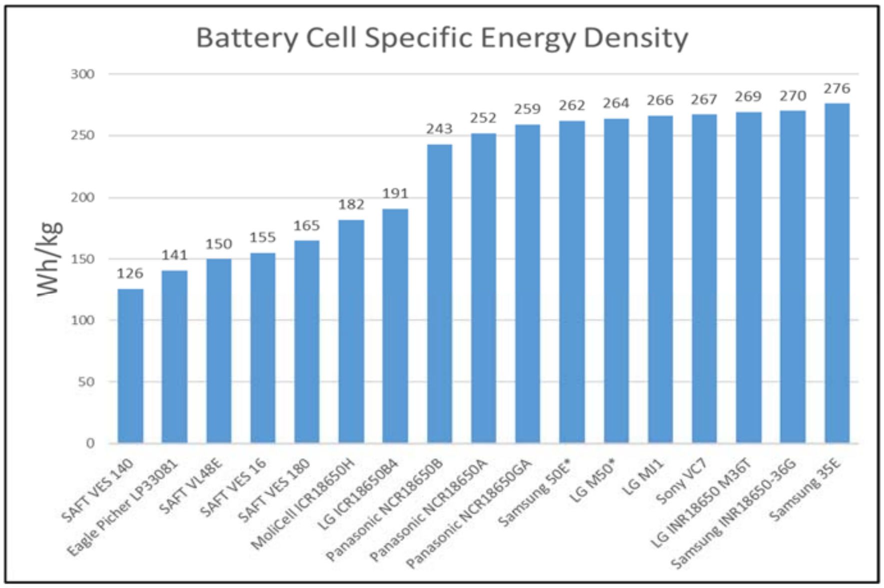


Figure 3.10: Battery cell energy density. Credit: NASA.

Table 3-2: Battery Product Energy Density				
Product	**Manufacturer**	**Specific Energy ($W\ h\ kg^{-1}$)**	**Cells Used**	**TRL**
40 W hr CubeSat Battery	AAC Clyde Space	119	Clyde Space Li-Polymer	9
COTS 18650 Li-ion Battery	ABSL	90 – 243	Sony, MoliCell, LG, Sanyo, Samsung	8
BAT-100	Berlin Space Technologies	58.1	Lithium-Ferrite (Li-Fe)	9
BCT Battery	Blue Canyon Technologies	Unk	Li-ion or LiFePo4	9
BP-930s	Canon	132	Four 18650 Li-ion cells	9
Rechargeable Space Battery (NPD-002271)	EaglePicher	105 – 117	EaglePicher Li-ion	7
NanoPower BP4, BPX	GomSpace	143, 154	GomSpace NanoPower Li-ion	9
Modular SmallSat Battery	ibeos	109.8	Unk	Unk
4S1P VES16 battery	Saft	155	SAFT Li-ion	9
Li-MnO2 and Li-CFx	Ultralife Corporation	350 – 450	Li-MnO2 and Li-CFx	9
Li-ion Battery Block VLB-X	Vectronic	Unk	SAFT Li-ion	9

Due to the extremely short mission durations with primary cells, the current state-of-the-art energy storage systems use lithium ion (Li-ion) or lithium polymer (LiPo) secondary cells, so this subsection will focus only on these electrochemical compositions, with some exceptions.

3.3.1 Secondary Li-ion and Li-po Batteries

Typically, Li-ion cells deliver an average voltage of 3.6 V, while the highest specific energy obtained is well in excess of 150 W h kg^{-1} (21). Unlike electronics, battery cells do not typically show significant damage or capacity losses due to radiation. However, in an experiment done by JPL, some capacity loss is seen among these latest lithium ion battery cells under high dosage of Cobalt-60. The results are shown below in figure 3.11 (22).

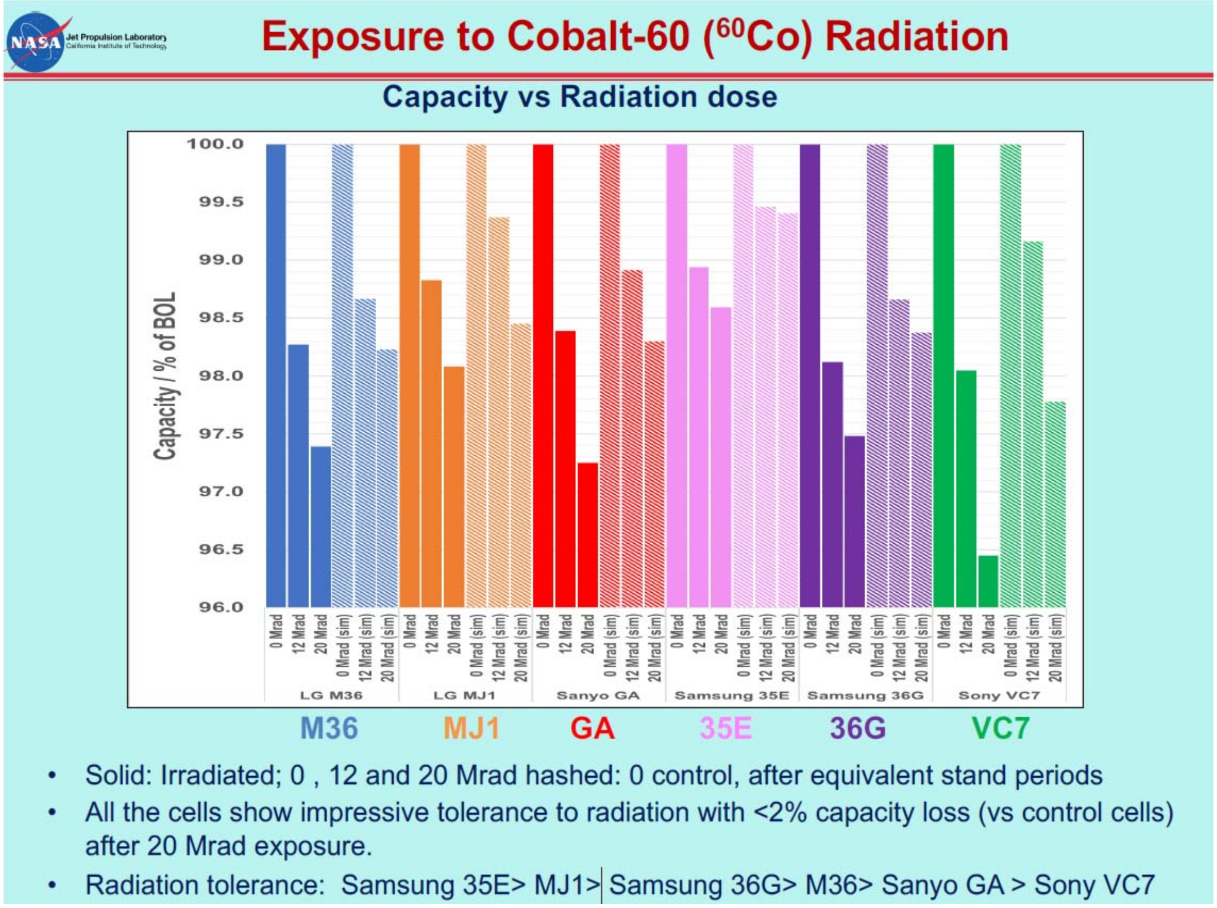


Figure 3.11: Capacity vs. radiation dose. Credit: JPL.

AAC CLYDE SPACE

AAC Clyde Space has designed Li-polymer batteries (Optimus) specifically for small spacecraft and CubeSats, leveraging a vast investment in Li-polymer technology. The model featured in table 3-2 has a specific energy of 119 W h kg^{-1} and voltage of 6.2 – 8.4 V (figure 3.12). Battery temperature, voltage, current and telemetry can be monitored via an integrated digital interface. The use of Li-polymer cells allows the AAC Clyde Space flat-packed batteries to be mass and volume efficient. Their third generation CubeSat battery line

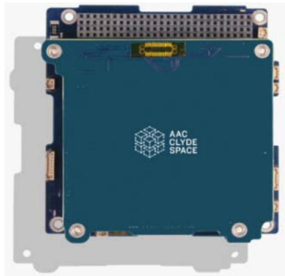


Figure 3.12: AAC Clyde Space battery pack. Credit: AAC Clyde Space.

provides 30 – 80 W h standalone batteries that interface with their Electrical Power System (EPS) offerings built on a standard PC104 interface (23).

ABSL

ABSL's Li-ion 18650 cells have an energy density range of 130 – 275 W h kg^{-1}. ABSL's heritage military and space grade cells (figure 3.13) have proven long-term reliability and charge life, with safety & protection features built into the battery cells (ABSL 2007). ABSL provides spacecraft batteries of all sizes ranging from 4.5 A h to greater than 390 A h capacity. ABSL's commercial offering for small spacecraft has a nominal voltage of 29.6 V, capacity of 8.4 A h, and nominal mass of 1.66 kg. Customs solutions are available beyond the commercial offering to meet specific spacecraft or mission needs.

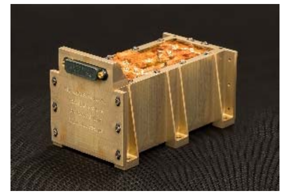


Figure 3.13: ABSL COTS Li-ion battery. Credit: ABSL.

DHV Technology

DHV Technology has designed and manufactured a battery pack configurable for different CubeSat sizes and requirements, see figure 3.14. The main board (motherboard) has 2 battery cells connected in series and the electronics to control the power storage, then the daughter boards (auxiliary boards) are connected in a very efficient volume package in parallel with the motherboard, being able to select the power storage needed from 10 W h up to 40 W h. The voltage of the battery pack is 7.4 V at nominal conditions and 8.4 V when fully charged. TRL 9 is expected by the end of 2020. DHV Technology is going to fly this subsystem in D3-Cubesat (D3-University of Florida, Gainesville), SOC-I CubeSat (University of Washington) and NEPTUNO-I (Deimos Space) missions.

Figure 3.14: DHV battery pack. Credit: DHV.

Eagle Picher

Eagle Picher has been making primary and secondary cells for military and aerospace since the beginnings of the space race, including cells that flew on the Apollo missions and several other missions since. Eagle Picher produces a number of cells and batteries for military and aerospace applications including advanced Li-ion cells and a host of rechargeable space batteries. Both cells have a high energy density and a TRL of 9. These advanced cells have a specially formulated electrolyte that allows charging and discharging at reduced temperatures as low as -20°C. Their integrated space battery offerings have slightly less heritage than their cells, but they use the same flight-proven cells.

GomSpace

GomSpace offers a range of CubeSat subsystems, including Li-ion batteries. Their NanoPower BP4 Quad-Battery-Pack is designed to integrate seamlessly with their P-series PMADs. It is stackable and available in an International Space Station compliant version. NanoPower BP4 has a TRL of 9, having flown on board the GOMX-1 mission. The BPX series allows a wide range of parallel/series combinations and connections of up to sixteen cells (25). The NanoPower P31u, developed for nanosatellite platforms, is optimal for 1 and 2U platforms. The P31u, rated at 20 W h capacity, can provide up to 30 W at 8 V (26).

Ibeos

Ibeos' 45 W h, 14 V lithium-ion battery module is a radiation tolerant, fault tolerant, and International Space Station (ISS) compliant energy storage system (figure 3.15). The aluminum and PEEK packaging is rigid, thermally conductive, and enables flexible mechanical and thermal spacecraft interfacing. A thermistor and polyimide thermofoil heater allow for thermal control. Radiation tolerant battery interface electronics (BIE) provide a remove-before-flight inhibit in addition to over-voltage, over-current, and under-voltage protection. The chassis design enables mechanical integration with a second module to achieve a 90 W h capacity. The individually protected/inhibited battery modules can be connected in parallel to achieve a desired capacity and charge/discharge current. This battery module is designed for turn-key integration with the Ibeos 150-Watt CubeSat EPS (27).

Figure 3.15: Ibeos 14 V lithium-ion battery. Credit: Ibeos.

SAFT

SAFT is a European commercial battery manufacturer and through their Special Battery Group (SBG) they have offered batteries for space applications for more than 80 years. They are a full service battery house offering individual lithium Ion cells both prismatic and cylindrical. The VES16 is a standard cylindrical cell with flight heritage that touts up to 12 years life in low-Earth orbit applications. They also offer complete assembled batteries with integrated circuit breakers, thermal controls, and full flight testing and certifications. Their standard design for space applications is a 4S1P VES16 battery. It has a 64 W h capacity, at 13.2 – 16.4 V, with safe operation from 10 to 30°C.

Ultralife Corporation

There are two battery cells from Ultralife for small spacecraft applications where primary batteries are an option. The Li-MnO2 and Li-CFx provide an energy density ranging from 350 to 450 W h kg^{-1}. Lithium manganese dioxide cells offer excellent temperature characteristics, a flat discharge curve, and a hermetically sealed, nickel-plated steel container for long-term shelf life. Lithium Carbon Monoflouride cells have the highest energy density and performance characteristics of all lithium based battery chemistries with a strong passivation layer, which allows for long storage periods with minimal loss in cell capacity (28). Ultralife's newest hybrid primary cell technology improves upon lithium manganese dioxide chemistry by providing almost a 50% increase in both capacity and shelf-life, whilst also reducing initial suppression of cell voltage that is typical of pure CFx chemistries due to passivation during storage. The Ultralife Hybrid cells come in a variety of sizes (19650, 26500, 26650 and 34610) and are TRL 9 (28).

18650 Cells

18650 cylindrical cells (18 x 65 mm) have been an industry standard for lithium ion battery cells. LG's ICR18650 B3 Li-ion cells have a specific energy of 191 W h kg^{-1} and have flown on NASA's PhoneSat spacecraft, housed in a 2S2P battery holder from BatterySpace (30). Panasonic produces the NCR18650B (3350 mA h) Li-ion cells, which have a high energy density of 243 W h kg^{-1}. Molicel offers several different 18650 battery pack modules that are space proven. They manufacture the ICR18650H Li-ion cell with a high specific energy of 182 W h kg^{-1} which requires pack control circuitry (31). A Li-Ion 18650 Battery Holder (2S2P) flew on NASA's EDSN mission, in conjunction with LG ICR18650 B3 Li-ion cells. Canon's BP-930s battery pack is an affordable, flight-proven option for power storage (32). The pack contains four 18650 Li-cells and has flown successfully on NASA's TechEdSat missions.

Two new 18650-sized products promise improved performance over heritage devices. The Panasonic NCR18650GA, at 3450 mA h, provides a specific energy density of 258 W h kg^{-1}. The LG MJ1, currently under evaluation at NASA Johnson Space Center (JSC), is rated to 3500 mA h.

21700 Cells

21700 (21 x 70mm) is another type of cylindrical cells that are getting more popular. Samsung 50E and LG M50 both offer 5000 mA h of energy while the Samsung cells are slightly heavier. The specific energy densities are 262 W h kg^{-1} and 264 W h kg^{-1} respectively. Although 21700 cells are slightly larger than 18650 cells, they are among some of the cells with highest energy densities. They could offer some mechanical packaging benefits with fewer cells for certain missions.

3.4 Power Management and Distribution

PMAD systems control the flow of power to spacecraft subsystems and instruments and are often custom designed by mission engineers for specific spacecraft power requirements. However, several manufacturers have begun to provide a variety of PMAD devices for inclusion in small spacecraft missions. Several manufacturers supply EPS which typically have a main battery bus voltage of 8.2 V, but can distribute a regulated 5.0 V and 3.3 V to various subsystems. The EPS also protects the electronics and batteries from off-nominal current and voltage conditions. As the community settles on standard bus voltages, PMAD standardization may follow. Well-known producers of PMAD systems that focus on the small spacecraft market include Pumpkin, GomSpace, Stras Space and AAC Clyde Space. However, a number of new producers have begun to enter the PMAD market with a variety of products, some of which are listed below. Table 3-3 lists PMAD system manufacturers; it should be noted that this list is not exhaustive.

3.4.1 AAC Clyde Space

AAC Clyde Space provides three Power Conditioning and Distribution Unit (PCDU) products for both nanosatellites and larger small spacecraft. The STARBUCK-MICRO, -MINI, -NANO, and -PICO are equipped with different user interfaces and designed for easy integration of payloads, sensors, and sub-systems on advanced small satellites. The STARBUCK-Pico and -Nano are specifically for 1U – 16U spacecraft, and the STARBUCK-MINI and -MICRO PCDUs for larger small spacecraft. The STARBUCK-MINI can delivered an average power up to 500 W at 28 V and uses RS485 as well as CAN Bus. The Starbuck-NANO (figure 3.16) is a CubeSat/PC104 formatted EPS that distributes 3.3 V, 5 V and 12 V, and the main communication protocol is I^{2}C (33).

Figure 3.16: STARBUCK-NANO EPS. Credit: AAC Clyde Space.

3.4.2 Crystalspace

The Vasik P1U power supply is optimized for 1U and 2U CubeSats. The battery output traverses though redundant converters that can provide 3.3 V, 5 V and 12 V. The supply's energy rating is 3 A h (11 W h), with a mass of 0.08 kg (34). Unregulated 3.7 V and regulated buses are also available. This EPS architecture was successfully flight-tested on the ESTCube-1 satellite and is TRL 9.

3.4.3 DHV Technology

Figure 3.17: EPS for CubeSats. Credit: DHV Technology.

DHV Technology CubeSat EPS is defined by a scalability (motherboard with the control electronics for the system, and daughterboard to increase the number of solar panels to be connected) for different CubeSat sizes and an optimized mass of 0.066 kg for the configuration of a 3U CubeSat with body mounted panels. The CubeSat EPS (figure 3.17) is designed for maximum power point tracking and provides thermal knife control for solar panels deployment. The maximum power input is 60 W and the voltage input range is 4.5 V to 28 V. The CubeSat EPS provide output regulated buses of 3.3 V (5 A max), 5 V (5 A max) and 12 V (4 A max) and it has an efficiency of more than 90% for the battery charge regulators. This CubeSat EPS will be tested in-orbit on the D3-CubeSat (D3-University of Florida, Gainesville), SOC-I CubeSat (University of Washington) and NEPTUNO-I (Deimos Space) missions. TRL9 is expected by the end of 2020.

3.4.4 EnduroSat

Figure 3.18: EPS Type 1. Credit: EnduroSat.

Three Three CubeSat EPS modules are provided by EnduroSat: CubeSat Power Module 1, 1 Plus and 2. EPS 1 and 1 Plus are most suitable for 1U, 1.5U and 2U CubeSat Satellites, and are integrated with one or two Li-Po battery packs. The EPS Type 2 is configurable for 3U, 6U, 12U and 27U NanoSats with 1 or multiple battery packs (carrying 4 – 8 battery cells per pack).The CubeSat Power Module Type 1 (figure 3.18) has a 4.2 V battery pack, a total mass of 0.198 kg (one battery pack), and 10.4 W h capacity. This EPS has undergone space qualification testing. The CubeSat Power Module 1 Plus includes two battery packs with a total mass of 0.278 kg, 20.8 W h battery capacity, and 4.2 V pack voltage. Qualification tests are pending for this EPS. Finally, the Type II CubeSat EPS can be configured with either one or two battery packs with different sizes; total mass is 0.9 – 1.3 kg per module + battery pack with 42 – 84 W h capacity and 17 – 34 V maximum pack voltage.

3.4.5 Ibeos

Figure 3.19: Small EPS. Credit: Ibeos.

Ibeos' 150 W SmallSat Electric Power Subsystem (EPS) in figure 3.19 is a radiation tolerant (30 Krad), flexible peak power tracking solution capable of efficient solar array power conversion and battery charging. The EPS card provides regulated 3.3 V, 5 V, and 12 V power, as well as unregulated battery power through switched and unswitched, current-limited outputs. The system accepts commands and provides telemetry via SPI and I_2C interfaces. The EPS includes battery under/over-voltage and over-current protection in addition to a configurable watchdog timer for spacecraft loads (36).

3.4.6 Innovative Solutions In Space (ISIS)

The ISIS Electrical Power System (iEPS) in figure 3.20 is the second-generation compact power system for nanosatellites, ideal for 1U up to 3U CubeSats. The system leverages wide bandgap semiconductor technologies, implementing GaN-FETs to improve solar power conversion efficiency and performance. It is equipped with an integrated heater, hardware-based Maximum Power Point Tracking (MPPT) and hardware voltage and over-current protection. The iEPS provides 3.3 V and 5 V regulated buses, as well as an unregulated bus. An add-on daughter board allows additional configurations to suitably power the system and payload instruments (37).

Figure 3.20: iEPS. Credit: ISIS.

3.4.7 NanoAvionics

The Power Supply System EPSL is a low-power, 23 W h configuration containing two 7.4 V, 3200 mA h cells. The EPSH high-power (46 W h) configuration measures 92.9 x 89.3 x 25 mm, contains four 7.4 V cells (6400 mA h total), and weighs 0.3 kg (38). This system is TRL 9 in low-Earth orbit.

3.4.8 Pumpkin, Inc.

Figure 3.21: EPS1. Credit: Pumpkin, Inc.

The Electrical Power System 1 (figure 3.21) is an efficient, high power option for all nanosatellite platforms developed at Pumpkin. This low-mass system has a total mass of <0.3 kg, features up to 3 W, and a 60 V power ring topology that has been space-proven on multiple missions (39). This board has flown on several small spacecraft and CubeSat form factors.

3.4.9 Surrey Satellite Technology Ltd

Surrey Satellite Technology sells a full PMAD system in the form of their low-Earth orbit PCDU. It is based on a modular design that is intended to be scalable and customizable. The PCDU system is made up of a battery conditioning module and a power distribution module and has flown on serval SmallSat missions (40).

Table 3-3: Product of Power Management and Distribution Systems

Product	Manufacturer	Technology Type	TRL
Starbuck-MICRO, -MINI, -NANO, -PICO	AAC Clyde Space	EPS	Unk
BCT CubeSat Electrical Power System	Blue Canyon Tech	EPS	9
P1U "Vasik"	Crystalspace	EPS	9
EPS for 2U, 3U and 6U CubeSats	DHV Technology	EPS	9
iEPS	ISIS	EPS	9
CubeSat EPS Type I, II and I Plus	EnduroSat	EPS	9
NanoPower P31U	GomSpace	PMAD	9
150-Watt SmallSat EPS	ibeos	EPS	Unk
EPSL	NanoAvionics	EPS	9

Power and Control Unit	Magellan Aerospace	PMAD	9
CubeSat Kit EPS 1	Pumpkin, Inc.	EPS	9
3u cPCI Power Supply	SEAKR	EPS	9
LEO PCDU	Surrey Satellite Technology, Ltd.	PMAD	9
Power Storage and Distribution	Tyvak	PMAD	9

3.5 On the Horizon – Power Generation

New technologies continue to be developed for space qualified power generation. Promising technologies applicable to small spacecraft include advanced multi-junction, flexible and organic solar cells, hydrogen fuel cells and a variety of thermo-nuclear and atomic battery power sources.

3.5.1 Multi-junction Solar Cells

Fraunhofer Institute for Solar Energy Systems have developed different four-junction solar cell architectures that currently reach up to 38% efficiency under laboratory conditions, although some designs have only been analyzed in terrestrial applications and have not yet been optimized (Lackner). Fraunhofer ISE and EV have achieved 33.3% efficiency of a 0.002 mm thin silicon based multi-junction solar cell, and future investigations are needed to solve current challenges of the complex inner structure of the subcells (41). Additionally, Boeing Spectrolabs has been experimenting with 5- and 6-junction cells with a theoretical efficiency as high as 70% (42).

3.5.2 Flexible Solar Cells

Flexible and thin-film solar cells have an extremely thin layer of photovoltaic material placed on a substrate of glass or plastic. Traditional photovoltaic layers are around 350 microns thick, while thin-film solar cells use layers just one micron thick. This allows the cells to be flexible and lightweight and, because they use less raw material, are cheap to manufacture. The performance of commercial flexible CIGSis was investigated and reported in relation to potential deep space applications at the University of Oklahoma. The authors found promising thin film solar material using Cu(In,Ga)Se2 (CIGS) solar cells with record power conversion efficiencies up to 22.7% (43).

3.5.3 Organic Solar Cells

Another on the horizon photovoltaic technology uses organic or “plastic” solar cells. These use organic electronics or organic polymers and molecules that absorb light and create a corresponding charge. A small quantity of these materials can absorb a large amount of light making them cheap, flexible and lightweight.

Toyobo Co., Ltd. and the French government research institute CEA have succeeded in making trial organic photovoltaic (OPV) small cells on a glass substrate. Trial OPV modules on a lightweight and thin PET (polyethylene terephthalate) film substrate were demonstrated during their joint research project. Toyobo and CEA succeeded in making the OPV small cells on a glass substrate with the world’s top-level conversion efficiency by optimizing the solvents and coating technique. In a verification experiment under neon lighting with 220 lux, equivalent to the brightness of a dark room, the trial product was confirmed to have attained a conversion efficiency of about 25%, or 60% higher than that of amorphous silicon solar cells commonly used for desktop calculators (44).

In October 2016, the Optical Sensors based on CARbon materials (OSCAR) stratospheric-balloon flight test demonstrated organic-based solar cells for the first time in a stratospheric environment. While more analysis is needed for terrestrial or space applications, it was concluded that organic solar energy has the potential to disrupt “conventional” photovoltaic technology (45). Since then, a joint collaborative agreement between the German Aerospace Center and the Swedish National Space Board REXUS/BEXUS has made the balloon payload available for European university student experiments with collaboration of the ESA (46).

While no standardized stability tests are yet available for organic-based solar cell technology, and challenges remain on creating simultaneous environmental influences that would permit in-depth understanding of organic photovoltaic behavior, these achievements are enabling progress in organic-based solar cell use.

In 2018, Chinese researchers in organic photovoltaics were able to reach 17% power conversion energy using a tandem cell strategy. This method uses different layers of material that can absorb different wavelengths of sunlight, which enable the cells to use more of the sunlight spectrum, which has limited the performance of organic cells (47).

3.5.4 Fuel Cells

Hydrogen fuel cells are appealing due to their small, light and reliable qualities, and a high energy conversion efficiency. They also allow missions to launch with a safe, storable, low pressure and non-toxic fuel source. An experimental fuel cell from the University of Illinois that is based on hydrogen peroxide rather than water has demonstrated an energy density of over 1000 W h kg^{-1} with a theoretical limit of over 2580 W h kg^{-1} (48). This makes them more appealing for interplanetary missions and during eclipse periods, however unlike chemical cells, they cannot be recharged on orbit. Carrying a large fuel tank is not feasible for small or nanosatellite missions. Regenerative fuel cells are currently being researched for spacecraft application. Today, fuel cells are primarily being proposed for small spacecraft propulsion systems rather than for power sub-systems (49).

3.5.5 Nuclear Power

Another source of spacecraft power comes from harnessing the energy released during radioactive decay. Radioisotope Thermoelectric Generators (RTGs) are associated with longer lifetimes, high reliability, predictable power production, and are more appealing beyond Mars orbit (>3 AU) than relying on batteries and solar panels. Unlike fuel cells, an RTG may operate continuously for decades without refueling. A full-sized RTG, such as on New Horizons, has a mass of 56 kg and can supply 300 W (6.3% efficiency) at the beginning of its life (50).

Although a radioisotope power system has not yet been integrated on a small spacecraft, they might be considered for small spacecraft missions that traverse interplanetary space. This concept would require substantial testing and modified fabrication techniques to facilitate use on smaller platforms.

3.5.6 TPV

A thermophotovoltaic (TPV) battery consists of a heat source or thermal emitter and a photovoltaic cell which transforms photons into electrical energy. Thermophotovoltaic power converters are similar to high TRL thermoelectric converters, with the difference that the latter uses thermocouples and the former uses infrared-tuned photovoltaic cells.

A planar TPV system with very high efficiency and output power has been numerically demonstrated a near-field at large vacuum gaps, illustration in figure 3.22. Example performances include: The 50 W scale-up TPV power supply along with 1.5 kg of fuel has a projected weight specific energy density of 645 W h kg^{-1}. This is 4 times larger than for a Li-ion battery (51).

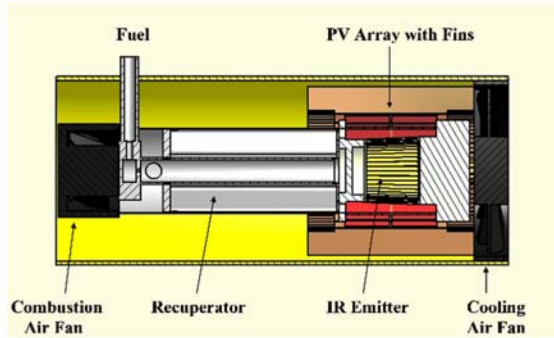


Figure 3.22: (top) Design of TPV power supply and (bottom) functional stand-alone TPV power supply. Credit: Fraas et al. (2017).

3.5.7 Alpha- and Beta-voltaics

Alpha- and beta-voltaic power conversion systems use a secondary material to absorb the energetic particles and re-emit them via luminescence. These photons can then be absorbed by photovoltaic cells. Methods for retrieving electrical energy from radioactive sources include beta-voltaic, alpha-voltaic, thermophotovoltaic, piezoelectric and mechanical conversions. This technology is currently in the testing/research phase.

3.6 Power Storage

In the area of power storage there are several efforts at improving storage capability and the relative power and energy densities in a Ragone Chart illustration of different energy devices is shown in figure 3.23. For example, the Rochester Institute of Technology and NASA Glenn Research Center (GRC) developed a nano-enabled power system on a CubeSat platform. The power system integrates carbon nanotubes into lithium-ion batteries that significantly increases available energy density. The energy density has exceeded 300 W hours per kilogram during testing, a roughly two-fold increase from the current state-of-the-art. The results in this program were augmented from a separate High Altitude Balloon Launch in July 2018 organized through NASA GRC and showed typical charge and discharge behavior on ascent up to an altitude of 19 km (52). A collaborative project between the University of Miami and NASA Kennedy Space Center (KSC) is aiming to develop a multifunctional structural battery system that uses an electrolytic carbon fiber material that acts as both a load bearing structure and a battery system. This novel battery system will extend mission life, support larger payloads, and significantly reduce mass. While several panel prototypes have shown successively increased electrochemical performance, further testing of the individual components can improve the accuracy of the computational models (53).

3.6.1 Supercapacitors

While the energy density for supercapacitors, also called ultracapacitors, is low (up to 7 kW kg^{-1}), they offer very high power density (up to 100 kW kg^{-1}). This property could be useful for space applications that require power transients. Their fast charge and discharge time, and their ability to withstand millions of charge / discharge cycles and wide range of operational temperatures (-40°C to +70°C), makes them a perfect candidate for several space applications (launchers and

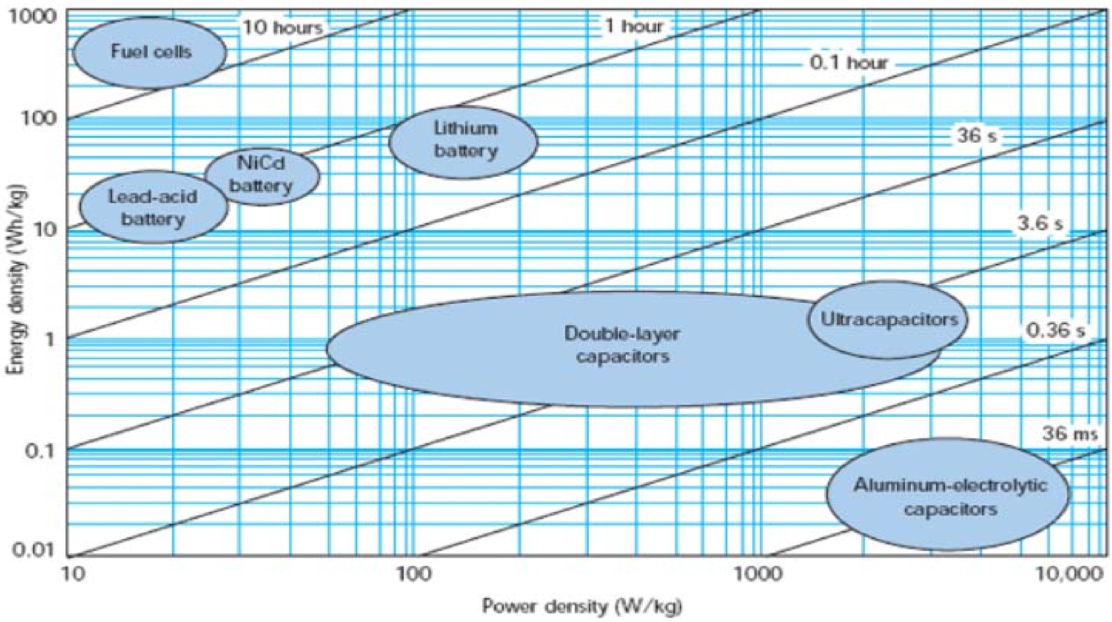


Figure 3.23: Relative power and energy densities Ragone chart illustration of different energy devices. Credit: US Defense Logistics Agency.

satellites). This was demonstrated in an ESA Study Contract No. 21814/08/NL/LvH entitled "High Power Battery Supercapacitor study" completed in 2010 by Airbus D&S (54). Currently the Nesscap 10F component and a bank of supercapacitor based on Nesscap 10F component are space qualified after the completion in 2020 of the ESA Study Contract No. 4000115278/15/NL/GLC/fk entitled "Generic Space Qualification of 10F Nesscap Supercapacitors". Although not likely to replace Li-ion batteries completely, supercapacitors could drastically minimize the need for a battery and help reduce weight while improving performance in some applications. Figure 3.24 shows a comparison chart (55), and table 3-4 lists differences in Li-ion batteries and supercapacitors (56).

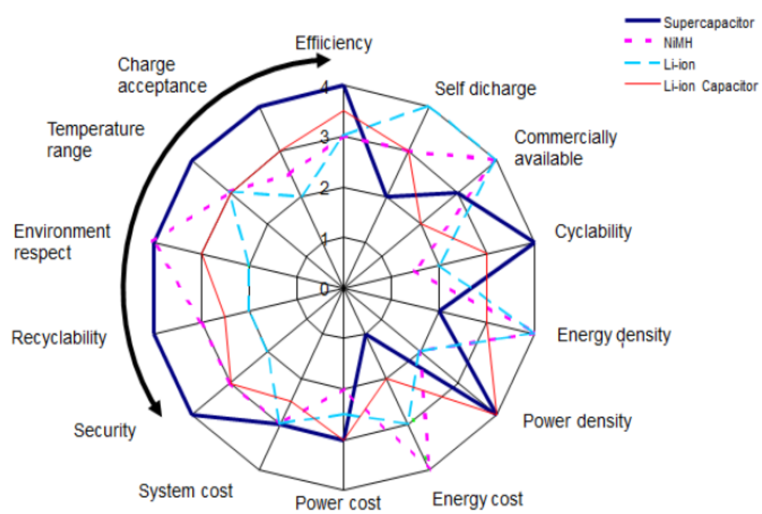


Figure 3.24: Supercapacitor comparison chart. Credit: Airbus Defense and Space and ESA (2016).

Table 3-4: Battery-vs-Supercapacitor Specifications		
Feature	**Li-Ion Battery**	**Supercapacitor**
Gravimetric energy (W h kg^{-1})	100 – 265	4 – 10
Volumetric energy (W h L^{-1})	220 – 400	4 – 14
Power density (W kg^{-1})	1,500	3,000 – 40,000
Voltage of a cell (V)	3.6	2.7 – 3
ESR (mΩ)	500	40 - 300
Efficiency (%)	75 – 90	98
Cyclability (nb charges)	500 – 1,000	500,000 – 20, 000,000
Life (years)	5 – 10	10 – 15
Self-discharge (% per month)	2	40 – 50 (descending)
Charge temperature	0 to 45°C	-40 to 65°C
Discharge temperature	yes	no
Deep discharge pb	yes	no
Overload pb	yes	no
Risk of explosion	yes	no
Charging 1 cell	complex	easy
Charging cells in series	complex	complex
Voltage on discharge	stable	decreasing
cost ($) per kW h	235 – 1,179	11,792

3.7 Power Management and Distribution

For small spacecraft, traditional EPS architecture is centralized (each subsystem is connected to a single circuit board). This approach provides simplicity, volume efficiency, and inexpensive component cost. However, a centralized EPS is rarely reused for a new mission, as most of the subsystems need to be altered based on new mission requirements. A modular, scalable EPS for small spacecraft was detailed by Timothy Lim and colleagues, where the distributed power system is separated into three modules: solar, battery and payload. This allows scalability and reusability from the distributed bus, which provides the required energy to the (interfaced) subsystem (57).

University of Toronto's Space Flight Laboratory (SFL) has developed an in-house, scalable and reusable Modular Power System (MPS) and has flown systems derived from this architecture on several missions: Norsat-1 & 2, and CanX-7 (58).

3.8 Summary

Driven by weight and mostly size limitations, small spacecraft are using advanced power generation and storage technology such as >32% efficient solar cells and lithium-ion batteries. The higher risk tolerance of the small spacecraft community has allowed both the early adoption of technologies like flat lithium-polymer cells, as well as COTS products not specifically designed for spaceflight. This can dramatically reduce cost and increase mission-design flexibility. In this way, power subsystems are benefiting from the current trend of miniaturization in the commercial electronics market as well as from improvements in photovoltaic and battery technology.

Despite these developments, the small spacecraft community has been unable to use other, more complex technologies. This is largely because the small spacecraft market is not yet large enough to encourage the research and development of technologies like miniaturized nuclear energy sources. Small spacecraft power subsystems would also benefit from greater availability of flexible, standardized power management and distribution systems so that every mission need not be designed from scratch. In short, today's power systems engineers are eagerly adopting certain innovative Earth-based technology (like lithium polymer batteries) while, at the same time, patiently waiting for important heritage space technology (like fuel cells and RTGs) to be adapted and miniaturized. Despite the physical limitations and technical challenges these power generation technologies have to solve, most small and nanosatellites in the foreseeable future will still likely carry batteries to support the transient load.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

References

(1) Alia-Novobilski, M.: "Advanced Multi-junction Solar Cells Deliver High Efficiency, Reduced Costs for Space." [Online] Jan 4, 2018. [Cited: July 15, 2018.] https://phys.org/news/2018-01-advanced-multi-junction-solar-cells-high.html#jCp.

(2) Green, M. A.: "Third Generation Photovoltaics: Advanced Solar Energy Conversion." Springer. Vol. 12. 2003.

(3) AzurSpace. 32% Quadruple Junction GaAs Solar Cell. [Online] 2020. [Cited: May 15, 2020.] http://www.azurspace.com/images/0005979-01-00_DB_4G32C_Advanced.pdf.

(4) EMCORE. BTJ Space Solar CelLS. 2015.

(5) Yeh, C Heng, et al.: "Estimation of Online Power Beavior of Phoenix's Electrical Power System." [Online] 2017. http://ir.lib.ncku.edu.tw/bitstream/987654321/173170/1/4010104000-000024_1.pdf.

(6) Spectrolab. [Online] May 16, 2020. [Cited: May 16, 2020.] https://www.spectrolab.com/photovoltaics/XTE-SF%20Data%20Sheet%20_12.23.19.pdf.

(7) Spectrolab. 30.7% Triple Juntion Space Grade Solar Cell. [Online] 2018. [Cited: July 15, 2018.] https://www.spectrolab.com/DataSheets/cells/XTJ_Prime_Data_Sheet_7-28-2016.pdf.

(8) SpectroLab. Ultra Triple Junction (UTJ) Cells. [Online] 2018. [Cited: July 16, 2018.] http://www.spectrolab.com/DataSheets/cells/2015%20UTJ%20CIC%20Datsheet.pdf.

(9) SolAero Technologies. Space Solar Cells / Coverglass Interconnected Cells (CIC). 2015.

(10) AAC-Clyde. Solutions for a New Age in Space Capability Overview. 2018.

(11) EnduroSat. CubeSat 3U Solar Panel X/Y MTQ. [Online] 2017. https://www.endurosat.com/products/cubesat-3u-solar-panel-x-y-mtq/.

(12) GomSpace. Solar Panels for Aerospace Applications. 2018.

(13) ISIS. ABSL's COTS Li-Ion Cell Suite Development. 2007.

(14) MIST – the MIniature Student saTellite. [Online] May 2020. [Cited: May 16, 2020.] https://mistsatellite.space/basic-facts/.

(15) NanoAvionics. Solar-panels-and-power-systems: cubesat-gaas-solar-panel. [Online] 2020. [Cited: May 16, 2020.] https://nanoavionics.com/cubesat-components/cubesat-gaas-solar-panel/.

(16) MMA. HAWK (PAT.) CUBESAT SOLAR ARRAYS. 2015.

(17) MMA. E-HAWK (PAT.) NANOSAT SOLAR ARRAYS. 2015.

(18) MMA_Design. rHaWK Solar Array. [Online] May 16, 2020. [Cited: May 16, 2020.] https://mmadesignllc.com/product/r-hawk-solar-array/.

(19) SpectroLab. SpectroLab Space Solar Panels. 2010.

(20) Nelson, R. A.: "Spacecraft Battery Technology." 1999.

(21) Jung, D. S. and Manzo, M. A.: "NASA Aerospace Flight Battery Program." NASA/TM-2010-216728/Vol I. 2010.

(22) JPL. NASA Battery Workshop. [Online] Nov 19, 2019. [Cited: May 16, 2020.] https://www.nasa.gov/sites/default/files/atoms/files/3-nasa_battery_workshop_nov_2019_high_power_li-ion_cells_final.pdf.

(23) AAC-Clyde. User Manual: 3rd Generation CubeSat. [Online] May 18, 2020. [Cited: May 18, 2020.] https://www.aac-clyde.space/satellite-bits/batteries.

(24) ABSL. ABSL COTS Li-Ion Cell Suite Development. 2007.

(25) GomSpace. NanoPower Modules. 2015.

(26) GomSpace. NanoPower P31u. [Online] 2018. [Cited: July 16, 2018.] https://gomspace.com/Shop/subsystems/power-supplies/nanopower-p31u.aspx.

(27) ibeos. Cubesat Product Overview. [Online] 2020. https://ibeos.com/products.html.

(28) Ultralife Corporation. SPOON Submission, Li-MnO2 and Li-CFx. 2018.

(29) Vectronic Aerospace. Li-Ion Battery Block VLB-4/ -8 /-16. 2014.

(30) LG Chem. Product Specification: Rechargeable Lithium Ion Battery Model ICR18650 B3 2600mAh. 2007.

(31) Molicel. Panasonic Lithium Ion NCR18650B. 2012.

(32) Canon. BP-930 Material Safety Data Sheet. 2011.

(33) AAC-Clyde. EPS. [Online] 2020. https://www.aac-clyde.space/satellite-bits/eps.

(34) Crystal Space. Crystalspace P1U "Vasik" Power Supply. 2015.

(36) ibeos. 150-Watt SmallSat Electric Power Subsystem (EPS) datasheet. 2019.

(37) Innovative Solutions in Space. IEPS Electrical Power System. [Online] 2020. https://www.isispace.nl/product/ieps-electrical-power-system/.

(38) NanoAvionics. CubeSat Electrical Power System "EPS" CubeSat Solar Panels & Power Systems. *Electrical Power System “EPS”.* [Online] 2017. [Cited: July 15, 2018.] https://n-avionics.com/cubesat-components/solar-panels-and-power-systems/cubesat-electrical-power-system-eps/.

(39) Pumpkin, Inc. CubeSat Kit Electrical Power Sysyem 1 (EPS1). 2018.

(40) Surrey Satellite Technology ltd. LEO PCD. 2015.

(41) Seeger, Daniel: "Fraunhofer ISE Announces 33% Efficiency for Multi-junction Solar Cell. [Online] 2018. https://www.pv-magazine.com/2018/04/04/fraunhofer-ise-announces-33-efficiency-for-multi-junction-solar-cell/.

(42) King, R.: "*Raising the Efficiency Ceiling in Multijunction Solar Cells.” Stanford Photonics Research Center Symposium, 2009.* 2015.

(43) Brown, Collin, et al.: "*An Investigation of Flexible Cu(In,Ga)Se2 Solar Cells Under Low Intensity Low Temperature for Potential Applications for Outer Planetary Missions."* IEEE Journal of Photovoltaics. 2019.

(44) Toyobo Co., Ltd. "Toyobo to practicalize power-generating material for organic photovoltaicswith world’s top-level conversion efficiency under room light." 03 23, 2020.

(45) Cardinaletti, I., et al.: "*Organic and Perovskite Solar Cells for Space Applications."* Solar Energy Materials and Solar Cells, p. 182. 2018.

(46) Nagels, S.: "OSCAR: the First Hasselt University Aerospace Project." 2020.

(47) Meng, Lingxian, et al.: "*Organic and Solution-processed Tandem Solar Cells with 17.3% efficiency."* 6407, Vol. 361. 2018.

(48) N. Luo et al.: *"Hydrogen-Peroxide-Based Fuel Cells for Space Power Systems." Vol. 24, no. 3.* 2008.

(49) Ethier, V, et al.: *"Development of a CubeSat Water-Electrolysis Propulsion System."* 2013.

(50) *"Radioisotope Power Systems (RPS) Program."* National Aeronautics and Space Administration. 2015.

(51) Joannopoulos, Aristeidis Karalis and J. D.: "*'Squeezing' near-field thermal emission for ultra-efficient high-power thermophotovoltaic conversion."* 2016.

(52) Raffaelle, Ryne: "Demonstration of a Nano-Enabled Space." [Online] 2018. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170011060.pdf.

(53) Karkkainen, Ryan L.: "Development of Lightweight CubeSat with Multi-Functional Structural Battery Systems." [Online] 2018. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170011078.pdf.

(54) Faure, Bertrand, Cosqueric, Laurence Gineste, and Valéry: "*Evaluation and Qualification of Commercial Off-The-Shelf Supercapacitors for Space."* 2nd Space Passive Component Days (SPCD) International Symposium. Noordwijk, The Netherlands: s.n., 2016.

(55) SupercapTech. SupercapTech. [Online] May 21, 2016. [Cited: June 1, 2020.] https://www.supercaptech.com/battery-vs-supercapacitor.

(56) POWERBOX. "The Silent Power of Supercapacitors." *White paper 017.* 2019.

(57) Lim, T M, et al.: "*A Modular Electrical Power System."* IEEE. 2017.

(58) Johnston-Lemke, B, et al.: "*Modular Power System: Enabling Scalable Missions for the 1W to 1kW Range."* 27th Annual AIAA/USU Conference on Small Satellites. 2013.

(59) Wagner, R.: "Battery Fuel Gauges: Accurately Measuring Charge Level." 2006.

(60) AAC_Clyde. EPS. [Online] May 18, 2020. [Cited: May 18, 200.] https://www.aac-clyde.space/satellite-bits/eps.

(61) DHV Technology. Products - Solar Panels for CubeSats. [Online] 2020. https://dhvtechnology.com/products/.

4.0 In-Space Propulsion

4.1 Introduction

In-space propulsion devices for small spacecraft are rapidly increasing in number and variety. In one development path, systems and components with past flight heritage are being reconsidered to meet the needs of smaller spacecraft. This approach minimizes new product development risk and time to market by creating devices similar to those with existing spaceflight heritage, albeit accounting for small spacecraft volume, mass, power, safety and cost considerations. Such incremental advancement benefits from existing spaceflight data, physics-based models, and customer acceptance of the heritage technologies, which eases mission infusion. In an alternative development path, novel technologies are being conceived specifically for small spacecraft. These technologies often use innovative approaches to propulsion system design, manufacturing, and integration. While the development of novel technologies typically carries a higher risk and slower time to market, these new technologies strive to offer small spacecraft a level of propulsive capability not easily matched through the miniaturization of heritage technologies. Such novel devices are often highly integrated and optimized to minimize the use of a small spacecraft's limited resources, lower the product cost, and simplify integration. Regardless of the development approach, the extensive efforts by commercial industry, academia, and government to develop new propulsion solutions for small spacecraft suggest the availability of a range of devices with diverse capabilities in the not too distant future.

In the near-term, the surge in public and private investments in small spacecraft propulsion technologies, in combination with the immaturity of the overall small spacecraft market, has resulted in an abundance of confusing, unverified, sometimes conflicting, and otherwise incomplete technical literature. Furthermore, the rush by many device developers to secure market share has resulted in some confusion surrounding the true readiness of these devices for mission infusion. As third parties independently verify device performance, and end-users demonstrate these new devices in their target environments, the true maturity, capability, and flight readiness of these devices will become evident. In the meantime, this report will attempt to reduce confusion by compiling a list of publicly described small spacecraft propulsion devices, identifying publicly available technical literature for further consideration, recognizing missions of potential significance, and organizing the data to improve comprehension for both neophytes and subject matter experts.

Recognizing a lack of sufficient in-depth technical insight into current propulsion devices based on publicly available data, this chapter avoids a direct technology maturity assessment (TMA) based on the NASA Technology Readiness Level (TRL) scale. An accurate TRL assessment requires a high degree of technical knowledge on a subject device as well as an understanding of intended spacecraft bus and target environment. Although the authors strongly encourage a TMA well-supported with technical data prior to infusing new technologies into programs, the authors believe TRLs are most accurately determined when assessed by a program within the context of the program's unique requirements. Rather than assessing TRL, this chapter introduces a novel classification system that simply recognizes Progress towards Mission Infusion (PMI) as an early indicator of the efficacy of the manufacturers' approach to system maturation and mission infusion. PMI should not be confused with TRL as PMI does not directly assess technology maturity. However, PMI may prove insightful in early trades. The PMI classification system used herein is described in detail below.

4.1.1 Document Organization

This chapter organizes the state-of-the-art in small spacecraft propulsion into the following categories:

1. In-Space Chemical Propulsion (4.6.1)
2. In-Space Electric Propulsion (4.6.2)
3. In-Space Propellant-less Propulsion (4.6.3)

Each of these categories is further subdivided by the prevailing technology types. The subsections organize data on each prevailing technology type as follows:

a. Technology Description
b. Key Integration and Operational Considerations
c. Missions
d. Summary Table of Devices

The organizational approach introduces newcomers to each technology, presents technology-specific integration and operation concerns for the reader's awareness, highlights recent or no04. Proptable missions that may raise the TRL of specific devices, and finally tabulates procurable devices of each technology. While the key integration and operational considerations are not all-inclusive, they provide initial insights that may influence propulsion system selection. In the cases where a device has significant flight heritage, this chapter reviews only select missions.

4.2 Public Data Sources and Disclaimers

This chapter is a survey of small spacecraft propulsion technologies as discussed in open literature and does not endeavor to be an original source. This chapter only considers literature in the public domain to identify and classify devices. Commonly used sources for data include manufacturer datasheets, press releases, conference papers, journal papers, public filings with government agencies, and news articles.

This chapter summarizes device performance, capabilities, and flight history, as presented in publicly available literature. Data not appropriate for public dissemination, such as proprietary, export controlled, or otherwise restricted data, are not considered. As such, actual device maturity and flight history may be more extensive than what is documented herein. Device manufacturers should be consulted for the most up-to-date and relevant data before performing a TMA.

This chapter's primary data source is literature produced by device manufacturers. Unless otherwise published, do not assume independent verification of device performance and capabilities. Performance and capabilities described may be speculative or otherwise based on limited data.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that technology maturity designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and maturity of the described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

Suggestions or corrections to this document should be submitted to the NASA Small Spacecraft Virtual Institute (Agency-SmallSat-Institute@mail.nasa.gov) for consideration prior to the publication of future issues. When submitting comments, please cite appropriate publicly accessible references. Private correspondence is not considered an adequate reference.

4.3 Definitions

- *Device* refers to a component, subsystem, or system, depending on the context.
- *Technology* refers to a broad category of devices or intangible materials, such as processes.

4.4 Technology Maturity

4.4.1 Application of the TRL Scale to Small Spacecraft Propulsion Systems

NASA has a well-established guideline for performing TMAs, described in detail in the NASA Systems Engineering Handbook (1). A TMA determines a device's technological maturity, which is usually communicated according to the NASA TRL scale. The TRL scale is defined in NASA Procedural Requirements (NPR) 7123 (2). The NASA Systems Engineering Handbook and NPR 7123 can be accessed through the NASA Online Directives Information System (NODIS) library. Assessment of TRLs for components, systems, or software allows for coherent communication between technologists, program managers, and other stakeholders on the maturity of a technology. Furthermore, TRL is a valuable tool to communicate the potential risk associated with the infusion of technologies into programs. In order for TRLs to be applied across all technology categories, the NASA TRL definitions are written broadly and rely on subject matter experts (SME) in each discipline to interpret appropriately.

Recently, U.S. Government propulsion SMEs suggested an interpretation of the TRL scale specifically for micro-propulsion. The Micro-Propulsion Panel of the JANNAF Spacecraft Propulsion Subcommittee in 2019 published the *JANNAF Guidelines for the Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems* (3). This guideline suggests an interpretation of TRL for micro-propulsion and reflects both NASA and DOD definitions for TRL. The JANNAF panel consisted of participants from the Air Force Research Laboratory (AFRL), Glenn Research Center (GRC), Jet Propulsion Laboratory (JPL), and Goddard Space Flight Center (GSFC). The panel further received feedback from the non-Government propulsion community. While this JANNAF guideline focuses on micro-propulsion (e.g., for CubeSats), the guideline still has relevance to rigorously assessing TRLs for the more general category of small spacecraft in-space propulsion. By establishing a common interpretation of TRL for small spacecraft propulsion, a more coherent and consistent communication of technology maturity can occur between small spacecraft propulsion providers and stakeholders. The JANNAF guideline is unlimited distribution and may be requested from the Johns Hopkins University Energetics Research Group (JHU ERG). Ensure the use of the latest JANNAF guideline, as the guideline is anticipated to evolve with further community input.

A fundamental limitation of the JANNAF guideline for TRL assessment, and TMA in general, is an assumption of in-depth technical knowledge of the subject device. In the absence of detailed technical knowledge, especially in a broad technology survey as presented herein, a TMA may be conducted inaccurately or inconsistently. Furthermore, assessment of TRL assumes an understanding of the end-user application. The same device may be concluded to be at different TRLs for infusion into different missions. For example, a device may be assessed at a high TRL for application to low-cost small spacecraft in low-Earth orbits, while assessed at a lower TRL for application to geosynchronous communication satellites or NASA interplanetary missions due to different mission requirements. Differences in TRL assessment based on the operating environment may result from considerations such as thermal environment, mechanical loads, mission duration, or radiation exposure. Propulsion-specific variances between missions might include propellant type, total propellant throughput, throttle set-points, burn durations, and the total number of cycles. As such, an accurate TRL assessment not only requires an in-depth technical understanding of a device's development history, including specifics on past flight-qualification activities, but also an understanding of mission-specific environments and interfaces. This challenge of assessing an accurate TRL poses a significant burden for data collection, organization, and presentation in a broad technology survey. Such activities are better suited for the programs seeking to infuse new technologies into their missions.

Given the rapid evolution of small spacecraft propulsion technologies and the variety of mission environments, as well as generally limited device technical details in open literature, the propulsion chapter implements a novel system to classify technical maturity according to Progress towards Mission Infusion (PMI). This novel classification system is not intended to replace TRL, but is a complementary tool to provide initial insight into device maturity when it is not feasible to accurately and consistently apply the TRL scale. This novel classification system is discussed in detail below.

Readers using this survey are strongly encouraged to perform more in-depth technical research on candidate devices based on the most up-to-date information available, as well as to assess risk within the context of their specific mission(s). Thoughtful TMA based on examination of detailed technical data through consultation with device manufactures can reduce program risk and in so doing increase the likelihood of program success. This survey is not intended to replace the readers' own due diligence. Rather, this survey and PMI seek to provide early insights that may assist in propulsion system down-select to a number of devices where an in-depth TMA becomes feasible.

4.4.2 Progress Towards Mission Infusion (PMI)

Rather than directly assessing a device's technical maturity via TRL, propulsion devices described herein are classified according to evidence of progress towards mission infusion. This is a novel classification system first introduced in this survey. Assessing the PMI of devices in a broad survey, where minimal technical insight is available, may assist with down-selecting propulsion devices early in mission development. Once a handful of devices are selected for further consideration, an in-depth technical examination of the select devices may be more practical to conduct and rigorously assess TRL. The PMI classification system sorts devices into one of four broad technology development categories: Concept, In-Development, Engineering-to-Flight, and Flight-Demonstrated. The following sections describe the PMI classification system in-detail. Furthermore, figure 4.1 summarizes the PMI classifications.

Concept, 'C'

The *Concept* classification reflects devices in an early stage of development, characterized by feasibility studies and the demonstration of fundamental physics. Concept devices typically align with the NASA TRL range of 1 to 3. At a minimum, these devices are established as scientifically feasible, perhaps through a review of relevant literature and/or analytical analysis. These devices may even include experimental verification that supports the validity of the underlying physics. These devices may even include notional designs. While Concept devices are generally not reviewed herein, particularly promising Concept devices will be classified in tables with a 'C'.

In-Development, 'D'

The *In-Development* classification reflects the bulk of devices being actively matured and covered in this survey, where only a modest number of devices may progress to regular spaceflight. In-Development devices typically align with the NASA TRL range of 4 to 5. While In-Development devices may have specific applications attributed by their developers, no selection for a specific mission has been publicly announced. In the absence of a specific mission, device development activities typically lack rigorous system requirements and a process for independent requirement validation. Furthermore, qualification activities conducted in the absence of a specific mission typically require a delta-qualification to address mission-specific requirements. At a minimum, In-Development devices are low-fidelity devices that have been operated in an appropriate environment to demonstrate basic functionality and support prediction of the device's ultimate capabilities. They may even be medium- or high-fidelity devices operated in a simulated final environment, but lacking a specific mission pull to define requirements and a qualification program. They may even be medium- or high-fidelity devices operated in a spaceflight demonstration, but lacking sufficient fidelity or demonstrated capability to reflect the anticipated final product. These devices are typically described as a technology push, rather than a mission pull. In-Development devices will be classified in tables with a 'D'.

Engineering-to-Flight, 'E'

The *Engineering-to-Flight* classification reflects devices with a publicly announced spaceflight opportunity. This classification does not necessarily imply greater technical maturity than the In-Development classification, but it does assume the propulsion device developer is receiving mission-specific requirements to guide development and qualification activities. Furthermore, the Engineering-to-Flight classification assumes a mission team performed due diligence in the selection of a propulsion device, and the mission team is performing regular activities to validate that the propulsion system requirements are adequately met. Thus, while the PMI classification system does not directly assess technical maturity, there is an underlying assumption of independent validation of mission-specific requirements, where a mission team does directly consider technical maturity in the process of device selection and mission infusion. Engineering-to-Flight devices typically align with the NASA TRL range of 5 to 6. At a minimum, these are medium-fidelity devices that have been operated in a simulated final environment and demonstrate key capabilities relative to the requirements of a specific mission. These devices may even be actively undergoing or have completed a flight qualification program. These devices may even include a spaceflight, but in which key capabilities failed to be demonstrated or further engineering is required. These devices may even include a previously successful spaceflight, but the devices are now being applied in new environments or platforms that necessitate design modifications and/or a delta-qualification. These devices must have a specific mission pull documented in open literature. A design reference mission (DRM) may be considered in place of a specific mission pull, given detailed documentation in open literature, which includes a description of the DRM, well-defined propulsion system requirements, technical maturation consistent with the DRM requirements, and evidence of future mission need. Engineering-to-Flight devices will be classified in tables with an 'E'.

Flight-Demonstrated, 'F'

The *Flight-Demonstrated* classification reflects devices where a successful technology demonstration or genuine mission has been conducted and described in open literature. Flight-Demonstrated devices typically align with the NASA TRL range of 7 to 9. These devices are high-fidelity components or systems (in fit, form, and function) that have been operated in the target in-space environment (i.e., low-Earth orbit, GEO, deep space) on an appropriate platform, where all key capabilities were successfully demonstrated. These devices may even be final products, which have completed genuine missions (not simply flight demonstrations). These devices may even be in repeat production and routine use for a number of missions. The devices must be described in open literature as successfully demonstrating key capabilities in the target environment to be considered Flight-Demonstrated. If a device has flown, but the outcome is not publicly known, the classification will remain Engineering-to-Flight. Flight-Demonstrated devices will be classified in tables with an ‘F’.

Concept, 'C'

- At minimum, an idea has been established as scientifically feasible.
- May even include experimental verification of the underlying physics.
- May even include notional device designs.
- Approximately aligns to NASA TRL 1-3

In-Development, 'D'

- At minimum, a low-fidelity device that has been operated in an appropriate environment to demonstrate the basic functionality and predict the ultimate capabilities.
- May even be a medium- or high-fidelity device operated in a simulated final environment, but the device lacks a specific mission pull to define requirements and a qualification program.
- May even be a medium- or high-fidelity device operated in a flight demonstration, but the device lacks sufficient fidelity or demonstrated capability to reflect the anticipated final product.
- Approximately aligns to NASA TRL 4-5

Engineering-to-Flight, 'E'

- At minimum, a medium-fidelity device that has been operated in a simulated final environment and demonstrates key capabilities relative to the requirements of a specific mission.
- May even include a qualification program in-progress or completed.
- May even include a spaceflight, but the device fails to demonstrate key capabilities.
- May even include a successful spaceflight, but the device is now being applied in a new environment or platform, necessitating a delta-qualification.
- A specific mission opportunity must be identified in open literature.
- Approximately aligns to NASA TRL 5-6

Flight-Demonstrated, 'F'

- At minimum, a high-fidelity component or system (fit, form, and function) that has been operated in the intended in-space environment (e.g., LEO, GEO, deep space) on an appropriate platform, where key capabilities have been successfully demonstrated.
- May even be a final product that has completed a mission (not strictly a technology demonstration).
- May even be a product in repeat production and routine use for a number of missions.
- A successful spaceflight must be identified and the outcome described in open literature.
- Approximately aligns to NASA TRL 7-9

Figure 4.1: Progress towards mission infusion (PMI) device classifications. Credit: NASA.

4.5 Overview of In-Space Propulsion Technology Types

In-space small spacecraft propulsion technologies are generally categorized as (i) chemical, (ii) electric, or (iii) propellant-less. This chapter surveys propulsion devices within each technology category. Additionally, liquid-propellant acquisition and management devices are reviewed as an important component of in-space propulsion systems. Although other key subsystems have not yet been reviewed, such as small spacecraft propulsion power processing units, they may be included in future updates of this publication. Table 4-1 lists the in-space propulsion technologies reviewed. Figure 4.2 graphically illustrates the range of thrust and specific impulse for these small spacecraft propulsion devices. The thrust and specific impulse ranges provided in table 4-1 and figure 4.1 only summarize the performance of small spacecraft devices covered in this survey and may not reflect the broader capability of the technologies beyond small spacecraft or the limits of what is physically possible with further technology advancement.

Chemical systems have enabled in-space maneuvering since the onset of the space age, proving highly capable and reliable. These include hydrazine-based systems, other mono- or bipropellant systems, hybrids, cold/warm gas systems, and solid propellants. Typically, these systems are sought when high thrust or rapid maneuvers are required. As such, chemical systems continue to be the in-space propulsion technology of choice when their total impulse capability is sufficient to meet mission requirements.

On the other hand, the application of electric propulsion devices has been historically far more limited. While electric propulsion can provide an order of magnitude greater total impulse than chemical systems, research and development costs have typically eclipsed that of comparable chemical systems. Furthermore, electric propulsion generally provides thrust-to-power levels below 75 mN/kW. Thus, a small spacecraft capable of delivering 500 W to an electric propulsion system may generate no more than 38 mN. Therefore, while the total impulse capability of electric propulsion is generally quite considerable, these systems may need to operate for hundreds or thousands of hours, compared to the seconds or minutes that chemical systems necessitate for a similar impulse. That said, the high total impulse and low thrust requirements of specific applications, such as station keeping, have maintained steady investment in electric propulsion over the decades. Only in recent years has the mission pull for electric propulsion reached a tipping point where electric propulsion may overtake chemical for specific in-space applications. Electric propulsion system types considered herein include electrothermal, electrospray, gridded ion, Hall-effect, pulsed plasma and vacuum arc, and ambipolar.

Propellant-less propulsion technologies such as solar sails, electrodynamic tethers, and aerodynamic drag devices have long been investigated, but they have yet to move beyond small-scale demonstrations. However, growing needs such as orbital debris removal may offer compelling applications in the near future.

Some notable categories are not covered in this survey, such as nuclear in-space propulsion technologies. While substantial investment continues in such areas for deep space science and human exploration, such technologies are generally at lower TRL and typically aim to propel spacecraft substantially larger than the 180 kg limit covered by this report.

Whenever possible, this survey considers complete propulsion systems, which are composed of thrusters, feed systems, pressurization systems, propellant management and storage, and power processing units, but not the electrical power supply. However, for some categories, components (i.e., thruster heads) are mentioned without consideration of the remaining subsystems necessary for their implementation. Depending on the device's intended platform (i.e., NanoSat, MicroSat, SmallSat), the propulsion system may be either highly integrated or distributed within the spacecraft. As such, it is logical to describe highly integrated propulsion units at the system level, whereas components of distributed propulsion systems may be logically treated at the sub-system level, where components from a multitude of manufacturers may be mixed-and-matched to create a unique mission-appropriate propulsion solution.

Table 4-1: Summary of Propulsion Technologies Surveyed

Technology	Thrust Range	Specific Impulse Range [sec]
4.6.1 CHEMICAL PROPULSION TECHNOLOGIES		
Hydrazine Monopropellant	0.25 – 22 N	200 – 235
Other Mono- and Bipropellants	10 mN – 30 N	160 – 310
Hybrids	1 – 10 N	215 – 300
Cold / Warm Gas	10 µN – 3 N	30 – 110
Solid Motors	0.3 – 260 N	180 – 280
Propellant Management Devices	N/A	N/A
4.6.2 ELECTRIC PROPULSION TECHNOLOGIES		
Electrothermal	2 – 100 mN	50 – 185
Electrosprays	10 µN – 1 mN	250 – 5,000
Gridded Ion	0.1 – 15 mN	1,000 – 3,500
Hall-Effect	1 – 60 mN	800 – 1,900
Pulsed Plasma and Vacuum Arc Thrusters	1 – 600 µN	500 – 2,400
Ambipolar	0.25 – 10 mN	500 – 1,400
4.6.3 PROPELLANTLESS PROPULSION TECHNOLOGIES		
Solar Sails	TBD	N/A
Electrodynamic Tethers	TBD	N/A
Aerodynamic Drag	TBD	N/A

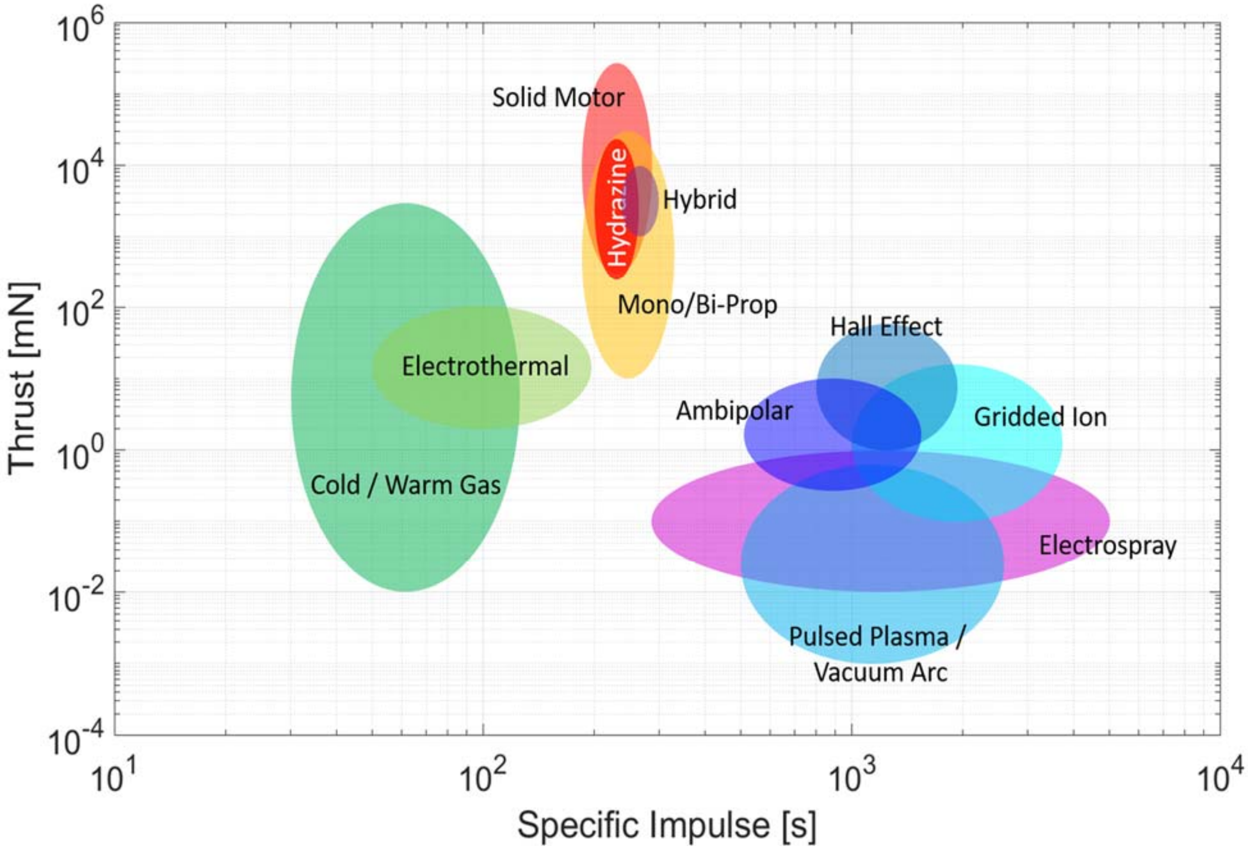


Figure 4.2: Typical small spacecraft in-space propulsion trade space (thrust vs. specific impulse). Credit: NASA.

4.6 State-of-the-Art in Small Spacecraft Propulsion

4.6.1 In-Space Chemical Propulsion

Chemical propulsion systems are designed to satisfy high-thrust impulsive maneuvers. They offer lower specific impulse compared to their electric propulsion counterparts but have significantly higher thrust to power ratios.

Hydrazine Monopropellant

Hydrazine monopropellant systems use catalyst structures (such as S-405 granular catalyst) to decompose hydrazine or a derivative such as monomethyl hydrazine (MMH) to produce hot gases. Hydrazine thrusters and systems have been in extensive use since the 1960's. The low mass and volume of a significant number of larger spacecraft hydrazine propulsion systems allow those systems to also be suitable for some small spacecraft buses. Thrusters that perform small corrective maneuvers and attitude control in large spacecraft may be large enough to perform high-thrust primary maneuvers for small spacecraft and can act as the main propulsion system. Hydrazine specific impulses are achievable in the 200 – 235 second range for 1-N class or larger thrusters.

See table 4-2 for current state-of-the-art hydrazine monopropellant devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

Since hydrazine has been in use for some time, its traits are well defined (4). However, hydrazine (and its derivatives) is corrosive, toxic and potentially carcinogenic. Its vapor pressure requires the use of Self Contained Atmospheric Protective Ensemble (SCAPE) suits. This overhead increases the ground processing flow of spacecraft and may impose undesirable constraints on secondary spacecraft. Hydrazine propulsion systems typically incorporate redundant serial valves to prevent spills or leaks.

Because hydrazine systems are so widely used for larger spacecraft, a robust ecosystem of components and experience exists, and hydrazine propulsion systems are frequently custom-designed for specific applications using available components. Typically, they also have the advantage of being qualified for multiple cold starts, which may be beneficial for power-limited buses if the lifespan of the mission is short.

b. Missions

ArianeGroup has developed a 1-N class hydrazine thruster that has extensive flight heritage, including use on the ALSAT-2 small spacecraft (5) (6).

Aerojet Rocketdyne has leveraged existing designs with flight heritage from large spacecraft that may be applicable to small buses, such as the MR-103 thruster used on New Horizons for attitude control application (7). Other Aerojet Rocketdyne thrusters potentially applicable to small spacecraft include the MR-111 and the MR-106 (8). These thrusters have successfully flown on a number of missions.

Moog-ISP has extensive experience in the design and testing of propulsion systems and components for large spacecraft. These may also apply to smaller platforms, as some of their flight-proven thrusters are light-weight and have moderate power requirements. The MONARC-5 thrusters flew on NASA JPL’s Soil Moisture Active Passive (SMAP) spacecraft in 2015 and provided 4.5 N of steady state thrust. Other thrusters potentially applicable to small spacecraft buses include the MONARC-1 and the MONARC-22 series (9).

Other Mono- and Bipropellants

Alternative propellants are increasingly being sought as a replacement for hydrazine, owing to hydrazine’s handling and toxicity concerns. These include replacements such as the emerging ‘green’ ionic liquids, and more conventional propellants like hydrogen peroxide or electrolyzed water (bi-propellant hydrogen/oxygen).

The so-called ‘green propellants’ have reduced toxicity due in large part to the lower danger of component chemicals and significantly reduced vapor pressures as compared to hydrazine. The ‘green’ affiliation also results in potentially removing Self-Contained Atmospheric Protective Ensemble (SCAPE) suit requirements. The elimination of the SCAPE suit requirement reduces operational oversight by safety and emergency personnel, and potentially reduces secondary payload requirements. The ‘green propellants’ include ionic liquids, such as blends of hydroxyl ammonium nitrate (HAN) or ammonium dinitramide (ADN), and are ideally used as direct replacements for hydrazine. Usually, these green propellants are decomposed and combusted over a catalytic structure similar to hydrazine systems, which often requires pre-heating to adequately decompose the propellant.

While other alternative propellant choices (such as electrolyzed water or hydrogen peroxide) are not ‘green’ propellants like the ionic liquids, they may also be considered within the ‘green’ category. They exhibit more benign characteristics relative to hydrazine and are therefore an alternative option to hydrazine. These alternative propellants are seen as particularly useful for small satellite applications, where the comparatively low mission cost can provide a mutual benefit in technology advancement and development while providing needed mission capabilities (10).

See table 4-3 for current state-of-the-art other mono- and bipropellant devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

Range Safety AFSPCMAN91-710 (11) requirements state that if a propellant is less prone to external leakage, which is often seen with the ionic liquid ‘green’ systems due to higher viscosity of the propellant, then the hazardous classification is reduced. External hydrazine leakage is considered “catastrophic,” whereas using ionic liquid green propellants reduces the hazard severity classification to “critical” and possibly “marginal” per MIL-STD-882E (Standard Practice for System Safety) (12). A classification of “critical” or less only requires two-seals to inhibit external leakage, meaning no additional latch valves other isolation devices are required in the feed system (12). While these propellants are not safe for consumption, they have been shown to be less toxic compared to hydrazine. This is primarily due to green propellants having lower vapor pressures, being less flammable, and producing more benign constituent product gasses (such as water vapor, hydrogen and carbon dioxide) when combusted.

Fueling spacecraft with green propellants, generally permitted as a parallel operation, may require a smaller exclusionary zone, allowing for accelerated launch readiness operations (13). These green propellants are also generally less likely to exothermically decompose at room temperature due to higher ignition thresholds. Therefore, they require fewer inhibit requirements, fewer valve seats for power, and less stringent temperature storage requirements.

Green propellants also provide higher specific impulse performance than the current state-of-the-art hydrazine monopropellant thrusters for similar thrust classes and have higher density-specific impulse achieving improved mass fractions. Additionally, these propellants also have lower minimum storage temperatures which may be beneficial in power-limited spacecraft as tank and line heater requirements are lower.

The primary ionic liquid propellants with flight heritage or upcoming spaceflight plans are LMP-103S, which is a blend of Ammonium Dinitramide (ADN), and AF-M315E (now: referred to as “ASCENT”), a blend of Hydroxylammonium Nitrate (HAN). While generally the components (e.g. thrusters) are relatively mature (TRL > 5), incorporating them into readily-producible propulsion systems is more challenging and the maturity of stand-alone propulsion systems is lagging the components.

As a majority of these non-toxic propellants are in development, systems using these propellants present additional technical challenges including increased power consumption for thruster pre-heating and a smaller selection of compatible materials due to higher combustion temperatures. Options where performance is traded for more benign operating conditions (and thus lower cost materials) are also being explored.

Other alternative propellants, such as hydrogen peroxide, are also available and have been in use for many years. Some of these may be lower performing than hydrazine but offer more benign operating environments and have more readily available and lower-cost material selections. These propellants do carry with them their own unique handling considerations. For instance, high purity hydrogen peroxide is a strong oxidizer and can exothermically decompose rapidly if not properly stored and handled. Hydrogen peroxide, however, has been used as a rocket propellant for many decades, and there is a lot of information on safe handling, materials selection, and best practices. Electrolyzed water is another propellant option, wherein water is decomposed into hydrogen and oxygen and combusted as a traditional bi-propellant thruster. However, generating and managing the power required to electrolyze the water in a compact spacecraft presents its own unique challenges. Yet it does provide a safe-to-launch system with very benign constituents.

b. Missions

Planet Labs launched a constellation of Earth observing satellites, called SkySat. These satellites are approximately 120 kg, and incorporate the Bradford-ECAPS HPGP system (a LMP-103S based system shown in figure 4.3). The SkySat HPGP system includes four 1-N thrusters. As of summer 2020, 15 SkySat small spacecraft were launched and are fully operational (14).

Figure 4.3: ECAPS HPGP thruster. Credit: Bradford ECAPS.

The JPL-led Lunar Flashlight mission manifested for Artemis I will map the lunar south pole for volatiles. The mission will demonstrate several technological firsts, including being the first CubeSat to reach the Moon, the first planetary CubeSat mission to use green propulsion, and the first mission to use lasers to look for water ice (15). NASA Marshall Space Flight Center (MSFC) partnered with the Georgia Institute of Technology (GT) to build the Lunar Flashlight Propulsion System, a self-contained unit that can deliver over 3000 Ns of total impulse for this mission. The LFPS is a pump-fed system that has four 100-mN ASCENT thrusters (figure 4.4), built by Plasma Processes LLC., and a novel micro-pump built by Flight Works Inc. The LFPS system will undergo qualification testing in fall 2020.

Figure 4.4: Plasma Processes LLC 100mN thruster. Credit: NASA MSFC.

Another ASCENT-based propulsion system flew as a technology demonstration on the NASA Green Propellant Infusion Mission (GPIM) launched in July 2019 (16). This small spacecraft was designed to test the performance of this propulsion technology in space by using five 1-N class thrusters (figure 4.5) for small attitude control maneuvers (17). Aerojet completed a hot-fire test of the GR-1 version in 2014 and further tests in 2015. An updated variant of the GR-1 to improve manufacturability is in-development. Initial plans to incorporate the GR-22 thruster (22-N class) on the GPIM mission were deferred in mid-2015 in order to allow for more development and testing of the GR-22. As a result, the GPIM mission only carried and demonstrated five GR-1 units when launched (18).

Figure 4.5: GR1 thruster. Credit: Aerojet.

NASA Ames Research Center (ARC) and GRC are working on the Pathfinder Technology Demonstration (PTD) project which consists of a series of 6U CubeSats that will be launched to test the performance of new subsystem technologies in orbit. Tethers Unlimited, Inc. is developing a water electrolysis propulsion system called HYDROS-C, which is less than 2.4U in volume and uses water as propellant. In-orbit, water is electrolyzed into oxygen and hydrogen and these propellants are combusted as in a traditional bi-propellant thruster. This thruster provides an average thrust of 1.2 N with an I_{SP} of 310 s, and requires 10 – 15 minutes of recharge time for each 1.75 N-s thrust event. This system has been selected for NASA's first Pathfinder Demonstration CubeSat Mission planned for launch in late 2020 (19). A variant of the HYDROS-C system is the HYDROS-M system, which is intended to be sized for MicroSats.

CisLunar Explorer is part of a NASA Centennial Challenge mission planned for Artemis I. The CisLunar Explorer's concept consists of a pair of spacecraft on a mission to orbit the Moon. These two spacecraft are mated together as a "6U"-sized box, and after deployment from the launch vehicle, they will split apart and each give their initial rotation in the process of decoupling. The spacecraft will then enter and attempt to maintain lunar orbit. The propulsion system for this mission is a water electrolysis system developed by Cornell University (20).

NanoAvionics has developed a non-toxic mono-propellant propulsion system called Enabling Propulsion System for Small Satellites (EPSS) which was demonstrated on LituanicaSAT-2, a 3U CubeSat, to correct orientation and attitude, avoid collisions, and extend orbital lifetime. It uses an ADN-blend as propellant and gives 213 s of specific impulse that is designed to provide 400 N-s of total impulse. LituanicaSAT-2 was launched June 2017 and successfully separated from the primary payload (Cartosat-2) as part of the European QB50 initiative. According to product literature, multiple missions have since launched, with the latest being in April 2019 (21).

Dawn Aerospace (formerly: Hyperion) has developed a 0.5 N bi-propellant system that consists of a single thruster with a gimbal to provide thrust in two axes. The 1U configuration (figure 4.6) provides 850 N-s of total impulse with a minimum impulse bit of 35 mN-s (22). First flight of this system is scheduled for Q3 2020.

DAWN AEROSPACE

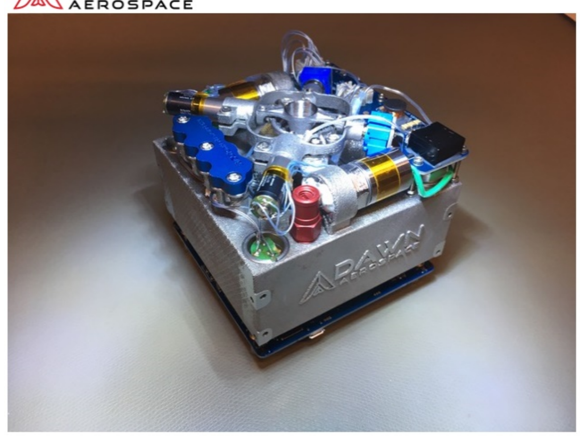


Figure 4.6: PM200. Credit: Dawn Aerospace.

Rocket Lab's Electron rocket has a liquid propellant kick-stage that uses a cold-gas RCS. The Rocket Lab Kick Stage, powered by the Curie engine, is designed to deliver small satellites to precise orbits before deorbiting itself to leave no part of the rocket in space. The kick stage was flown and tested onboard the Still Testing flight that was successfully launched on January 21, 2018. With the new kick stage Rocket Lab can execute multiple burns to place numerous payloads into different orbits. The kick stage is designed for use on the Electron launch vehicle with a payload capacity of up to 150 kg, and will be used to disperse CubeSat constellations fast and accurately, enabling satellite data to be received and used soon after launch (23) (24).

Hybrids

Hybrid propulsion is a mix of both solid and liquid/gas forms of propulsion. In a hybrid rocket, the fuel is typically a solid grain and the oxidizer (often gaseous oxygen) is stored separately. The rocket is then ignited by injecting the oxidizer into the solid motor and igniting it with a spark or torch system. Since combustion can only occur while oxidizer is flowing, these systems can readily be started and shut-down by controlling the flow of oxidizer.

See table 4-4 for current state-of-the-art hybrid devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

Because there is no oxidizer pre-mixed with the solid motor, these systems are inherently safer from a handling standpoint than solid motor systems, as the risk of pre-mature ignition is greatly reduced. They offer the best of both worlds of solids (storability & handling) and liquids (restart & throttling). Yet they do have drawbacks, as performance tends to not be as high as either system and regression rate control and slag tend to be more problematic in these designs.

b. Missions

A novel arc-ignition 'green' CubeSat hybrid thruster system prototype was developed at Utah State University. This system is fueled by 3-D printed acrylonitrile butadiene styrene (ABS) plastic for its unique electrical breakdown properties. Initially, high-pressure gaseous oxygen (GOX) was to be used as the oxidizer. However, for the sake of the technology demonstration and after safety considerations by NASA Wallops High Pressure Safety Management Team, it was concluded the oxidizer needed to contain 60% nitrogen and only 40% oxygen. On March 25th, 2018, the system was successfully tested aboard a sounding rocket launched from NASA Wallops Flight Facility (WFF) into space and the motor was successfully re-fired 5 times. During the tests, 8 N of thrust and a specific impulse of 215 s were achieved as predicted (25) (26). The Space Dynamics Lab has miniaturized this technology to be better suited for CubeSat applications (0.25 - 0.5 N). A qualification unit is currently in development for the miniaturized system.

Cold Gas / Warm Gas

Cold gas systems are relatively simple systems that provide limited spacecraft propulsion and are one of the most mature technologies for small spacecraft. Thrust is produced by the expulsion of a propellant which can be stored as a pressurized gas or a saturated liquid. Warm gas systems, in which the propellant is heated but there is still no chemical reaction, have been used to increase thrust and specific impulse. Warm gas systems use the same basic principle as cold gas systems, and have higher performance at the cost of added power requirements to heat the propellant. Electrothermal systems, a type of warm-gas system where the gas is electrically heated in the thruster body or nozzle, are described in more detail in the Electric Propulsion section.

See table 4-5 for current state-of-the-art cold gas / warm gas devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

Cold gas thrusters are often attractive and suitable for small buses due to their relatively low cost and complexity. Many cold gas thrusters use inert, non-toxic propellants, which are an advantage for secondary payloads that must adopt “do no harm” approaches to primary payloads. Such systems are well suited to provide attitude control, since they technically provide very low minimum impulse bits for precise maneuvering. However, the low specific impulse of these systems limit them from providing large orbit correction maneuvers. Recently, new designs have improved the capability of these systems for nanosatellite buses such as 3U CubeSats.

b. Missions

A cold gas thruster developed by Marotta flew on the NASA ST-5 mission (launch mass 55 kg) for fine attitude adjustment maneuvers. It incorporates electronic drivers that can operate the thruster at a power of less than 1 W. It has less than 5 ms of response time and it uses gaseous nitrogen as propellant (27).

The Micro-Electromechanical-based PICOSAT Satellite Inspector, or MEPSI, built by the Aerospace Corporation flew aboard STS-113 and STS-116. The spacecraft included both target and imaging/inspector vehicles connected via tether. The two vehicles were 4 x 4 x 5 in^3 in volume, each, and had five cold-gas thrusters, producing ~20 mN. The MEPSI propulsion system was produced using stereo-lithography. It was suited as a propulsion research unit for picosats (28).

Surrey Satellite Technology Ltd. (SSTL) has included a butane propulsion system in several small spacecraft missions for a wide range of applications in low-Earth orbit and Medium Earth Orbit (MEO). In this system, propellant tanks are combined with a resistojet thruster and operation is controlled by a series of solenoid valves (figure 4.7). It requires power to heat the thruster and improve the specific impulse performance with respect to the cold gas mode. It has been in design for more than five years and uses a RS-422 electrical interface (29) (30).

Figure 4.7: SSTL butane propulsion system. Credit: Surrey Satellite Technology Ltd.

In June 2014, Space Flight Laboratory at University of Toronto Institute for Aerospace Research (UTIAS) launched two 15 kg small spacecraft to demonstrate formation flying. The Canadian Nanosatellite Advanced Propulsion System (CNAPS), shown in figure 4.8, consisted of four thrusters fueled with liquid sulfur hexafluoride. This non-toxic propellant was selected because it has high vapor pressure and density, which is important for making a self-pressurizing system (31). This propulsion module is a novel version of the previous NanoPS that flew in the CanX-2 mission in 2008 (32).

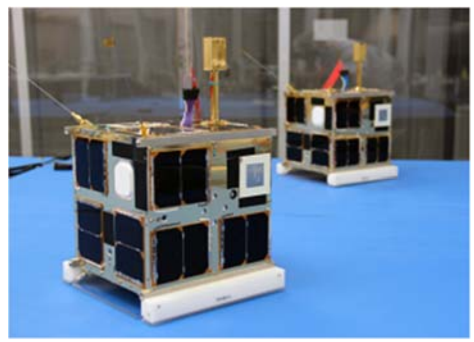


Figure 4.8: CanX-4 and CanX-5 formation flying nanosatellites with CNAPS propulsion systems. Credit: UTIAS SFL.

Another flight-demonstrated propulsion system was flown in the POPSAT-HIP1 CubeSat mission (launched June 2014), which was developed by Microspace Rapid Pte Ltd in Singapore. It consisted of a total of eight micro-nozzles that provided control for three rotation axes with a single-axis thrust for translational applications. The total delta-v has been estimated from laboratory data to be between 2.25 and 3.05 ms^{-1}. Each thruster has 1 mN of nominal thrust by using argon propellant. An electromagnetic microvalve with a very short opening time of 1 m-s operates each thruster (33).

Two related butane propulsion systems have been developed by GomSpace: the NanoProp 3U and NanoProp 6U. Both use proportional thrust control of four nozzles to control spacecraft attitude while providing delta-v. The 6U configuration was flown on GOMX-4B in 2018 as a formation flight demonstration (34) (35).

An ACS cold gas propulsion system using R-236fa was produced and tested by Lightsey Space Research for the NASA ARC BioSentinel mission, a 6U CubeSat scheduled to launch on Artemis I. This propulsion system uses a 3D-printed propellant tank in order to reduce part count and use the available volume more efficiently (36) (37).

A complete cold gas propulsion system has been developed for CubeSats with a microelectromechanical system (figure 4.9) that provides accurate thrust control with four butane propellant thrusters. While thrust is controlled in a closed loop system with magnitude readings, each thruster can provide a thrust magnitude from zero to full capacity (1 mN) with 5-μN resolution. The dry mass of the system is 0.220 kg and average power consumption is 2 W during operation (38). This system is based on flight-proven technology flown on larger spacecraft (PRISMA mission, launched in 2010). The MEMS cold gas system was included on the bus of the TW-1 CubeSat, launched in September 2015 (39).

Figure 4.9: NanoSpace MEMS cold gas system. Credit: GomSpace.

The CubeSat Proximity Operations Demonstration (CPOD) is a mission led by Tyvak Nano-Satellite Systems (40). It incorporates a cold gas propulsion system built by VACCO Industries that provides up to 186 N-s of total impulse. This module operates at a steady state power of 5 W and delivers 40-s of specific impulse while the nominal thrust is 10 mN (41). It uses self-pressurizing refrigerant R236fa propellant to fire a total of eight thrusters distributed in pairs at the four corners of the module. It has gone through extensive testing at the US Air Force Research Lab. Endurance tests consisted of more than 70,000 firings.

JPL is supporting the InSight mission, launched in March 2018, which incorporated two identical CubeSats as part of the Mars Cube One (MarCO) technology demonstration. These spacecraft performed five trajectory correction maneuvers (TCMs) during the mission to Mars. The CubeSats included an integrated propulsion system developed by VACCO Industries, which contained four thrusters for attitude control and another four for TCMs. The module uses cold gas refrigerant R-236FA as propellant, produces 75 N-s of total impulse, and weighs 3.49 kg (42) (43).

NEA Scout is a NASA MSFC mission that is going to be launched as part of Artemis I scheduled for 2021. For its main propulsion system, NEA Scout will deploy a sail of 80 m^2 with 0.0601-mm s^{-2} of characteristic acceleration, and will be steered by active mass translation via a VACCO cold gas MiPS (R236FA propellant). This module is approximately 2U in volume and will use six 23-mN thrusters to provide 30 m s^{-1} of delta-v (44).

Solid Motors

Solid rocket technology is typically used for impulsive maneuvers such as orbit insertion or quick de-orbiting. Due to the solid propellant, they achieve moderate specific impulses and high thrust magnitudes that are compact and suitable for small buses.

There are some electrically controlled solid thrusters that operate in the milli-newton (mN) range. These are restartable, have steering capabilities, and are suitable for small spacecraft applications, unlike larger spacecraft systems that provide too much acceleration.

See table 4-6 for current state-of-the-art solid motor devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

Thrust vector control systems can be coupled with existing solid rocket motors to provide controllable high delta-v in relatively short time. While some solid motors are restartable, in general solid motors are often considered a single-burn event system. In order to achieve multiple burns, the system must be either electrically restartable (aka electric solid propellants), or several small units must be matrixed into an array configuration. Because electrically-controlled solid propellant (ESPs) are electrically ignited, they are safer than traditional solid energetic propellants.

b. Missions

A flight campaign tested the ability of these thrust vector control systems coupled with solid motors to effectively control the attitude of small rocket vehicles. Some of these tests were performed by using state-of-the-art solid rocket motors such as the ISP 30 developed by Industrial Solid Propulsion and the STAR 4G by ATK (now: Northrop Grumman) (45).

SpinSat, a 57 kg spacecraft, was deployed from the International Space Station (ISS) in 2014 and incorporated a set of first-generation solid motors, the CubeSat Agile Propulsion System (figure 4.10), which was part of the attitude control system developed by Digital Solid State Propulsion LLC (DSSP). The system was based on a set of ESP thrusters that consist of two coaxial electrodes separated by a thin layer of electric solid propellant. This material is highly energetic but non-pyrotechnic and is only ignited if an electric current is applied. The thrust duration can be better controlled and allows for better burn control, and the lack of moving parts make the system suitable for small spacecraft (46).

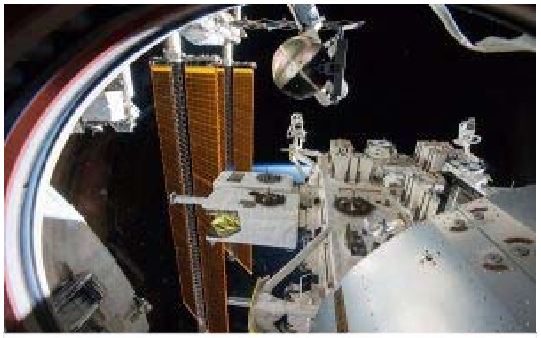


Figure 4.10: SpinSat at the ISS. Credit: NASA.

The Modular Architecture Propulsion System (MAPS) by Pacific Scientific Energetic Materials Company (PacSci EMC) Propulsion array (figure 4.11) has a 10-plus year in-orbit lifespan. The MAPS system provides three axes capability to control such areas as attitude control, deorbit, drag makeup, and plane and attitude changes with a delta-v greater than 50 m s^{-1}. The capability of MAPS “plug-and-play” bolt-on design and clean-burning propellant array is scalable and can be custom fit for a range of interfaces. MAPS was flown aboard the PACSCISAT (47) (48).

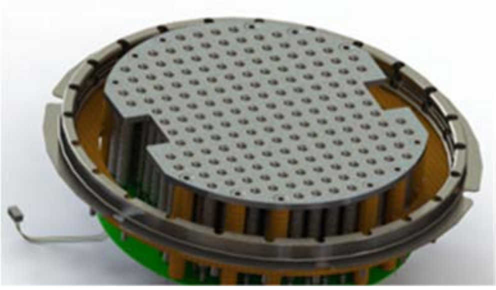


Figure 4.11: PacSci EMC MAPS sealed solid propellant rocket motor array. Credit: PacSci.

Propellant Management Devices

While not specifically a propulsion type, propellant management devices (PMDs) are frequently used in larger liquid propulsion systems to deliver propellant to the thruster units. As small spacecraft start looking towards more complex propulsion systems, PMDs will undoubtedly play an integral part. Historically, small spacecraft have used bellows or membrane tanks to ensure propellant delivery and expulsion. However, there is the potential to incorporate PMD structures into additively manufactured tanks and propulsion systems, permitting much more conformal structures to be created for small spacecraft missions while still meeting mission performance targets. Hence, PMDs are a critical part of any in-space propulsion system that doesn’t use bellows or membrane type tanks, and they are briefly covered here for awareness. A more detailed treatment and explanation can be found in the literature, and a good overview is provided by Hartwig (49).

a. Key Integration and Operational Considerations

The purpose of propellant management devices (PMDs) is to separate liquid and vapor phases within the propellant storage tank upstream of the thruster, and to transfer vapor-free propellant in any gravitational or thermal environment. PMDs have flight heritage with all classical storable systems, have been flown once with LMP-103S, have no flight heritage with cryogenic propellants, and have been implemented in electric propulsion systems. Multiple PMDs are often required to meet the demands of a particular mission, whether using storable or cryogenic propellants. A comprehensive, up-to-date list of the types of propellant management devices, as well as missions employing PMDs, is available in Hartwig (49).

b. Missions

The Lunar Flashlight Propulsion System will employ a PMD sponge and ribbon vane. Surface tension properties, a necessary parameter for PMD sizing, have been determined for the ASCENT propellant by Kent State University, funded and managed by NASA.

4.6.2 In-Space Electric Propulsion

In-space electric propulsion (EP) is any in-space propulsion technology wherein a propellant is accelerated through the conversion of electrical energy into kinetic energy. The electrical energy source powering in-space EP is historically solar, therefore these technologies are often referred to as solar electric propulsion (SEP), although other energy sources are conceivable such as nuclear reactors or beamed energy. The energy conversion occurs by one of three mechanisms: electrothermal, electrostatic, or electromagnetic acceleration (87) (88). Each of these technologies are covered herein.

This survey of the state-of-the-art in EP does not attempt to review all known devices, but focuses on those devices that can be commercially procured or devices that appear on a path towards commercial availability. The intent is to aid mission design groups and other in-space propulsion end-users by improving their awareness of the full breadth of potentially procurable EP devices that may meet their mission requirements.

Metrics associated with the nominal operating condition for each propulsion device are published herein, rather than metrics for the complete operating range. A focus on the nominal operating condition was decided to improve comprehension of the data and make initial device comparisons more straightforward. When a manufacturer has not specifically stated a nominal operating condition in literature, the manufacturer may have been contacted to determine a recommended nominal operating condition, otherwise a nominal operating condition was assumed based on similarity to other devices. For those metrics not specifically found in published literature, approximations have been made when calculable from available data. Readers are strongly encouraged to follow the references cited to the literature describing each device's full performance range and capabilities.

Electrothermal

Electrothermal technologies use electrical energy to increase the enthalpy of a propellant, whereas chemical technologies rely on exothermal chemical reactions. Once heated, the propellant is accelerated and expelled through a conventional converging-diverging nozzle to convert the acquired energy into kinetic energy, similar to chemical propulsion systems. The specific impulse achieved with electrothermal devices is typically of similar magnitude as chemical devices given that both electrothermal and chemical devices are fundamentally limited by the working temperature limits of materials. However, electrothermal technologies can achieve somewhat higher specific impulses than chemical systems, since they are not subject to the limits of chemical energy storage.

Electrothermal devices are typically subclassified within one of the following three categories.

1. *Resistojet devices* employ an electrical heater to raise the temperature of a surface that in turn increases the bulk temperature of a gaseous propellant.
2. *Arcjet devices* sustain an electrical arc through an ionized gaseous propellant, resulting in ohmic heating.
3. *Electrodeless* thrusters heat a gaseous propellant through an inductively or capacitively coupled discharge or by radiation.

Systems where the propellant enthalpy is increased by electrical heating within the propellant tank, rather than heating in the thruster head, are covered in the chemical propulsion section under cold/warm gas systems.

See table 4-7 for current state-of-the-art electrothermal devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

- **Propellant Selection:** Electrothermal technologies offer some of the most lenient restrictions on propellant selection for in-space propulsion. Whereas chemical systems require propellants with both the right chemical and physical properties to achieve the desired performance, electrothermal systems primarily depend on acceptable physical properties. For example, electrothermal devices can often employ inert gases or even waste products such as water and carbon dioxide. They also allow consideration of novel propellants such as high storage density refrigerants or in-situ resources. That said, not all propellants can be electrothermally heated without negative consequences. Thermal decomposition of many complex molecules result in the formation of polymers and other inconvenient byproducts. These byproducts may result in clogging of the propulsion system and/or spacecraft contamination.
- **Propellant Storage:** Electrothermal devices may require that propellants be maintained at a high plenum pressure to operate efficiently. This may require a high-pressure propellant storage and delivery system.
- **High Temperature Materials:** The working temperature limit of propellant wetted surfaces in the thruster head is a key limitation on the performance of electrothermal devices. As such, very high temperature materials, such as tungsten and molybdenum alloys, are often employed to maximize performance. The total mass and shape of these high temperature materials are a safety consideration for spacecraft disposal. While most spacecraft materials burnup on re-entry, the behavior of these high temperature materials will be considered when assessing the risk of re-entry debris to life and property.
- **Power Processing:** While some simple resistojet devices may operate directly from spacecraft bus power, other electrothermal devices may require a relatively complex power processing unit (PPU). For example, a radio-frequency electrodeless thruster requires circuitry to convert the DC bus power to a high-frequency alternating current (AC). In some cases, the cost and integration challenges of the PPU can greatly exceed those of the thruster.
- **Thermal Soak-back:** Given the high operating temperatures of electrothermal devices, any reliance on the spacecraft for thermal management of the thruster head should be considered. While the ideal propulsion system would apply no thermal load on the spacecraft, some thermal soak-back to the spacecraft is inevitable, whether through the mounting structure, propellant lines, cable harness, or radiation.

b. Missions

The Bradford (formerly Deep Space Industries) Comet water-based electrothermal propulsion system (figure 4.12) has been implemented by three customers operating in low-Earth orbit: HawkEye 360, Capella Space, and BlackSky Global (89). All three missions employ the same Comet thruster head, while the BlackSky Global satellites use a larger tank to provide a greater total impulse capability. The three HawkEye 360 pathfinder spacecraft employ the Space Flight Laboratory NEMO platform with each spacecraft measuring 20 x 20 x 44 cm^3 with a mass of 13.4 kg (90) (91). The Comet provides each HawkEye 360 a total delta-v capability of 96 m s^{-1}. The approximate dimensions of the BlackSky Global spacecraft are 55 x 67 x 86 cm^3 with a mass of 56 kg (92).

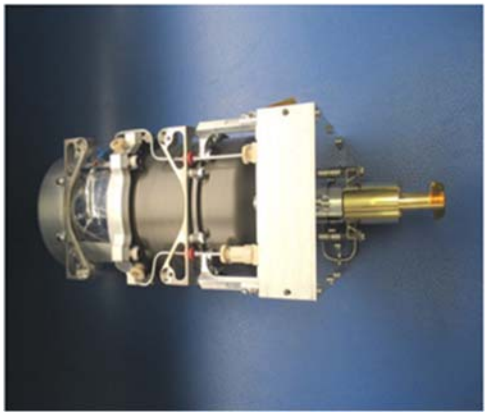


Figure 4.12: Comet-1000. Credit: Bradford Space.

The Propulsion Unit for CubeSats (PUC) system (93), figure 4.13, was designed and fabricated by CU Aerospace (Champaign, IL) and VACCO Industries under contract with the U.S. Air Force to supply two government missions (94). The system was acquired for drag makeup capability to extend asset lifetime in low-Earth orbit. The system uses SO_2 as a self-pressurizing liquid propellant. The propulsion system electrothermally heats the propellant using a micro-cavity discharge (MCD) and expels the propellant through a single nozzle (95). It can alternatively use R134a or R236fa propellants, but only in a cold-gas mode with reduced performance. Eight (8) flight units were delivered to the Air Force in 2014. It is unknown if any of the units have flown.

Figure 4.13: PUC module. Credit: CU Aerospace.

In 2019, CU Aerospace was selected for a NASA STMD Tipping Point award to design, fabricate, integrate, and perform mission operations for the DUPLEX 6U CubeSat having two of CU Aerospace's micro-propulsion systems on board, one Monofilament Vaporization Propulsion (MVP) (96) (97), figure 4.14, and one Fiber-Fed Pulsed Plasma Thruster (FPPT) (98) (99) (100) (101), figure 4.31. The MVP is an electrothermal device that vaporizes and heats an inert solid polymer propellant fiber to 1100 K. The novel approach for propellant storage and delivery addresses common propellant safety concerns, which often limit the application of propulsion on low-cost CubeSats. In-orbit operations will include inclination change, orbit raising and lowering, drag makeup, and deorbit burns demonstrating multiple mission capabilities with approximately 20 hours of operation for MVP and >1,000 hours for FPPT. Launch is anticipated in mid-2022 (102).

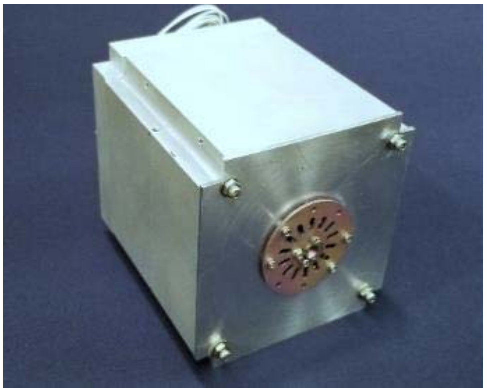


Figure 4.14: MVP module. Credit: CU Aerospace.

AuroraSat-1 is a technology demonstration 1.5U CubeSat that will demonstrate multiple propulsion devices by Aurora Propulsion Technologies. AuroraSat-1 will carry Aurora's smallest version of their Attitude and Orbit Control System (AOCS) (103), figure 4.15, and a demonstration unit of their Plasma Brake Module (PBM). The AOCS integrated in AuroraSat-1 has six resistojet thrusters for full 3-axis attitude control and 70 grams of water propellant, providing a total impulse of 70 Ns. AuroraSat-1 is built by SatRevolution with Aurora providing the payloads. The satellite is anticipated to be launched on a SpaceX Falcon 9 with a Momentus Space Vigoride mission in December 2020 (104). Momentus will deploy AuroraSat-1 into a 550 km sun synchronous orbit (SSO). See section 4.6.3 for discussion of the PBM module.

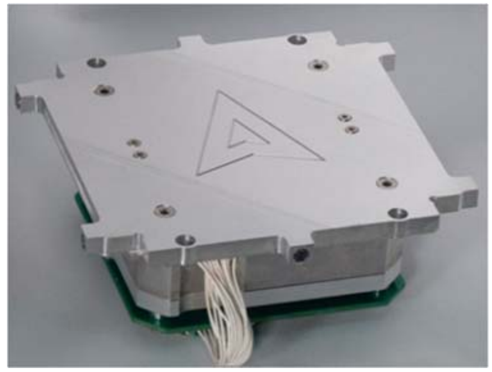


Figure 4.15: ARM-A AOCS module. Credit: Aurora Propulsion Technologies.

Electrosprays

Electrospray propulsion systems generate thrust by electrostatically extracting and accelerating ions or droplets from a low-vapor-pressure, electrically-conductive, liquid propellant (figure 4.16). This technology can be generally classified into the following types according to the propellant used:

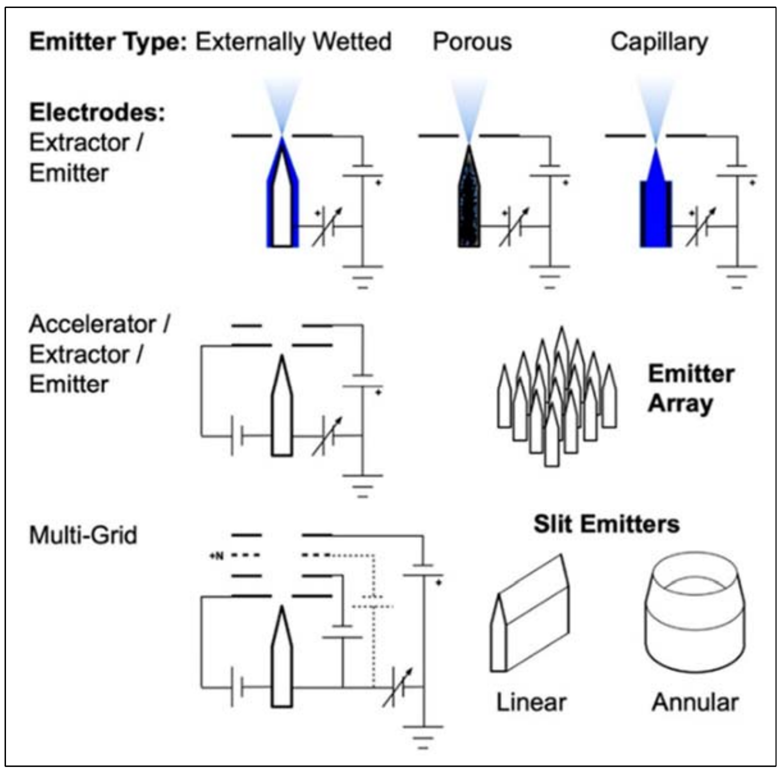


Figure 4.16: Schematic of typical electrospray emitter and electrode configurations. Credit: NASA.

Ionic-Liquid Electrosprays: These technologies use ionic liquids (i.e., salts in a liquid phase at room conditions) as the propellant. The propellant is stored as a liquid, and onboard heaters may be present to maintain propellant properties within the desired operational temperature range. Commonly used propellants include 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF4) and bis(trifluoromethylsulfonyl)imide (EMI-Im). Thrusters that principally emit droplets are also referred to as colloidal thrusters.

Field Emission Electric Propulsion (FEEP): These technologies use low-melting-point metals as the propellant. The propellant is typically stored as a solid, and onboard heaters are used to liquefy the propellant prior to thruster operations. Common propellants include indium and cesium.

Feed systems for electrospray technologies can be actively fed via pressurant gas or passively fed via capillary forces. The ion (high-I_{SP}) or droplet (moderate-I_{SP}) emission can be controlled by modulation of the high-voltage (i.e., >1 kV) input in a closed-loop feedback with current measurements. Stable operations in either emission mode can provide very precise impulse bits. Propellants that result in both anion and cation emission may not require the presence of a cathode neutralizer to maintain overall charge balance; such neutralizers are included as part of the electrospray propulsion system for propellants that only emit positively-charged species.

See table 4-8 for current state-of-the-art electrospray devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

- **Plume Contamination**: Because propellants for electrospray propulsion systems are electrically conductive and condensable as liquids or solids, impingement of the thruster plume on spacecraft surfaces may lead to electrical shorting and surface contamination of solar panels and sensitive spacecraft components.
- **Propellant Handling and Thruster Contamination**: Ionic liquids and metallic propellants can be sensitive to humidity and oxidation, so care is needed if extended storage prior to flight is required. Electrospray technologies can also be sensitive to contamination of the thruster head during propellant loading, ground testing (e.g., backsputter or outgassed materials from the test facility), and handling (i.e., foreign object debris). Precautions should be taken to minimize such contamination risks from manufacturing, through test, and to launch. Post-launch, ionic liquids can outgas (e.g., water vapor) when exposed to the space environment, and such behavior should be accounted for in the mission ConOps.
- **Performance Stability and Lifetime**: As an electrospray propulsion system operates over time, the propulsive performance can degrade as the plume impinges upon and deposits condensable propellant on thruster head surfaces; in time, sufficiently deposited propellant buildup can electrically short out the thruster electrodes and terminate thruster operations. Especially for missions with large total impulse requirements, having lifetime testing or validated life models of the electrospray propulsion system in a relevant environment is important for understanding end-of-life behavior.
- **Specific Impulse**: Even for electrosprays that principally emit ions, operational thruster modes and instabilities can result in droplet emission that degrade the specific impulse and thrust efficiency. Caution is advised when considering claimed specific impulse or other propulsive properties (e.g., thrust vector and beam divergence) derived from plume characteristics; having verification test data in a relevant environment is important for properly assessing these claims.
- **Precision Thrust**: Electrospray devices have the potential of providing very fine thrust precision during continuous operations. For devices that can operate in pulsed mode via pulsed modulation of the high-voltage input, fine impulse bits (i.e., <10 μN-s) may be achievable. Such operations permit precise control over spacecraft attitude and maneuvering. Verification test data in a relevant environment should be used to properly assess the degree of thrust precision.

b. Missions

The ESA Laser Interferometer Space Antenna (LISA) Pathfinder spacecraft was launched in December 2015, on Vega flight VV06. Onboard were two integrated propulsion modules associated with the NASA Space Technology 7- Disturbance Reduction System (ST7 DRS). Each propulsion module contained four independent Busek Colloid MicroNewton Thrusters (CMNT), propellant-less cathode neutralizers, power processing units, digital control electronics, and low-pressure propellant tanks. The propulsion system was successfully commissioned in-orbit in January 2016, after having been fully fueled and stored for almost eight years. The electrospray modules (figure 4.17), were operated at the Earth-Sun Lagrange Point 1 for 90 days to counteract solar disturbance forces on the spacecraft; seven of the eight thrusters demonstrated performance consistent with ground test results, and the full propulsion system met the mission-level performance requirements (105).

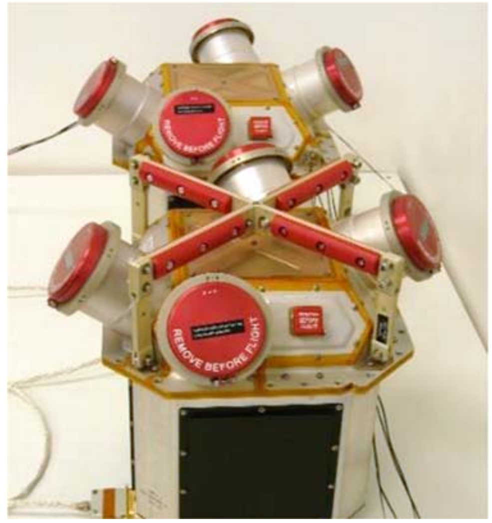


Figure 4.17: Flight CMNT modules for LISA Pathfinder. Credit: Busek.

Enpulsion's IFM Nano FEEP (figure 4.19), was first integrated onboard a 3U Planet Labs Flock 3P' CubeSat and launched via PSLV-C40 in January 2018. The indium-propellant propulsion system (with integrated thruster head, propellant storage, and power processing unit) was demonstrated in a 491 km by 510 km orbit. Two thruster firing sequences were reported, with the first a 15 minute firing in non-eclipse and the second a 30 minute firing in eclipse. Global Positioning System (GPS) telemetry data onboard the spacecraft indicated good agreement with the ~220 μN commanded thrust (106). Since this initial demonstration, the IFM Nano has flown onboard other spacecraft, but limited in-orbit data is publicly available. These missions include the ICEYE X2 (launched onboard Falcon-9 flight F9-64 in December 2018) to provide low-Earth orbit interferometric synthetic aperture radar observations (107) (108) and the DOD-funded Harbinger technology demonstrator (launched onboard Electron flight STP-27RD in May 2019) (109) (110). The IFM Nano will also be used onboard the Zentrum für Telematik (Würzburg) NetSat formation-flying demonstrator mission, expected to be launched via Soyuz in August 2020 (111).

Figure 4.19: IFM Nano. Credit: Enpulsion.

The University Würzburg Experimental Satellite 4 (UWE-4) was launched as a secondary payload onboard the Soyuz Kanopus-V 5 and 6 mission in Deer 2018. This 1U spacecraft housed two Morpheus Space NanoFEEP systems, with each system consisting of two gallium-propellant thrusters, a power processing unit board for the UNISEC Europe bus, and a propellant-less cathode neutralizer. An experiment using one thruster as an attitude control actuator was reported, with the increased spacecraft rotation rate corresponding to a derived thrust magnitude of ~5 μN; anomalous torque was attributed to unexpected impingement of the thruster plume upon the spacecraft antenna (112) (113). A 3U-Cubsat implementation of the same NanoFEEP technology is shown in figure 4.18.

Figure 4.18: Eight NanoFEEP thrusters integrated on 3U-Cubesat bus. Credit: Morpheus

Massachusetts Institute of Technology's BeaverCube is an educational mission that is expected to launch as a secondary payload onboard the SpaceX CRS-21 mission in October 2020. The 3U CubeSat houses payloads to observe terrestrial weather along with technologies for in-orbit demonstration, including Accion System's TILE-2 (figure 4.20). Accion's TILE-3 technology (consisting of an integrated unit with thruster heads, propellant storage, and power processing unit) is also expected to be operated in a low-Earth orbit mission in 2021; under a NASA Tipping Point Partnership, this mission seeks to demonstrate comparable propulsive capability as the MarCO CubeSats, but instead using electrospray technology (114) (115) (116).

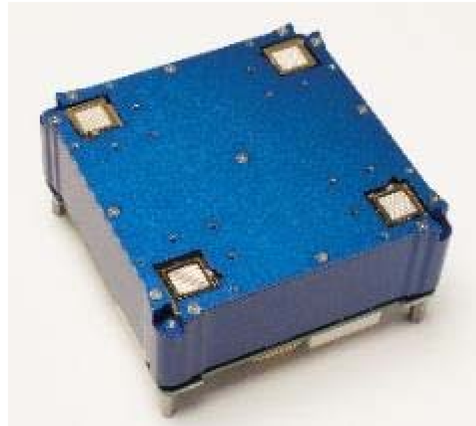


Figure 4.20: TILE-2. Credit: Accion Systems.

Gridded-Ion

Gridded-ion propulsion systems ionize gaseous propellant via a plasma discharge, and the resultant ions are subsequently accelerated via electrostatic grids (i.e., ion optics). This technology can be generally classified into the following types according to the type of plasma discharge employed:

- **Direct-Current (DC) Discharge**: The propellant is ionized via electron bombardment from an internal discharge cathode, figure 4.21.
- **Radio-Frequency (RF) Discharge**: No internal discharge cathode is present. Instead, the propellant is ionized via RF or microwave excitation from an RF generator, figure 4.22.

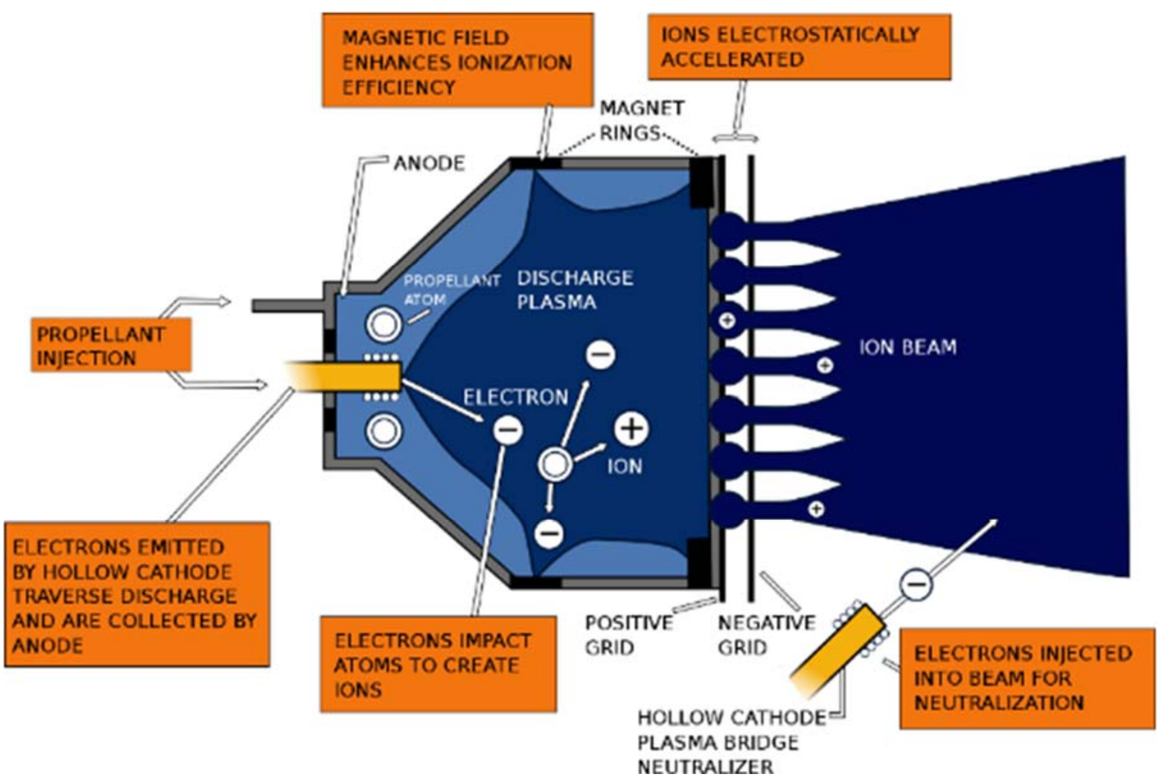


Figure 4.21: Schematic of typical DC-discharge gridded-ion thruster. Credit: NASA.

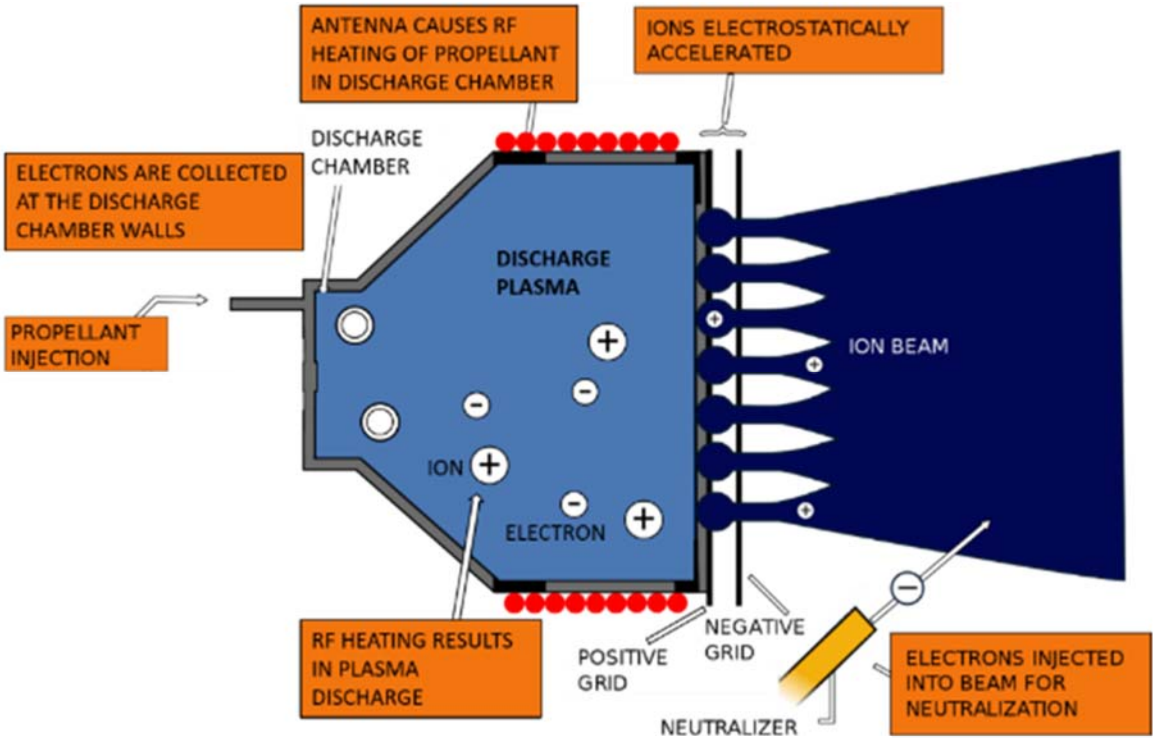


Figure 4.22: Schematic of typical RF-discharge gridded-ion thruster. Credit: NASA.

Gridded-ion thrusters typically operate at high voltages and include an external neutralizer cathode to maintain plume charge neutrality. High specific impulses can be achieved, but the thrust density is fundamentally limited by space-charge effects. While the earliest thruster technologies used metallic propellants (i.e., mercury and cesium), modern gridded-ion thrusters use noble gases (e.g., xenon) or iodine.

See table 4-9 for current state-of-the-art gridded-ion devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

- **Performance Prediction:** Due to the enclosed region of ion generation and acceleration, gridded ion thrusters tend to be less sensitive to test-facility backpressure effects than other devices such as Hall thrusters. This allows for more reliable prediction of in-flight performance based on ground measurements. Furthermore, the separation between ion generation and acceleration mechanisms within the device tend to make calculations of thrust and ion velocity (or I_{SP}) more straightforward.
- **Grid Erosion**: Charge-exchange ions formed in between and downstream of the ion optics can impinge upon and erode the grids. Over time, this erosion can lead to a variety of failure modes, including grid structural failure, an inability to prevent electrons from backstreaming into the discharge chamber, or the generation of an inter-grid electrical short due to the deposition of electrically conductive grid material. Proper grid alignment is important to reducing grid erosion, and this alignment must be maintained during thruster assembly, transport, launch, and operations. Random vibration tests at the protoflight level should be conducted to verify the survivability of the ion optics against launch loads, and validated thermal modeling may be needed to assess the impact of grid thermal expansion during thruster operations.

- **Foreign Object Debris**: The grids are separated by a small gap, typically less than 1 mm, in order to maximize the electric field and thrust capability of the device. As a result, gridded-ion thrusters tend to be sensitive to foreign object debris, which can bridge the inter-grid gap and cause electrical shorting. Precautions should be taken to minimize such contamination risks from manufacturing, through test, and to launch.
- **Cathode Lifetime**: Cathodes for plasma discharge or plume neutralization may be sensitive to propellant purity and pre-launch environmental exposure. Feed system cleanliness, bake-out, and use of a high-purity propellant are key factors in maximizing cathode lifetime. The technology provider may recommend a maximum cumulative atmospheric exposure and humidity to reduce risk.
- **Roll Torque**: Misalignments in the ion optics can lead to disturbances in the thrust vector, resulting in a torque around the roll axis that cannot be addressed by the mounting gimbal. For missions requiring extended thruster operations, a secondary propulsion system or reaction wheels may be needed to counter the torque buildup (117).
- **Electromagnetic Interactions**: For RF-discharge thrusters, electromagnetic interference and compatibility (EMI/EMC) testing may be critical to assess the impact of thruster operations on spacecraft communications and payload functionality.
- **Iodine Propellant:** To address the volume constraints of small spacecraft, iodine is an attractive propellant. Compared to xenon, iodine's storage density is three times greater. Furthermore, iodine stores as a solid with a low vapor pressure, which addresses spacecraft integration concerns associated with high-pressure propellant storage. However, iodine is a strong oxidizer with long-duration impact on the thruster and spacecraft that remain largely unknown. Upcoming flights will provide insight into potential spacecraft interactions and long-term reliability of feed system and thruster components.
- **Power Electronics:** Operation of gridded ion thrusters requires multiple high-voltage power supplies for discharge operation (ion generation), ion acceleration, and neutralization, leading to potentially complex and expensive power electronics.

b. Missions

Lunar IceCube is an upcoming NASA-funded CubeSat mission to characterize the distribution of water and other volatiles on the Moon from a highly-inclined lunar orbit with a perilune < 100 km. Led by Morehead State University, the mission will be conducted via a 6U spacecraft that is manifested as a secondary payload onboard Artemis I, expected to launch in November 2021 (118) (119).

Lunar Polar Hydrogen Mapper (LunaH-Map) is an upcoming NASA-funded CubeSat mission to map hydrogen distributions at the lunar south pole from a lunar orbit with a perilune < 20 km. Led by Arizona State University, the mission will be conducted via a 6U spacecraft that is manifested as a secondary payload onboard Artemis I, expected to launch in November 2021 (120).

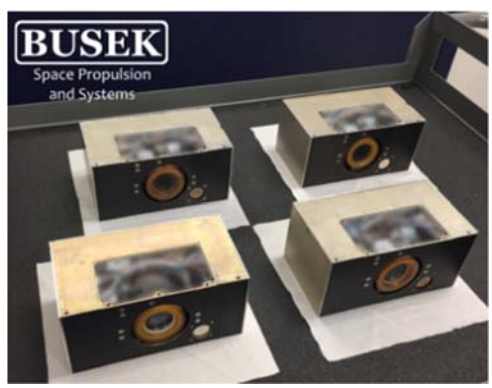


Figure 4.23: BIT-3 thruster. Credit: Busek.

Both missions use an onboard Busek BIT-3 propulsion system (figure 4.23) with solid iodine propellant. The BIT-3 system will be used as primary propulsion during the lunar transfer trajectory, followed by lunar orbit capture, orbit lowering, and spacecraft disposal. Each integrated

BIT-3 system includes a low-pressure propellant tank with heated propellant-feed components, a power processing unit to control the RF thruster and RF cathode, and a two-axis gimbal assembly.

Hall-Effect

The Hall-effect thruster (HET) is arguably the most successful in-space EP technology by quantity of units flown. The Soviet Union first flew a pair of EDB Fakel SPT-60 HETs on the Meteor-1-10 spacecraft in 1971. Between 1971 and 2018, over 300 additional HETs flew internationally, although EDB Fakel produced the vast majority. The first flight of a non-Russian HET was on board the European Space Agency (ESA) Small Missions for Advanced Research in Technology (SMART-1) spacecraft in 2003. SMART-1 employed the French PPS-1350 HET, produced by Safran (121). The first flight of a U.S. manufactured HET, the Busek BHT-200, was onboard the TacSat-2 spacecraft (122), a U.S. Air Force Research Laboratory (AFRL) experimental satellite in 2006. In 2010, Aerojet, another U.S. entity, began commercially delivering their 4.5 kW XR5 HET (123), formerly BPT-4000. Launches of HETs greatly accelerated in 2019 with the launch of 120 SpaceX Starlink and 6 OneWeb spacecraft (124), each including an HET. By early-August 2020, an additional 475 SpaceX and 68 OneWeb satellites launched into low-Earth orbit with HETs. Suffice to say that HETs have become a mainstream in-space propulsion technology.

The rapid growth in demand for HETs can be attributed to their simple design, historically well-demonstrated reliability, good efficiency, high specific impulse, and high thrust-to-power ratio. Although, the higher voltage gridded-ion thrusters (GIT) can achieve even higher specific impulse, HETs can achieve higher thrust-to-power ratios because the HET's higher density quasi-neutral plasma is not subject to space-charge limitations. The HET's higher thrust-to-power ratio will typically shorten spacecraft transit time. On the other end of the spectrum, arcjets provide significantly higher thrust than HETs, however material limitations prevent arcjets from matching the HET's electrical efficiency and specific impulse. For many missions, HETs provide a good balance of specific impulse, thrust, cost, and reliability.

HETs are a form of ion propulsion, ionizing and electrostatically accelerating the propellant. Historically, all HETs flown in space have relied on xenon propellant, given its high molecular weight, low ionization energy, and ease of handling. The recent exception is the SpaceX Starlink spacecraft using krypton propellant. While HETs operate less efficiently with krypton propellant and krypton has more challenging storage requirements, krypton gas is considerably lower cost than xenon gas, which is a compelling attribute when the potential number of spacecraft are projected in the thousands, as with constellations. Many other propellants have been considered and ground tested for Hall-effect thrusters, but to date only Hall-effect thrusters using xenon or krypton have flown.

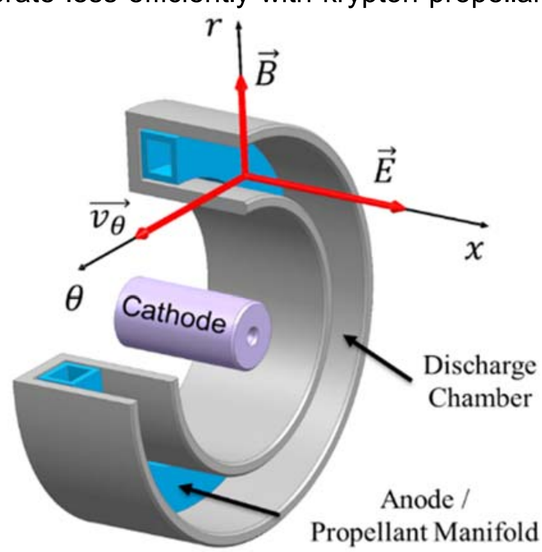


Figure 4.24: Hall-effect Thruster schematic. Credit: NASA.

As schematically shown in figure 4.24, HETs apply a strong axial electric field and radial magnetic field near the discharge chamber exit plane. The **E x B** force greatly slows the mean axial velocity of electrons and results in an azimuthal electron current many times greater than the beam current. This azimuthal current provides the means by which the incoming neutral propellant is collisionally ionized. These ions are electrostatically accelerated and only weakly affected by the magnetic field. The electron source is a low work function material typically housed in a refractory metal structure, historically located external to the HET body, although many recent thruster designs have begun centrally mounting the cathode in the HET body as shown in figure 4.24. The cathode feeds electrons to the HET plasma and neutralizes the plasma plume ejected from the thruster. The high voltage annular anode sits at the rear of the discharge chamber and typically functions as the propellant distribution manifold.

See table 4-10 for current state-of-the-art HET devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

- **Ground Facility Effects:** Ground facility effects may result in inconsistencies between ground and flight performance. The significance of the inconsistencies are dependent on factors such as test facility scale, test facility pumping speed, intrusiveness of diagnostics, and thruster electrical configuration.
- **Contamination:** Plume ions of an HET can affect spacecraft surfaces by erosion or contamination, even at large plume angles. Ground facility measurement of ion density at large angles may under predict flight conditions.
- **Thermal Soak-Back:** HET core temperature may exceed 400°C with the cathode exceeding 1000°C. Most HET waste heat radiates directly from the HET surfaces. However, some thermal soak-back to the spacecraft will occur through the mounting structure, propellant feed lines, electrical harness, and radiation.
- **Survival Heaters:** Given the thermal isolation between the HET and spacecraft, the HET may require a survival heater depending on the qualification temperature and flight environments.
- **Performance:** HET performance may vary over the life of the device due to erosion and contamination of the plasma wetted HET surfaces. Magnetically shielded thrusters demonstrate less time dependency to their performance than classical HETs.
- **Thruster Lifetime:** Classical HETs are primarily life-limited by erosion of the discharge chamber wall. Magnetically shielded HETs are primarily life-limited by erosion of the front pole covers.
- **Cathode Lifetime:** Cathode lifetime may be sensitive to propellant purity and pre-launch environmental exposure. Feed system cleanliness, bake-out, and use of a high purity propellant are key factors in maximizing cathode lifetime. The HET manufacturer may recommend a maximum cumulative atmospheric exposure and humidity. Some cathode emitter formulations are less sensitive to propellant impurities and atmospheric exposure, but these formulations may require other trades such as a higher ignition temperature.
- **Roll Torque**: The **E x B** force results in a slight swirl torque. For missions requiring extended thruster operations, a secondary propulsion system or reaction wheels may be needed to counter the torque buildup. The roll torque may largely be countered by periodically reversing the direction of the magnetic field. Field reversal requires switching the polarity of current to the magnet coils. Field reversal is only possible with HETs using electromagnets.
- **Thrust Vector**: Non-uniformity of the azimuthal plasma, magnetic field, or propellant flow may result in slight variations of the thrust vector relative to the HET physical centerline. Temperature variation of the HET, such as during startup, also results in a slight walking of the thrust vector.
- **Heaterless Cathodes:** Heaterless cathode technologies continue to mature. The benefit of a heaterless cathode is elimination of the cathode heater, typically an expensive component due to rigorous manufacturing and acceptance processes. However, the physics of heaterless cathode life-limiting processes require further understanding.

Nevertheless, heaterless cathode demonstrations have empirically shown significant promise. Heaterless cathode requirements on the EP system differ from an HET with a cathode heater. Impacts on the power processing unit and feed system should be understood when trading heaterless versus heated cathode.

- **Throttling Range:** HETs typically throttle stably over a wide range of power and discharge voltage. This makes an HET attractive for missions requiring multiple throttle set-points. However, an HET operates most efficiently at specific throttle conditions. Operating at off-nominal conditions may result in decreased specific impulse and/or electrical efficiency.

b. Missions

Canopus-V (alternative spelling Kanopus-V) is a Russian Space Agency spacecraft for Earth observation with a design life of 5 years. The 450 kg spacecraft launched in 2012 employed a pair of EDB Fakel SPT-50 thrusters. Similarly, the Canopus-V-IK (Kanopus-V-IK) launched in 2017 with a pair of SPT-50. The SPT-50 thrusters have a long history of spaceflight dating back to the late 1970s. Although the Canopus bus exceeds 450 kg, the power class and physical scale of the SPT-50 are appropriate for smaller spacecraft. The SPT-50 is nominally a 220 W thruster operated on xenon propellant (125) (126) (127).

The KazSat-1 and KazSat-2 spacecraft produced by Khrunichev Space Center in cooperation with Thales Alenia Space launched in 2006 and 2011, respectively. The KazSat spacecraft are geosynchronous communication satellites. These spacecraft employ the EDB Fakel SPT-70BR thruster. The SPT-70BR is Fakel's latest version of the SPT-70 product line. EDB Fakel optimized the SPT-70 for operation between 600 and 700 W, but no more than 900 W. Experiments demonstrate a lifetime of 3,100 hours, equating to about 450 kNs. The SPT-70 thrusters have a long history of spaceflight dating back to the early 1980s. Control of KazSat-1 was lost in 2008 (128) (129).

Figure 4.25: BHT-200 thruster. Credit: Busek.

The Busek BHT-200 (figure 4.25) has the distinction of being the first U.S.-made HET to operate in space. The BHT-200 has flight heritage from demonstrations on the TacSat-2 mission launched in 2006, FalconSat-5 mission launched in 2010, and FalconSat-6 mission launched in 2018. A Busek PPU powered the 200 W HET for each of the FalconSat missions (130). Ground testing of the BHT-200 includes multiple propellants, although all spaceflights have used xenon. Busek developed an iodine compatible derivative of the BHT-200 for the NASA iSat mission. It was determined during the course of the iSat project that additional development related to iodine compatible cathodes was required before conducting an in space demonstration of the technology at this scale of thruster (131) (132).

The Israel Space Agency and the French National Center for Space Studies (CNES) jointly developed the VENuS (Vegetation and Environment monitoring on a New MicroSatellite) spacecraft launched in 2017. The 268 kg VENuS spacecraft includes a pair of Rafael IHET-300

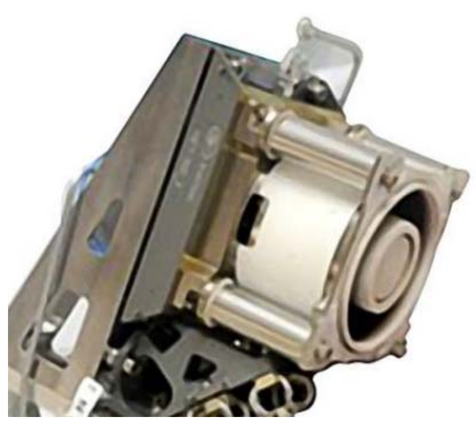


Figure 4.26: IHET-300 thruster. Credit: Rafael.

thrusters (figure 4.26) and 16 kg of xenon propellant. The propulsion system initially maintains the spacecraft in a 720 km orbit. In 2020, the propulsion system will transfer VENuS to and maintain a 410 km orbit. Inflight operations have demonstrated operation between 250 and 600 W. Rafael developed the IHET-300, nominally operating at 300 W, specifically for small spacecraft (133) (134) (135) (136) (137).

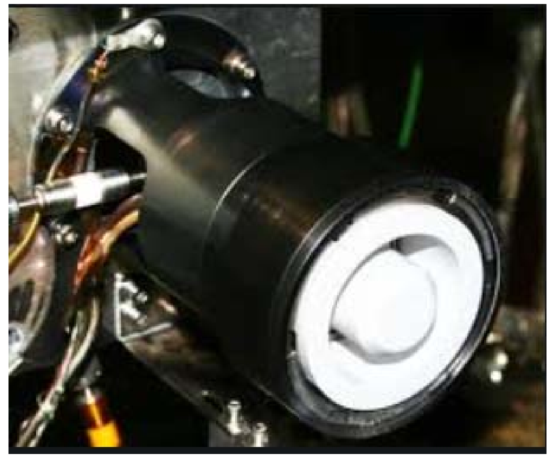


Figure 4.27: HT100 thruster. Credit: SITAEL.

The European and Italian space agencies selected the SITAEL HT100 (figure 4.27) for an in-orbit validation program to evaluate the device's capabilities for orbital maintenance and accelerated reentry of a small spacecraft. The uHETSat mission will be the first in-orbit demonstration of the HT100. SITAEL is currently performing ground qualification of the complete propulsion system. The HT100 is nominally a 175 W device operating on xenon propellant. The uHETSat will use the SITAEL S-75 microsatellite platform. The S-75 is 75 kg with dimensions of 60 x 40 x 36 cm^3. The anticipated launch date is unclear (138) (139) (140).

Figure 4.28: ACE thruster. Credit: Apollo Fusion.

The Astro Digital Ignis satellite is a technology demonstration spacecraft built to the 6U CubeSat standard. The spacecraft bus is the Astro Digital Corvus-6 design, which is 32 x 21 x 11 cm^3 with a mass no more than 12 kg. The Ignis includes the Apollo Fusion Apollo Constellation Engine (ACE), figure 4.28. Apollo Fusion offers the ACE compatible with xenon, krypton, and a proprietary high-density propellant. This first flight of the ACE HET will employ 1.1 kg of the proprietary propellant, providing approximately 12,000 Ns of total impulse. The anticipated lifetime of the spacecraft is less than 3 years in low-Earth orbit with an altitude of 500 km. Ignis is anticipated to launch in 2020 (141) (142).

Figure 4.29: ExoMG-nano thruster. Credit: Exotrail.

Exotrail anticipates launching its first in-orbit demonstration mission including the ExoMG-nano (figure 4.29) thruster in 2020. NanoAvionics and Exotrail partnered to integrate the ExoMG-nano into NanoAvionics' M6P nanosatellite 6U bus. Exotrail and its partners designed, built, integrated, and qualified the ExoMG-nano demonstrator in 10 months. Exotrail further signed a contract with AAC Clyde Space to provide propulsion for the Eutelsat ELO 3 and ELO4 6U CubeSats anticipated to launch in 2021 (143) (144) (145) (146).

ExoTerra has received a NASA Tipping Point award to perform an in-orbit demonstration of their 12U Courier SEP spacecraft bus with a target launch date of December 2021. The bus includes ExoTerra's Halo thruster (figure 4.30), propellant distribution, power processing unit and deployable solar arrays. The Courier spacecraft provides up to 1 km s^{-1} of delta-v, while hosting a 2U, 4 kg payload. The Tipping Point mission objective is to demonstrate the SEP system by spiraling to 800 km from a drop-off orbit of 400 km and then deorbiting. Primary mission objectives include demonstration of the solar array deployment and power generation, PPU efficiency, and 2 kg of thruster propellant throughput. The 0.67 kg, 1/4U thruster will nominally operate at 135 W. During the mission operations, a variation in thruster power and discharge voltage will demonstrate a performance range of 135 to 185 W and 150 to 400 V, respectively (147) (148) (149).

Figure 4.30: Halo thruster. Credit: ExoTerra Resource.

AST & Science (AST) of Midland, Texas, selected the Aurora Hall-Effect Propulsion System manufactured by Orbion Space Technology for its SpaceMobile network. AST anticipates SpaceMobile to be a low-Earth orbit constellation of hundreds of satellites providing cellular coverage for 4G and 5G smartphones. Orbion's Aurora thrusters will provide propulsion for orbital maintenance, collision avoidance, and de-orbiting at end-of-life. Orbion's Aurora propulsion system consists of a thruster, cathode, power processing unit, propellant flow controller, and cable harness. The anticipated launch date for the first satellites of the SpaceMobile constellation is unclear (150) (151).

Pulsed Plasma and Vacuum Arc Thrusters

Pulsed Plasma Thrusters (PPT) produce thrust by first triggering an electric arc between a pair of electrodes that typically ablates a solid-state propellant like polytetrafluoroethylene (PTFE) or ionizes a gaseous propellant. The plasma may be accelerated by either electrothermal or electromagnetic forces. Whether the mechanism of acceleration is electrothermal, electromagnetic, or often some combination thereof is determined by the particular device topology (152).

Electrothermal PPTs characteristically include a chamber formed by a pair of electrodes and solid propellant, wherein propellant ablation and heating occurs. During and immediately following each electric discharge, pressure accumulates and accelerates the propellant through a single opening. Electromagnetic PPTs characteristically do not highly confine the propellant as a plasma forms. The current pulse, which may exceed tens of thousands of amps, highly ionizes the ablated material or gas. The current pulse further establishes a magnetic field, where the **j x B** force accelerates the plasma. PPT devices that are predominantly electrothermal typically offer higher thrust, while devices that are predominantly electromagnetic offer higher specific impulse.

The simplest PPTs have no moving parts, which may provide a high degree of reliability. However, as the solid propellant is consumed, the profile of the propellant surfaces are constantly changing. Thus, PPTs with static solid propellant demonstrate a change in performance over life and inherently have a relatively limited lifetime. More complex solid propellant PPTs include a propellant feed mechanism. Typically, the propellant surface profile changes during an initial burn-in period, but then settles into a steady-state behavior where the propellant advancement is balanced by the propellant ablation.

PPT devices are suitable for attitude control and precision pointing applications. PPTs offer small and repeatable impulse bits, which allow for very high precision maneuvering. The complete propulsion system consists of a thruster, an ignitor, and a power processing unit (PPU). Energy to form the pulsed discharge is stored in a high voltage capacitor bank, which often accounts for a significant portion of the system mass. Once the capacitors are charged, resulting in a large differential voltage between the electrodes, the ignitor provides seed material that allows the discharge between the electrodes to form. Various materials and gases (including water vapor) have been tested with PPTs, however PTFE remains most common.

Vacuum arc thrusters (VAT) are another type of pulsed plasma propulsion (153). This technology consists of two metallic electrodes separated by a dielectric insulator. Unlike PPTs, one VAT electrode is sacrificial, providing the propellant source. The mechanism for propellant acceleration is predominantly electromagnetic, resulting in a characteristically high specific impulse and low thrust. One variant of the VAT is predominantly electrostatic, by the inclusion of a downstream electrostatic grid.

See table 4-11 for current state-of-the-art pulsed plasma and vacuum arc devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

- **Safety**: PPT capacitor banks often store tens of joules of energy at potentially a couple thousand volts. Follow good electrical safety practices when operating and storing PPTs in a laboratory environment.
- **Input Power Range**: PPTs and VATs are pulsed devices, which operate by discharging energy stored in capacitors with each pulse. Thus, the propulsion system's average power draw from the spacecraft bus can be quite low or high depending on the capacitor energy storage and pulse frequency. This flexibility allows PPTs to be applied to spacecraft with limited power budgets of just a few watts, or ample power budgets of hundreds of watts.
- **Minimum Impulse Bit:** A compelling capability of pulsed devices is the ability to generate small, precise, and well-timed impulse bits for precise spacecraft maneuvering. By controlling the discharge voltage, very small impulse bits on the order of micronewtons-seconds are easily achieved.
- **Compact and Simple Designs:** PPTs and VATs are typically very simple and compact devices. While the total impulse capability is small compared to other forms of EP, these devices offer a particularly attractive solution for CubeSats, where low cost may be a more significant consideration than total impulse. The systems are also attractive for learning environments where propulsion expertise such as high pressure feed systems and propellant management may be lacking.
- **Late-Time Ablation**: Although pulsed devices allow for operation over a wide range of pulse frequency, thruster efficiency typically improves with higher pulse rate. Late time ablation is a key inefficiency of solid propellant pulsed devices, where material continues to ablate from the propellant surface well after the discharge pulse. Through higher frequency pulsing, the amount of material accelerated may be maximized.
- **Thrust-to-Power:** Pulsed devices suffer from a number of inefficiencies including late time ablation, frozen flow, and wall heating. Propulsion system efficiency is typically below 20% and may be as low as a few percent. Thus, although pulsed devices may have high specific impulse, the thrust-to-power is low. Small spacecraft with limited power for propulsion may find that large propellant loads provide little benefit as there is inherently a limitation to the number of pulses achievable over the life of the power-limited spacecraft.

- **Thermal Soak-back:** The low thruster efficiencies may result in large thermal loads on the spacecraft due to thermal soak-back, especially at high rates of pulsing. The spacecraft's ability to radiate this energy to limit heating may set an upper bound on pulse frequency.
- **Ignitor:** Pulsed devices usually require some form of ignitor to provide seed material to lower the impedance between the electrodes and initiate the discharge pulse. As such, the lifetime of the ignitor may dictate the lifetime of the thruster. Ignitors may fail due to erosion or fouling that prevents sparking.
- **Shorting:** The electrodes of pulsed devices are separated by isolating elements. Shadow shielding or other physical features are typically necessary to avoid shorting between electrodes as conductive material ejected by the thruster accumulates. While PTFE is an insulator, the PTFE is reduced to carbon and fluorine when ablated, where carbon accumulation provides a potentially conductive path. VATs employ metal propellants that can similarly result in unintended shorting.
- **Spacecraft Contamination:** As with any conductive propellant, contamination of the spacecraft is a concern. Plume interaction with the spacecraft must be understood to assess the impact of the plume on the operation of critical surfaces such as solar panels, antennas, and radiators.

b. Missions

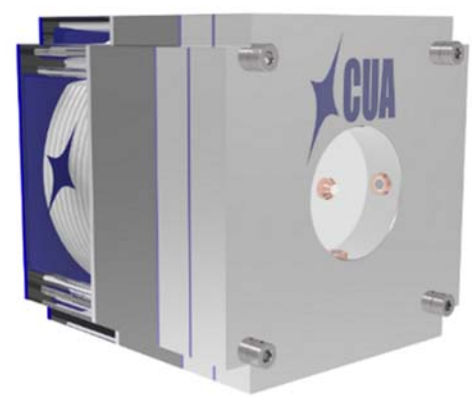


Figure 4.31: FPPT module. Credit: CU Aerospace.

In 2019, CU Aerospace was selected for a NASA STMD Tipping Point award to design, fabricate, integrate, and perform mission operations for the DUPLEX 6U CubeSat having two of CU Aerospace's micro-propulsion systems on board, one Monofilament Vaporization Propulsion (MVP) (96) (97), figure 4.14, and one Fiber-Fed Pulsed Plasma Thruster (FPPT) (98) (99) (100) (101), figure 4.31. The FPPT can provide a large total impulse primary propulsion for micro-satellites through implementation of a novel PTFE fiber propellant storage and delivery mechanism. A major enhancement of the FPPT technology over classical PPTs is the ability to control both the propellant feed rate and pulse energy, thereby providing control of both the specific impulse and thrust. The FPPT can also provide precision control capability for small spacecraft requiring capabilities such as precision pointing or formation flying. In-orbit operations will include inclination change, orbit raising and lowering, drag makeup, and deorbit burns demonstrating multiple mission capabilities with approximately 20 hours of operation for MVP and >1,000 hours for FPPT. Launch is anticipated in mid-2022 (102).

Ambipolar

Ambipolar thrusters ionize gaseous propellant within a discharge cavity via various means, including DC breakdown or RF excitation. The escape of high-mobility electrons from the discharge cavity creates a charge imbalance in the plasma discharge, and the subsequent ambipolar diffusion accelerates ions out of the cavity to generate thrust.

Because the thruster plume is charge neutral, no neutralizer assembly is necessary. A variety of propellants is theoretically usable due to the absence of exposed electrodes (and their associated material compatibility concerns).

See table 4-12 for current state-of-the-art ambipolar devices applicable to small spacecraft.

a. Key Integration and Operational Considerations

- **Propellant Agnostic**: While ambipolar thrusters may be operable on a variety of propellants thanks to the devices' lack of exposed electrodes, different propellants will have different ionization costs (i.e., impact on thruster efficiency), plume behavior, and propellant storage requirements that should be considered during propellant selection.
- **Electromagnetic Interactions**: For RF-discharge thrusters, electromagnetic interference and compatibility (EMI/EMC) testing may be critical to assess the impact of thruster operations on spacecraft communications and payload functionality.
- **Thermal Soakback**: Low thruster efficiencies may result in large thermal loads on the spacecraft due to thermal soakback. Validated thermal modeling should be considered to assess impacts to the host spacecraft.

b. Missions

The UniSat-7 mission, led by GAUSS, is a 36 kg microsatellite expected to launch via Soyuz in 2020. This technology demonstration mission includes a T4i iodine-propellant REGULUS module (figure 4.32); the integrated propulsion system includes thruster, power processing unit, and heated propellant-feed components. The propulsion demonstration is expected to include orbit raising and lowering between orbital altitudes of 300 and 400 km (154) (155).

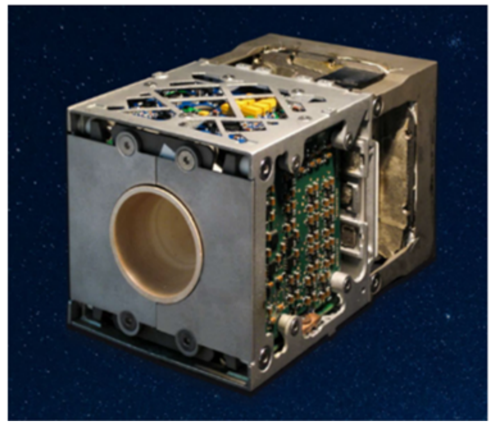


Figure 4.32: REGULUS propulsion module. Credit: T4i.

A 6U CubeSat from Team Miles has been awarded a rideshare slot onboard Artemis I (expected to launch in November 2021) as one of the winning teams in NASA's Cube Quest Challenge. The objective of the mission, led by Fluid & Reason, is to demonstrate deep space communications from beyond a 2.5 million mile range. Twelve ConstantQ iodine-propellant thrusters (figure 4.33) are integrated onboard the CubeSat to provide primary propulsion as well as 3-axis control (156) (157).

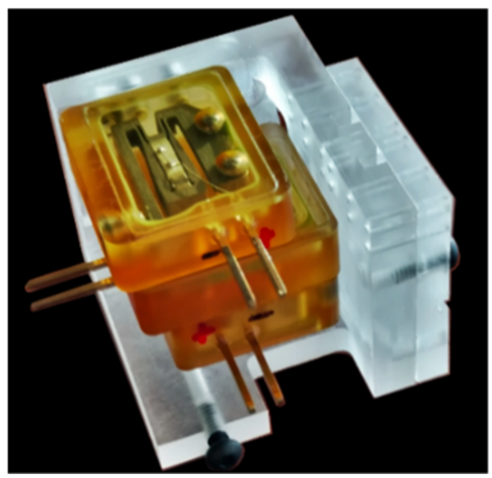


Figure 4.33: ConstantQ thruster head. Credit: Miles Space.

4.6.3 In-Space Propellant-less Propulsion

Propellant-less propulsion systems generate thrust via interaction with the surrounding environment (e.g., solar pressure, planetary magnetic fields, and planetary atmosphere). By contrast, chemical and electric propulsion systems generate thrust by expulsion of reaction mass (i.e., propellant). Three propellant-less propulsion technologies that have undergone in-space demonstrations to date include solar sails, electrodynamic tethers, and aerodynamic drag devices.

Solar Sails

Solar sails use solar radiation pressure to generate thrust by reflecting photons via lightweight, high-reflectivity membranes. While no commercial products are presently available, a handful of missions have sought to demonstrate the technology using small spacecraft. Recent missions include:

- NASA's NanoSail-D2 launched as a 3U CubeSat secondary payload onboard the Fast, Affordable, Science and Technology Satellite (FASTSAT) bus in November 2010. The 10 m^2 sail made of CP-1 deployed from a 650 km circular orbit and de-orbited the spacecraft after 240 days in orbit (158).
- The Planetary Society's LightSail 2 mission launched as a 3U CubeSat secondary payload on the Department of Defense's Space Test Program (STP-2) in June 2019. The 32 m^2 mylar solar sail was deployed at 720 km altitude and demonstrated apogee raising of ~10 km. Its mission was still ongoing as of August 2020 (159).
- The University of Illinois (Urbana, IL) and CU Aerospace (Champaign, IL) teamed to develop CubeSail, which launched as one of ten CubeSats on the Educational Launch of Nanosatellites ELaNA-19 mission on a Rocket Lab Electron rocket in December 2018. CubeSail launched as a mated pair of 1.5U CubeSats. When separated, they deploy a 250 m-long, 20 m^2 aluminized mylar film between them. The development team envisions the CubeSail mission as the first of many missions of progressively increasing scale and complexity. Progress of the mission is unknown (160).
- NASA's Near-Earth Asteroid (NEA) Scout mission is expected to launch as a secondary payload onboard Artemis I in November 2021. The 6U CubeSat will deploy an 85 m^2 solar sail and conduct a flyby of Asteroid 1991VG, approximately 1 AU from Earth (161).

Electrodynamic Tethers

Electrodynamic tethers employ an extended, electrically conductive wire with current flow. In addition to atmospheric drag on the wire, its interaction with the ambient magnetic field about a planetary body causes a Lorentz force that can be used for orbit raising or lowering. This technology currently provides a means for end-of-mission small spacecraft deorbit.

a. Missions

Georgia Institute of Technology's Prox-1 mission was launched as a secondary payload on the Department of Defense's Space Test Program (STP-2) in June 2019. The 70 kg spacecraft served as the host and deployer for the LightSail 2 mission. The Prox-1 spacecraft housed a Tethers Unlimited Nanosat Terminator Tape (NSTT), figure 4.34, which deployed a 70 m tether in September 2019 to lower the orbit from 717 km. Data from the Space Surveillance Network indicate that the NSTT is causing Prox-1 to deorbit more than 24 times faster than otherwise expected. This rate of orbital decay will enable Prox-1 to meet its 25-year deorbit requirement (162) (163) (164).

Figure 4.34: Nanosat Terminator Tape (NSTT). Credit: Tethers Unlimited.

The Naval Postgraduate School's NPSat-1 was launched as a secondary payload on STP-2 and is expected to deploy its NSTT later in 2020 (164).

TriSept's DragRacer technology demonstration mission, expected to launch as a rideshare onboard an Electron rocket in 2020, seeks to conduct a direct comparison of the deorbiting rates of two Millennium Space Systems satellites, one of which will use a 250 m NSTT (164).

AuroraSat-1 is expected to launch as a rideshare onboard a Falcon rocket in December 2020. The spacecraft is built by SatRevolution with Aurora Propulsion Technologies providing the payloads. This 1.5U spacecraft will deploy from a Momentus Space Vigoride into a 550 km sun synchronous orbit (SSO). The mission serves as a technology demonstration for a Plasma Brake module (figure 4.35), and an Attitude and Orbit Control System (AOCS) (103) (figure 4.15), both produced by Aurora. The Plasma Brake module on AuroraSat-1 is a dual redundant system for demonstration purposes. A 500-m tether will be deployed to demonstrate its deorbiting capability (104).

Figure 4.35: Plasma Brake Module (PBM) demo unit. Credit: Aurora Propulsion Technologies.

Aerodynamic Drag

Satellites have historically deorbited from low-Earth orbits with the aid of thrusters or passive atmospheric drag. Given the increasing rate of new spacecraft launched and in-turn potential for new orbital debris following completion of missions, orbital debris management has gained increasing attention. Space debris poses a growing threat to active satellites and human activity in space. Allowing decades for defunct spacecraft to decay naturally from low-Earth orbit may soon be insufficient. Aerodynamic drag devices may provide one method to rapidly remove spacecraft from low-Earth orbits upon mission completion.

Below about 1,000 km altitude, the atmosphere exerts a measurable drag force opposite the relative motion of any spacecraft, which results in a slow orbital decay. The intensity of the drag force exerted on the spacecraft depends on numerous factors such as local atmospheric density, the spacecraft forward facing area, the spacecraft velocity, and a drag coefficient. The drag coefficient accounts for the drag force’s dependency on an object’s unique geometric profile. While the spacecraft velocity and local atmospheric density are largely mission dependent, a spacecraft’s forward-facing area and drag coefficient can be altered by introducing aerodynamic drag devices such as exo-brakes and ballutes. These deployable or inflatable parachutes and balloons can greatly increase the drag force exerted on spacecraft by an order of magnitude or more and significantly increase the rate of orbital decay.

Furthermore, aerodynamic drag devices may be useful to reduce spacecraft propellant mass required for orbit capture and disposal at other planetary bodies, given sufficient atmospheric density exists.

For further details on these devices, see chapter on Deorbit Systems.

Table 4-2: Hydrazine Chemical Propulsion												
Manufacturer	Product	Propellant	Thrust per Thruster (Quantity)	Specific Impulse	Total Impulse	Mass	Envelope	Power	ACS	Status	Missions	References
---	---	---	[N]	[s]	[kN-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Integrated Propulsion Systems												
Aerojet Rocketdyne	MPS-120	Hydrazine	0.25 – 1.0 (4)	N/A	>2 (2U) >0.8 (1U)	1.6 – 2.5 † 1.2 – 1.5 ‡	1U – 2U	N/A	Y	D	-	(51)
Aerojet Rocketdyne	MPS-125	Hydrazine	0.25 – 1.0 (4)	N/A	>19 (8U) >13 (6U) >7 (4U)	6.2 – 12.1 † 3.6 – 5.1 ‡	4U – 8U	N/A	Y	D	-	(51)
Stellar Exploration	Biprop 12U CubeSat system	Hydrazine/ NTO	3 N	>285	N/A	N/A	N/A	N/A	Y	D	-	(52)
Thruster Heads												
Aerojet Rocketdyne	MR-103	Hydrazine	1 N	202-224	183	0.33-0.37	-	16 max total	-	F	numerous	(8)
Aerojet Rocketdyne	MR-111	Hydrazine	4 N	219-229	262	0.37	-	16 max total	-	F	numerous	(8)
Aerojet Rocketdyne	MR-106	Hydrazine	22 N	228-235	561	0.59	-	36 max total	-	F	numerous	(8)
ArianeGroup	1 N	Hydrazine	1 N	200 – 223	135	0.29	-	N/A	-	F	numerous	(6)
Moog	MONARC-1	Hydrazine	1 N	227.5	111	0.38	-	18 (Valve)	-	F	numerous	(9)
Moog	MONARC-5	Hydrazine	4.5 N	226.1	613	0.49	-	18 (Valve)	-	F	numerous	(9)
Moog	MONARC-22	Hydrazine	22 N	228-229	533 – 1,173	0.69-0.72	-	30 (Valve)	-	F	numerous	(9)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
† denotes a wet mass, ‡ denotes a dry mass, N/A = Not Available

Table 4-3: Other Monopropellant and Bipropellant Propulsion												
Manufacturer	**Product**	**Propellant**	**Thrust per Thruster (Quantity)**	**Specific Impulse**	**Total Impulse**	**Mass**	**Envelope**	**Power**	**ACS**	**Status**	**Missions**	**References**
---	---	---	[N]	[s]	[kN-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Integrated Propulsion Systems												
Aerojet Rocketdyne	MPS-130	AF-M315E	0.25 – 1.0 (4)	N/A	>2.7 (2U) >1.1 (1U)	1.7 – 2.8 † 1.1 – 1.4 ‡	1U – 2U	N/A	Y	D	-	(50) (51)
Aerojet Rocketdyne	MPS-135	AF-M315E	0.25 – 1.0 (4)	N/A	>19 (8U) >13.7 (6U) >7.3 (4U)	7.2 – 14.7 † 3.5 – 5.1 ‡	4U – 8U	N/A	Y	D	-	(51)
Aerospace Corp.	HyPer	Hydrogen Peroxide	N/A	N/A	N/A	N/A	~0.25U	N/A	N/A	D	-	(53)
Benchmark Space Systems	B125	HTP & Alcohol	100 mN-22 N	270	1.7-10	2.5-7.5†	2000 – 7800 cm^3	up to 10 W	Y	D	-	(54) (55)
Bradford-ECAPS	Skysat 1N HPGP Propulsion System	LMP-103S	1.0 (4)	200	>17	17	27U	10	Y	F	Skysat, PRISMA	(14) (62)
Busek	AMAC	AF-M315E	0.5 (1)	225	0.56	1.5 †	1U	N/A	N	D	-	(61)
Busek	BGT-X5 System	AF-M315E	0.5	220 – 225	N/A	1.5 (BOL)	1U	20	N	D	-	(63)
Cornell Univ.	Cislunar Explorer	Water (Electrolysis)	N/A	N/A	N/A	N/A	6U total (2-units)	N/A	N/A	E	CubeQuest Challenge (Artemis I)	(20)
CU Aerospace	MPUC	(CMP-8) Peroxide/ Ethanol blend	0.1 (1)	160 – 180	2.5	1.277 † 0.650 ‡	1U	3	N	D	-	(58) (65)
Dawn Aerospace	PM200	Nitrous Oxide & Propene	0.5 (1)	>285	>0.4 – 0.8	1.0 – 1.4	0.7 – 1U	12	Y	E	-	(22)
Moog	Monopropellant Propulsion Module	Green or 'Traditional'	0.5 (1)	224	0.5	1.01†	1U (baseline, scalable)	2 x 22.5 W/Thruster	N	D	-	(60)
MSFC/Plasma Processes/GT	LFPS	AF-M315E	0.1 (4)	N/A	N/A	N/A	N/A	N/A	Y	E	Lunar Flashlight (Artemis I)	(15)
NanoAvionics	EPSS C1K	ADN-blend	1.0 (1) BOL 0.22 (1) EOL	213	>0.4	1.2 † 1.0 ‡	1.3U	0.19 (monitor) 9.6 (preheat) 1.7 (firing)	N	F	Lituanica-2	(21)
Rocket Lab	Kick Stage	Unknown	120	N/A	N/A	N/A	N/A	N/A	Y	F	Electron 'Still Testing'	(23) (24)
Tethers Unlimited	HYDROS-C	Water (Electrolysis)	1.1 (1)	>310	>2	2.61 † 1.87 ‡	190 mm x 130 mm x 92 mm	5-25	N	E	Pathfinder Technology Demonstration	(59) (66)
Tethers Unlimited	HYDROS-M	Water (Electrolysis)	>1.2 (1)	>310	>18	12.6 † 6.4 ‡	381 mm dia. x 191 mm	7-40	N	D	-	(59)
VACCO	ArgoMoon Hybrid MiPS	LMP-103S/ cold-gas	0.1 (1)	190	1	14.7 † 9 ‡	~1.3U	13.6 20 (max)	Y	E	ArgoMoon (Artemis I)	(41) (69)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
† denotes a wet mass, ‡ denotes a dry mass, N/A = Not Available

Table 4-3 (cont.): Other Monopropellant and Bipropellant Propulsion												
Manufacturer	**Product**	**Propellant**	**Thrust per Thruster (Quantity)**	**Specific Impulse**	**Total Impulse**	**Mass**	**Envelope**	**Power**	**ACS**	**Status**	**Missions**	**References**
---	---	---	[N]	[s]	[kN-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Integrated Propulsion Systems (cont.)												
VACCO	Green Propulsion System (MiPS)	LMP-103S	0.1 (4)	190	4.5	5 † 3 ‡	~3U	15 (max)	Y	D	-	(41) (67)
VACCO	Integrated Propulsion System	LMP-103S	1.0 (4)	200	12.5	14.7 † 9 ‡	~1U – 19,000 cm^3	15 – 50 (max)	Y	D	-	(41) (68)
Thruster Heads												
Aerojet Rocketdyne	GR-1	AF-M315E	0.4-1.1	231	23	N/A	-	12	-	F	GPIM	(8) (12)
Aerojet Rocketdyne	GR-22	AF-M315E	8.0-25	248	74	N/A	-	28	-	E	GPIM	(8) (12)
Aerospace Corp.	Hydrogen Peroxide Vapor Thruster (HyPer)	Hydrogen Peroxide	<10 mN	N/A	N/A	N/A	-	N/A	-	D	-	(53)
Bradford-ECAPS	0.1 N HPGP (thruster)	LMP-103S	0.03 – 0.10	196 – 209	N/A	0.04 excl. FCV	-	6.3 – 8	-	E	ArgoMoon	(56)
Bradford-ECAPS	1 N HPGP (thruster)	LMP-103S	0.25 – 1.0	204 – 235	N/A	0.38	-	8 – 10	-	F	SkySat	(14) (56)
Bradford-ECAPS	1 N GP (thruster)	LMP-103S/LT	0.25 – 1.0	194 – 227	N/A	0.38	-	8 – 10	-	D	-	(57)
Bradford-ECAPS	5 N HPGP (thruster)	LMP-103S	1.5 – 5.5	239 – 253	N/A	0.48	-	15 – 25	-	D	-	(56)
Bradford-ECAPS	22 N HPGP (thruster)	LMP-103S	5.5 – 22	243 – 255	N/A	1.1	-	25 – 50	-	D	-	(56)
Busek	BGT-X1	AF-M315E	0.02 – 0.18	214	N/A	N/A	-	4.5	-	D	-	(64)
Busek	BGT-X5	AF-M315E	0.05 – 0.50	220 – 225	0.56	N/A	-	20	-	D	-	(63) (64)
Busek	BGT-5	AF-M315E	1.0 – 6.0	> 230	N/A	N/A	-	50	-	D	-	(64)
CU Aerospace	CMP-8 Thruster	(CMP-8) Peroxide/ Ethanol blend	>100 mN	>183	N/A	0.1	-	~3 (operating)	-	D	-	(58) (65)
NanoAvionics	EPSS-C1	ADN-blend	0.22 – 1.0	213	>0.4	N/A	-	9.6 (preheat) 1.7 (firing)	-	F	Lituanica-2	(21)
Plasma Processes LLC	100mN Thruster PP3490-B	AF-M315E	0.1 – 0.17	195 - 208	N/A	.08	-	7.5 – 10	-	E	Lunar Flashlight	(15)
Rocket Lab	Curie Engine	unknown	120	N/A	N/A	N/A	-	N/A	-	F	Electron ‘Still Testing’	(23) (24)
Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified. † denotes a wet mass, ‡ denotes a dry mass, N/A = Not Available												

Table 4-4: Hybrid Chemical Propulsion												
Manufacturer	**Product**	**Propellant**	**Thrust (Quantity)**	**Specific Impulse**	**Total Impulse**	**Mass**	**Envelope**	**Power**	**ACS**	**Status**	**Missions**	**References**
---	---	---	[N]	[s]	[N-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Thruster Heads												
JPL	Hybrid Rocket	PMMA/GOX	N/A	>300	N/A	N/A	N/A	N/A	-	D	-	(86)
Utah State Univ.	Green Hybrid Rocket	ABS/GOX	8	215	N/A	N/A	N/A	N/A	-	D	-	(25) (26) (70)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
† denotes a wet mass, ‡ denotes a dry mass, N/A = Not Available

Table 4-5: Cold and Warm Gas Propulsion												
Manufacturer	**Product**	**Propellant**	**Thrust (Quantity)**	**Specific Impulse**	**Total Impulse**	**Mass**	**Envelope**	**Power**	**ACS**	**Status**	**Missions**	**References**
---	---	---	[mN]	[s]	[N-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Integrated Propulsion Systems												
Aerospace Corp.	MEPSI	R236fa	20	N/A	N/A	0.188	4 in. x 4 in. x 5in.	N/A	Y	E	STS-113 and STS-116	(28)
GomSpace / NanoSpace	Nanoprop CGP3	Butane	0.01 – 1 (x4)	60-110	40	0.3‡ 0.35†	0.5U	<2	Y	D	-	(34) (82)
GomSpace / NanoSpace	Nanoprop 6U	Butane	1 – 10 (x4)	60-110	80	0.770‡ 0.900†	200 mm x 100 mm x 50 mm	<2	Y	F	GomX-4	(34) (35) (83)
Lightsey Space Research	BioSentinel Propulsion System	R236fa	40 - 70	40.7	79.8	1.08 kg ‡ 1.28 kg †	220 mm x 100 mm x 40 mm	<1 W idle <4 W operating	Y	E	BioSentinel	(36) (37)
Marotta	MicroThruster	Nitrogen	0.05 – 2.36 N	70	N/A	N/A	N/A	<1	N/A	F	numerous	(27)
Micro Space	POPSAT-HIP1	Argon	0.083 – 1.1 (x8)	43	N/A	N/A	N/A	N/A	N/A	F	POPSAT-HIP1	(33)
SSTL	Butane Propulsion System	Butane	0.5 N							D	-	(29) (30)
UTIAS/SFL	CNAPS	Sulfur Hexafluoride	12.5 – 40	30	81	N/A	N/A	N/A	N	F	CanX-4/CanX-5	(84) (85)
VACCO	MiPS Standard Cold Gas	R236fa	25 (x4)	40	98 – 489	553 – 957‡	0.4 – 1.38U	12 W (max)	Y	D	-	(41) (79)
VACCO	MarCO-A and -B MiPS	R236FA	25 (x8)	40	755	3.5	2U	15	Y	F	MarCO-A & -B	(41) (43) (80)
VACCO	C-POD	R134A	25 (x8)	40	186	1.3	0.8U	5	Y	E	CPOD	(41) (81)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
† denotes a wet mass, ‡ denotes a dry mass, N/A = Not Available

Table 4-6: Solid Motor Chemical Propulsion												
Manufacturer	**Product**	**Propellant**	**Thrust (Quantity)**	**Specific Impulse**	**Total Impulse**	**Mass**	**Envelope**	**Power**	**ACS**	**Status**	**Missions**	**References**
---	---	---	[N]	[s]	[N-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Integrated Propulsion Systems												
D-Orbit	D-Raise	N/A	N/A	N/A	N/A	50 – 78	N/A	N/A	N	D	-	(77)
D-Orbit	D3	N/A	N/A	N/A	N/A	16 – 257	32 cm x 32 cm x 25 cm to 1100 cm x 500 cm x 1000 cm	N/A	N	D	-	(78)
DSSP	CAPS-3	HIPEP-501A	0.3 (3)	N/A	0.125	0.023	0.92 cm x 2.79 cm x 4.2 cm	< 2.3	N	F	SPINSAT	(46) (71)
DSSP	MPM-7	HIPEP-H15	N/A	200	1.5	<750 g (PPU)	< 0.75 U	200	N	D	-	(72)
PacSci EMC	MAPS	N/A	N/A (176 per lightband)	210	N/A	N/A	38 cm x 10.5 cm	N/A	N/A	F	PACSCISAT	(47) (48)
PacSci EMC	P-MAPS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	D	-	(47)
Thruster Heads												
DSSP	CDM-1	AP/HTPB	186.8	235	226.4	0.046	0.64 dia x 0.47 length	< 5	-	D	Listed as “flight qualified”	(73) (74)
Industrial Solid Propulsion	ISP 30 sec. Motor	80% Solids HTPB/AP	37	187	996	0.95	5.7 cm	-	-	D	Optical target at Kirtland AFB	(45) (75)
Northrop Grumman (Former Orbital ATK)	STAR 4G	TP-H-3399	258	276	595	1.49	11.3 cm dia. x 13.8	-	-	D	-	(45) (76)
Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified. † denotes a wet mass, ‡ denotes a dry mass, N/A = Not Available												

Table 4-7: Electrothermal Electric Propulsion												
Manufacturer	**Product**	**Propellant**	**Thrust***	**Specific Impulse***	**Total Impulse***	**Mass**	**Envelope**	**Power**	**ACS**	**Status**	**Missions**	**References**
---	---	---	[mN]	[s]	[N-s]	[g]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Integrated Propulsion Systems												
Aurora Propulsion Technologies Finland	AOCS	H_2O	0.5	100	70	280†	0.3U	10£	Y	E	AuroraSat-1 (2020**)	(103) (104)
Busek USA	Micro Resistojet	Ammonia	10	150	404	1,250†	1U	15	Y	D	---	(165)
Bradford Space Netherlands	Comet-1000	H_2O	17	175	1,155	1,440†	2,600	55	N	F	HawkEye 360, Capella Space	(89) (90) (91)
Bradford Space Netherlands	Comet-8000	H_2O	17	175	8,348	6,675†	23,760	55	N	F	BlackSky Global	(89) (92)
CU Aerospace and VACCO USA	CHIPS	R134a	31	76	478	1,375†	1U	30	Y	D	---	(166) (167) (168) (169)
CU Aerospace and VACCO USA	CHIPS	R236fa	23	60	433	1,510†	1U	30	Y	D	---	(166) (167) (168) (169)
CU Aerospace and VACCO USA	PUC	SO_2	4.5	70	184	718†	0.35U	15	N	E	8 flight units delivered to AFRL	(93) (94) (95)
CU Aerospace USA	MVP	Delrin Fiber	4.5	66	334	1,140†	1.15U	45	N	E	DUPLEX (launch mid-2022**)	(96) (97)
Thruster Heads												
Sitael Italy	XR-150	Xe	65	57	NA	220‡	21.6	100	NA	D	---	(170) (171)
Sitael Italy	XR-150	Kr	67.2	70	NA	220‡	21.6	100	NA	D	---	(170) (171)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
*nominal values (see references for full performance ranges), ** anticipated launch date, † denotes a wet mass, ‡ denotes a dry mass, £ per active thruster, NA = Not Applicable

Table 4-8: Electrospray Electric Propulsion												
Manufacturer	**Product**	**Propellant**	**Thrust***	**Specific Impulse***	**Total Impulse***	**Mass**	**Envelope**	**Power**	**Neutralizer**	**Status**	**Missions**	**References**
---	---	---	[µN]	[s]	[N-s]	[kg]	[cm^3 or U]	[W]	---	C,D,E,F	---	---
Integrated Propulsion Systems												
Accion Systems USA	TILE-2	EMI-BF4 (ionic)	50	1,650	35	0.45†	0.5U	4	NA	E	BeaverCube (2020**),	(114) (115) (116) (183)
Accion Systems USA	TILE-3	EMI-BF4 (ionic)	450	1,650	755	2.25†	1U	20	NA	E	Tipping Point (2021**)	(116) (184)
Busek USA	CMNT (4x heads)	EMI-Im (ionic)	4 x 20	225	980	14.8†	29U	16.5	Propellant-less	F	LISA Pathfinder	(105)
Busek USA	BET-300-P (4x heads)	EMI-Im (ionic)	4 x 55	850	360	0.8†	872	15	Propellant-less	D	---	(172) (173) (174) (175)
Enpulsion Austria	IFM Nano	Indium (FEEP)	350	3,500	---	0.90†	10 x 10 x 8.3	40	Thermionic	F	Flock 3p', ICEYE X2, Harbinger, NetSat (2020**)	(106) (107) (108) (109) (110) (111) (176) (177) (178)
Enpulsion Austria	IFM Micro 100	Indium (FEEP)	1,000	3,000	---	3.9†	14 x 12 x 13.3	90	Thermionic	D	---	(179) (180)
Morpheus Space Germany	NanoFEEP (2x heads)	Gallium (FEEP)	<40	---	---	0.16‡	9 x 2.5 x 4.3	<3	Propellant-less	E	UWE-4	(112) (113) (181) (182)
Morpheus Space Germany	MultiFEEP (2x heads)	Gallium (FEEP)	<140	---	---	0.28‡	9 x 4.5 x 4.5	<19	Propellant-less	D	---	(181)
Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified. *nominal values (see references for full performance ranges), ** anticipated launch date, † denotes a wet mass, ‡ denotes a dry mass, NA = Not Applicable												

Table 4-9: Gridded-Ion Electric Propulsion												
Manufacturer	**Product**	**Propellant**	**Thrust***	**Specific Impulse***	**Total Impulse***	**Mass**	**Envelope**	**Power**	**Cathode Type**	**Status**	**Missions**	**References**
---	**---**	**---**	**[mN]**	**[s]**	**[kN-s]**	**[kg]**	**[cm³ or U]**	**[W]**	**---**	**C,D,E,F**	**---**	**---**
Integrated Propulsion Systems												
Avant Space [Russia]	GT-50 [RF]	Xenon	<7	---	---	<8†	<4U	<240	Hollow	D	---	(185) (186)
Busek [USA]	BIT-3 [RF]	Iodine	1.15	2,100	32	2.9† (with gimbal)	18 x 8.8 x 10.2	75	RF	E	Lunar IceCube (2021**); LunaH-Map (2021**)	(118) (119) (120) (187) (188) (189)
ThrustMe [France]	NPT30 [RF]	Xenon	<1.1	---	---	<1.7†	<2U	<60	Thermionic	D	---	(190)
ThrustMe [France]	NPT30-I2 [RF]	Iodine	<1.1	---	---	1.2†	1.5U	<65	Thermionic	D	---	(191) (192)
Thruster Heads												
Ariane Group [Germany]	RIT µX [RF]	Xenon	<0.5	---	---	0.44‡	7.8 x 7.8 x 7.6	<50	RF	D	---	(193) (194) (195) (196)
Ariane Group [Germany]	RIT 10 EVO [RF]	Xenon	<15	---	---	1.8‡	18.6 x 18.6 x 13.4	<435	Hollow	E	(Identical to RIT-10 with contemporary grid design)	(193) (195) (197)
Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified. *nominal values (see references for full performance ranges), ** anticipated launch date, † denotes a wet mass, ‡ denotes a dry mass, NA = Not Applicable, RF = Radio Frequency												

Table 4-10: Hall-Effect Electric Propulsion Thrusters												
Manufacturer	**Product**	**Propellant**	**Thrust***	**Specific Impulse***	**Total Impulse***	**Mass**	**Envelope**	**Thruster Power***	**Cathode Type**	**Status**	**Missions**	**References**
---	---	---	[mN]	[s]	[kN-s]	[kg]	[cm^3]	[W]	Notes	C,D,E,F	---	---
Apollo Fusion USA	ACE	Xenon	22	1,300	200	1.0	---	400‡	CM-HL	D	---	(198)
Apollo Fusion USA	ACE	Krypton	16	1,200	200	1.0	---	400‡	CM-HL	D	---	(198)
Apollo Fusion USA	ACE	Proprietary	24	1,250	---	1.0	---	400‡	CM-HL	E	Astro Digital Ignis (2020**)	(141) (142)
Busek USA	BHT-100	Xenon	6.3	1,086	150	1.2	275 wo cath.	105	EM-SH	D	---	(130) (199)
Busek USA	BHT-200	Xenon	13	1,390	84§	1.2	675 wo cath.	250‡	EM-SH	F	TacSat-2, FalconSat-5, -6	(130) (131) (200) (201)
Busek USA	BHT-200-I	Iodine	13	---	---	1.2	675 wo cath.	200	EM-SH	E	NASA iSat (Cancelled)	(131) (132) (200)
Busek USA	BHT-350	---	---	---	---	---	---	---	---	---	---	(130)
Busek USA	BHT-600	Xenon	39	1,500	>700§	3.3	1,470 wo cath.	680‡	EM-SH	D	---	(130) (202) (203)
Busek USA	BHT-600-I	Iodine	39	---	---	3.3	1,470 wo cath.	600	EM-SH	D	---	(131) (202) (203)
EDB Fakel Russia	SPT-50	Xenon	14	860	126§	1.2	1,092	220	EM-SH	F	Canopus-V	(125) (126) (127) (128) (204)
EDB Fakel Russia	SPT-50M	Xenon	14.8	930	266	1.3	---	220	EM-SH	D	---	(204)
EDB Fakel Russia	SPT-70BR	Xenon	39	1,470	435§	2.0	1,453	660	EM-SH	F	KazSat-1, KazSat-2	(128) (129)
EDB Fakel Russia	SPT-70M	Xenon	41.3	1,580	---	---	---	660	EM-SH	D	---	(129)
EDB Fakel Russia	SPT-70M	Krypton	31.3	1,460	---	---	---	660	EM-SH	D	---	(129)
ExoTerra USA	Halo	Xenon	7.1	1,110	100	0.67	220	185	CM-HL	E	Tipping Point (2021**)	(147) (148) (149)
Exotrail France	ExoMG nano	Xenon	2.0	800	5	---	---	53	EM-SH	E	M6P Demo (2020**), ELO3 and ELO4 (2021**)	(143) (144) (145) (146)
Exotrail France	ExoMG micro	Xenon	5	1,000	19	---	---	100	EM-SH	D	---	(143) (146)
JPL USA	MaSMi	Xenon	55	1,920	3,000	3.4	1,700	1,000	CM-HL	D	---	(205) (206) (207) (208) (209) (210)
Orbion USA	Aurora	Xenon	12	1,220	200	1.5	1,147	200	EM-SH	E	AST SpaceMobile (?**)	(150) (151) (211)
Rafael Israel	R-200HT	Xenon	---	---	---	---	---	200	EM-HL	D	---	(133)
Rafael Israel	IHET-300	Xenon	>14.3	>1,210	>135	1.5	1,836	300	EM-SH	F	VENuS	(133) (134) (135) (136)
Rafael Israel	R-800HT	Xenon	---	---	560	---	---	800	EM-HL	D	---	(133)
Safran France	PPS-X00	Xenon	43	1,530	1,000	---	---	650	EM-SH	D	---	(212)
SITAEL Italy	HT100	Xenon	9	1,300	73	---	407 wo cath.	175	EM-SH	E	uHETSat (?**)	(138) (139) (140)
SITAEL Italy	HT400	Xenon	27.5	1230	1,000	2.77	1,330	615	EM-SH	D		(213) (214) (215)
SETS Ukraine	ST25	Xenon	7.6	1,000	82	0.75	1,003	140	EM-SH	D	---	(216) (217)
SETS Ukraine	ST40	Xenon	25	1,450	450	1.1	1,170	450	EM-HL	D	---	(218)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
*nominal values (see references for full performance ranges), ** anticipated launch date, ‡ PPU input power, § demonstrated, CM = Center Mounted, EM = Externally Mounted, SH = Swaged Heater, HL = Heater-less, JPL = Jet Propulsion Laboratory, SETS = Space Electric Thruster Systems, EDB = Experimental Design Bureau

Table 4-11: Pulsed Plasma and Vacuum Arc Electric Propulsion

Manufacturer	Product	Propellant	Thrust*	Impulse Bit	Specific Impulse*	Total Impulse*	Mass	Envelope	Power*	ACS	Status	Missions	References
---	---	---	[μN]	[μNs]	[s]	[N-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Integrated Propulsion Systems													
Alameda Applied Sciences Corp. [USA]	Metal Plasma Thruster	Molybdenum	600	150	1,756	4,000	0.85	0.7U	50	N	D	---	(219)
Busek [USA]	BmP-220	PTFE	20	20	---	175	0.5	375 + ESV	3	N	D	---	(220)
Comat [France]	Plasma Jet Pack	(metal)	288	29	---	4,000	1.0	1U	30	N	D	---	(221) (222)
CU Aerospace [USA]	FPPT-1.6	PTFE Fiber	270	180	2,400	20,700	2.8†	1.6U	48	N	E	DUPLEX (launch mid-2022**)	(98) (99) (100)
Mars Space Ltd [UK] Clyde Space [Sweden]	PPTCUP	PTFE	40	40	655	48	0.27	0.33U	2.7	N	D	---	(223)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
*nominal values (see references for full performance ranges), ** anticipated launch date, † denotes a wet mass, ‡ denotes a dry mass, NA = Not Applicable, ESV = Ejector Spring Volume

Table 4-12: Ambipolar Electric Propulsion

Manufacturer	Product	Propellant	Thrust*	Specific Impulse*	Total Impulse*	Mass	Envelope	Power	ACS	Status	Missions	References
---	---	---	[mN]	[s]	[kN-s]	[kg]	[cm^3]	[W]	Y/N	C,D,E,F	---	---
Integrated Propulsion Systems												
Phase Four [USA]	Maxwell[RF]	Xenon	7.9	1,011	10	8.4†	19 x 13.5 x 19	<500	N	D	---	(224) (225) (226) (227)
T4i [Italy]	REGULUS[RF]	Iodine	0.55	550	3	2.5†	1.5U	50	N	E	UniSat-7 (2020**)	(154) (155) (228)
Thruster Heads												
Fluid & Reason [USA]	ConstantQ	Iodine	5	760	7.5	1.5†	0.5U	22	Y	E	Team Miles (2021**)	(156) (157) (229)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
*nominal values (see references for full performance ranges), ** anticipated launch date, † denotes a wet mass, ‡ denotes a dry mass, NA = Not Applicable, RF = Radio Frequency

Table 4-13: Propellant-less Propulsion

Manufacturer	Product	Propellant	Thrust*	Specific Impulse*	Total Impulse*	Mass	Envelope	Power	ACS	Status	Missions	References
---	---	---	[mN]	[s]	[kN-s]	[kg]	[cm^3]	[W]	Y/N	C,D,E,F	---	---
Aurora [Finland]	Plasma Brake Module	NA	---	NA	NA	<1	1U	<4	N	E	AuroraSat-1 (2020**)	(104) (230)
Tethers Unlimited [USA]	NSTT	NA	---	NA	NA	0.81	18 x 18 x 1.8	---	N	F	Prox-1, NPSat-1, DragRacer (2020**)	(162) (163) (164) (231)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
*nominal values (see references for full performance ranges), ** anticipated launch date, † denotes a wet mass, ‡ denotes a dry mass, NA = Not Applicable
See Chapter on Passive Deorbit Systems for review of aerodynamic drag devices.

References

(1) "NASA Systems Engineering Handbook." NASA/SP-2016-6105, Rev2.

(2) "NASA Systems Engineering Processes and Requirements." NPR 7123.1C, Effective 14 February 2020, Expiration 14 February 2025.

(3) JANNAF Spacecraft Propulsion Subcommittee, Micro-Propulsion Panel, "JANNAF Guidelines for the Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems." JANNAF 2019, Tampa, FL, Distribution Unlimited

(4) Marshall, W. M. and M. Deans. "Recommended Figures of Merit for Green Monopropellants." NASA TM-2013-216560. National Aeronautics & Space Administration. Cleveland, OH. August, 2013.

(5) "AlSat-2". https://directory.eoportal.org/web/eoportal/satellite-missions/a/alsat-2

(6) Arianegroup. "Chemical Monopropellant Thruster Family." Product Brochure. http://www.space-propulsion.com/brochures/hydrazine-thrusters/hydrazine-thrusters.pdf

(7) Stratton, J. 2004. "The use of the aerojet MR-103H thruster on the New Horizons mission to Pluto." 55th International Astronautical Congress.

(8) Aerojet Rocketdyne. "In-Space Propulsion Data Sheets: Monopropellant and Bipropellant Engines." Product Brochure. https://www.rocket.com/sites/default/files/documents/In-Space%20Data%20Sheets%209.13.19.pdf

(9) Moog Space and Defense Group. "Monopropellant Thrusters." Product Brochure. https://www.moog.com/content/dam/moog/literature/Space_Defense/spaceliterature/propulsion/Moog-MonopropellantThrusters-Datasheet.pdf

(10) Cavender, D., W. Marshall, and A. Maynard. "2018 NASA Green Propulsion Technology Development Roadmap." NASA/TP—2018–219861. National Aeronautics and Space Administration. August, 2018.

(11) United States Air Force – Air Force Space Command. AFSPCMAN 91-710. "Range Safety User Requirements." 1 July 2004. Certified Current 17 September, 2013.

(12) Spores, R., Masses, R., Kimbrel, S., McLean, C. AIAA-2013-3849. "GPIM AF-M315E Propulsion System." 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. San Jose.

(13) Mulkey, H., J. Miller, and C. Bacha. "Green Propellant Loading Demonstration at U.S. Range." AIAA-2016-4576. AIAA Propulsion and Energy Forum. Salt Lake City, UT. July 25-27, 2016.

(14) Friedhoff, P., K. Anflo, M. Persson, and P. Thormahlen. "Growing Constellation of Ammonium Dinitramide (ADN) Based High Performance Green Propulsion (HPGP) Systems." AIAA-2018-4754. AIAA Propulsion and Energy Forum, Cincinnati, OH, July 9-11, 2018.

(15) Jet Propulsion Laboratory, National Aeronautics and Space Administration. "Lunar Flashlight." https://www.jpl.nasa.gov/CubeSat/missions/lunar_flashlight.php.

(16) National Aeronautics and Space Administration. "Green Propellant Infusion Mission Fires Thrusters for the First Time." https://www.nasa.gov/directorates/spacetech/home/tdm/gpim_fires_thrusters_for_first_time

(17) McLean, C H, W D Deininger, B M Marotta, and et al. AIAA-2015-3751. "Green Propellant Infusion Mission Program Overview, Status, and Flight Operations." 51st AIAA/ASME/SAE/ASEE Joint Propulsion Conference.

(18) Masse, R K, M. Allen, E. Driscoll, L. Arrington, S. Schneider, and T. Vasek. AIAA-2016-4577. "AF-M315E Propulsion System Advances & Improvements." 52nd AIAA/SAE/ASEE Joint Propulsion Conference. Salt Lake City, UT., 25-27 July, 2016.

(19) Messier, D. "NASA Selects Tethers Unlimited's HYDROS-C Thruster for First PTD CubeSat Mission." http://www.parabolicarc.com/2018/06/30/nasa-selects-tuis-hydrosc-thruster-ptd-CubeSat-mission/

(20) NASA. 2017. "Cube Quest Challenge Team Spotlight: Cislunar Explorers." https://www.nasa.gov/directorates/spacetech/centennial_challenges/cubequest/cislunar-explorers

(21) NanoAvionics. "CubeSat Propulsion System EPSS." https://nanoavionics.com/CubeSat-components/CubeSat-propulsion-system-epss/

(22) DawnAerospace. "CubeSat Propulsion Module." Revision B. Product Brochure. https://static1.squarespace.com/static/5cb46b698d9740673f117259/t/5e3a2caed29b7f336bad9f52/1580870831508/CubeSat+Propulsion+Module+-+Dawn+Aerospace-compressed.pdf

(23) Rocket Lab. "The Rocket Lab Kick Stage." https://www.rocketlabusa.com/electron/kickstage/

(24) Rocket Lab. "Rocket Lab successfully circularizes orbit with new Electron kick Stage." https://www.rocketlabusa.com/news/updates/rocket-lab-successfully-circularizes-orbit-with-new-electron-kick-stage/

(25) Whitmore , S A, S L Merkley, Z S Spurrier, and S D Walker. 2015. "Development of a Power Efficient, Restartable, 'Green' Propellant Thruster for Small Spacecraft and Satellites." 29th Annual AIAA/USU Conference on Small Satellites.

(26) Bulcher, A. M. and S. A. Whitmore. "A Green Hybrid Thruster Using Moderately Enriched Compressed Air as the Oxidizer." AIAA-2018-4841. AIAA Propulsion and Energy Forum. Cincinnati, OH. July 9-11, 2018. doi: 10.2514/6.2018-4841

(27) Schappell, D T, E Scarduffa, P Smith, and N Solway. AIAA-2005-4055. "Advances in Marotta Electric and Satellite Propulsion Fluid Control Activities." 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference.

(28) Hinkley, D. "A Novel Cold Gas Propulsion System for Nanosatellites and Picosatellites." AIAA, 22nd Annual Conference on Small Satellites, SSC08-VII-7.

(29) Gibbon, D. 2010. "A review of the use of butane as a low-cost propellant." Space Propulsion Conference.

(30) Gibbon, D. and Underwood, C. "Low Cost Butane Propulsion System for Small Spacecraft," 15th AIAA / USU Conference on Small Satellites. SSC01-XI-1. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2030&context=smallsat

(31) Pauliukonis, R S. 2017. "Fuel system comprising sulfur hexafluoride and lithium containing fuel." https://patents.google.com/patent/US3325318.

(32) Bonin, G, N Roth, S Armitage, J Newman, B. Risi, and R. Zee. 2015. "CanX-4 and CanX-5 Precision Formation Flight: Mission Accomplished!" 29th Annual AIAA/USU Conference on Small Satellites.

(33) Manzoni, G, and Y L Brama. 2015. "CubeSat Micropropulsion Characterization in Low Earth Orbit." 29th Annual AIAA/USU Conference on Small Satellites.

(34) GOMSpace. "Attitude and Orbit Control Systems." https://gomspace.com/shop/subsystems/attitude-orbit-control-systems/default.aspx

(35) "GomX-4," https://directory.eoportal.org/web/eoportal/satellite-missions/g/gomx-4.

(36) National Aeronautics & Space Administration. "BioSentinel." Fact Sheet. https://www.nasa.gov/sites/default/files/atoms/files/biosentinel_fact_sheet-16apr2019_508.pdf

(37) Lightsey, E. G., T. Stevenson, and M. Sorgenfrei. "Development and Testing of a 3-D-Printed Cold Gas Thruster for an Interplanetary CubeSat." Proceedings of the IEEE, Vol. 106, No. 3, March, 2018. doi: 10.1109/JPROC.2018.2799898

(38) Kvell, U, M Puusepp, F Kaminski, and et al. 2014. "Nanosatellite orbit control using MEMS cold gas thrusters." Proceedings of the Estonian Academy of Sciences, 63, 2S, 279–285.
(39) Palmer, K., Sundqvist, J., Salaverri, A., Gronland, T., Li, Z., and Wu, S.. "In-Orbit Demonstration of a MEMS-based Micropropulsion System for CubeSats." Small Satellite Conference, August 2016.
(40) Bowen, J, M Villa, and A Williams. 2015. "CubeSat based Rendezvous, Proximity Operations, and Docking in the CPOD Mission." 29th Annual AIAA/USU Conference on Small Satellites.
(41) VACCO Industries. "CubeSat Propulsion Systems from VACCO." https://www.CubeSat-propulsion.com/
(42) Klesh, A, and J Krajewski. 2015. "MarCO: CubeSats to Mars in 2016." 29th Annual AIAA/USU Conference on Small Satellites.
(43) Jet Propulsion Laboratory, National Aeronautics and Space Administration. "Mars Cube One (MarCO)." https://www.jpl.nasa.gov/CubeSat/missions/marco.php.
(44) VACCO Industries. "NEA Scout Propulsion System." Product Brochure. https://www.CubeSat-propulsion.com/wp-content/uploads/2017/08/X16056000-data-sheet-080217.pdf
(45) Zondervan, K L, J Fuller, D Rowen, and et al. 2014. "CubeSat Solid Rocket Motor Propulsion Systems Providing Delta-Vs Greater than 500 m/s." 28th Annual AIAA/USU Conference on Small Satellites.
(46) Nicholas, A, T Finne, I Galysh, A Mai, and J Yen, W. Sawka, J. Ransdell, and S. Williams. 2013. "SpinSat Mission Overview." 27th Annual AIAA/USU Conference on Small Satellites.
(47) Pacific Scientific Energetic Materials Company (PacSci EMC). Product information website. https://psemc.com/products/satellite-propulsion-system/
(48) BusinessWire.com. 2017. "PacSci EMC Demonstrates First Ever Successful Orbital Maneuvers and Orbit Raising of a CubeSat Using a Commercial Solid Rocket Motor Array." https://www.businesswire.com/news/home/20170925006504/en/PacSci-EMC-Demonstrates-Successful-Orbital-Maneuvers-Orbit.
(49) Hartwig, J.W. "Propellant Management Devices for Low Gravity Fluid Management: Past, Present, and Future Applications." AIAA Journal of Spacecraft and Rockets Vol. 54, No. 4, 808 – 824. 2017.
(50) Carpenter, C, D Schmuland, J Overly, and R Masse. 2014. "Test Results for the MPS-120 and MPS-130 CubeSat Propulsion Systems." 28th Annual AIAA/USU Conference on Small Satellites. Logan.
(51) Aerojet Rocketdyne. "Modular Propulsion Systems." Product Brochure. https://www.rocket.com/sites/default/files/documents/CubeSat%20Mod%20Prop-2sided.pdf
(52) Stellar Exploration. "Nanosatellite Propulsion." Product Brochure.
(53) Aerospace Corporation. "Propelling the Field of Small Sats Forward." https://aerospace.org/article/propelling-field-small-sats-forward
(54) Gagne, K. R., M. R. McDevitt, and D. L. Hitt. "A Dual Mode Propulsion System for Small Satellite Applications." Aerospace. Vol. 5, No. 52. 2018. doi: 10.3390/aerospace5020052
(55) Benchmark Space Systems. "B125 SmallSat Bipropellant Thruster." Product Brochure. https://www.benchmarkspacesystems.com/b125
(56) Bradford ECAPS. "High Performance Green Propulsion." Product Brochure. https://www.ecaps.space/assets/pdf/Bradford_ECAPS_Folder_2017.pdf
(57) Bradford ECAPS. "1N GP Thruster." https://www.ecaps.space/products-1ngp.php
(58) CU Aerospace. "Small-Satellite Propulsion." https://www.cuaerospace.com/technology-products/compact-small-satellite-propulsion-unit-CubeSats

(59) Tethers Unlimited. "Hydros." Product Brochure. http://www.tethers.com/wp-content/uploads/2019/09/2019-HYDROS.pdf
(60) Moog, Inc. "Monopropellant Propulsion Module." Product Brochure. https://www.moog.com/content/dam/moog/literature/Space_Defense/spaceliterature/propulsion/moog-monopropellant-propulsion-module-datasheet.pdf
(61) Tsay, M., C. Feng, and J. Zwahlen. "System-Level Demonstration of Busek's 1U CubeSat Green Propulsion Module 'AMAC'." AIAA-2017-4946. 53rd AIAA/SAE/ASEE Joint Propulsion Conference. Atlanta, GA. 10-12 July, 2017.
(62) Anflo, K. and B. Crowe. "In-Space Demonstration of an ADN-based Propulsion System." AIAA-2011-5832. 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. San Diego, CA. July 31 – August 3, 2011.
(63) Busek Co., Inc. "BGT-X5 Green Monopropellant Thruster." Product Brochure. http://busek.com/index_htm_files/70008517E.pdf
(64) Busek Co., Inc. "Green Monopropellant Thrusters." http://busek.com/technologies__greenmonoprop.htm
(65) CU Aerospace. "Performance Metrices for CUA Propulsion Systems." Product Brochure. https://www.cuaerospace.com/Portals/2/SiteContent/pdfs/datasheets/CUA-Propulsion-Systems-v22.pdf
(66) NASA, 2015, "Pathfinder Technology Demonstrator." National Aeronautics & Space Administration. https://www.nasa.gov/directorates/spacetech/small_spacecraft/ptd.html.
(67) VACCO Industries. "Green Propulsion System." Product Brochure. https://www.CubeSat-propulsion.com/wp-content/uploads/2019/08/X19041000-Green-Propulsion-System-data-sheet-073019.pdf
(68) VACCO Industries. "Integrated Propulsion System." Product Brochure. https://www.CubeSat-propulsion.com/wp-content/uploads/2019/08/Integrated-Propulsion-System-datasheet-080519.pdf
(69) VACCO Industries. "ArgoMoon Propulsion System." Product Brochure. https://www.CubeSat-propulsion.com/wp-content/uploads/2017/08/X17025000-data-sheet-080217.pdf
(70) Utah State University. "USU Technology Highlight: GOX and Nitrox Hybrid Green Rocket System." Product Brochure. http://rgs.usu.edu/techtransfer/hybrid-green-rocket-system/
(71) Digital Solid State Propulsion, Inc. (DSSP) "CAPS-3." Product Brochure. https://dssptech.com/propellant-products
(72) DSSP. "MPM-7." Product Brochure. https://dssptech.com/propellant-products
(73) DSSP. "CDM-1." Product Brochure. https://dssptech.com/propellant-products
(74) Thrasher, J. and M. McPherson. "Design and Qualification of DSSP's CubeSat Delta-V Motor (CDM-1)." Digital Solid State Propulsion, Inc. Poster presented at Small Satellites Conference. Logan, UT. 2015. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3261&context=smallsat
(75) Industrial Solid Propellant, Inc. "Product Portfolio." Product Brochure. http://www.specificimpulse.com/
(76) Alliant Techsystems Inc. (ATK). "ATK Space Propulsion Products Catalog." Product Brochure. 2008. Available from: https://forum.nasaspaceflight.com/index.php?action=dlattach;topic=31042.0;attach=494063;sess=0
(77) D-Orbit. "D-Raise." Product Brochure. https://www.dorbit.space/d-raise
(78) D-Orbit. "D3." Product Brochure. https://www.dorbit.space/d3
(79) VACCO Industries. "Standard Propulsion System." Product Brochure. https://www.CubeSat-propulsion.com/wp-content/uploads/2019/08/Standard-MiPS-datasheet-080119.pdf

(80) VACCO Industries. "JPL MarCO – Micro CubeSat Propulsion System." Product Brochure. https://www.CubeSat-propulsion.com/wp-content/uploads/2015/11/X14102000-01_2019update.pdf
(81) VACCO Industries. "Reaction Control Propulsion Module." Product Brochure. https://www.CubeSat-propulsion.com/wp-content/uploads/2015/10/Reaction-control-propulsion-module.pdf
(82) GOMspace. "NanoProp CGP-3." Product Brochure. https://gomspace.com/UserFiles/Subsystems/flyer/gomspace_nanoprop_cgp3.pdf
(83) GOMspace. "NanoProp 6U." Product Brochure. https://gomspace.com/UserFiles/Subsystems/flyer/gomspace_nanoprop_cgp6_flyer.pdf
(84) Newman, J and Zee, R. E. "Drift Recovery and Station Keeping Results for the Historic CanX-4/CanX-5 Formation Flying Mission." 29th Annual AIAA/USU Conference on Small Satellites, Logan, UT, 2015.
(85) Risi, B.W. "Propulsion System Development for the CanX-4 and CanX-5 Dual Nanosatellite Formation Flying Mission." Master of Applied Science Thesis, University of Toronto, 2014.
(86) Jens, E., Karp, A., Williams, K., Nakazono, B., Rabinovitch, J., Dyrda, D., and Mechentel, F. "Low Pressure Ignition Testing of a Hybrid SmallSat Motor." AIAA-2019-4009, AIAA Propulsion and Energy Forum, 2019. https://doi.org/10.2514/6.2019-4009.
(87) Jahn, R. G. and Choueiri, E. Y. "Electric Propulsion." Academic Press, Encyclopedia of Physical Science and Technology, Third Edition, Volume 5, 2002.
(88) Goebel, D. M. and Katz, I. "Fundamentals of Electric Propulsion: Ion and Hall Thrusters." California Institute of Technology, Jet Propulsion Laboratory, JPL Space Science and Technology Series, 2008.
(89) Bradford Space, "Comet: Water-based Propulsion for Small Satellites." Company Website, Datasheet, Copyright 2019.
(90) Sarda, K., Roth, N., Zee, R. E., Cajacob, D., and Orr, N. G. "Making the Invisible Visible: Precision RF-Emitter Geolocation from Space by the HawkEye 360 Pathfinder Mission." 32nd AIAA/USU Conference on Small Satellites, Logan, UT, 2018.
(91) eoPortal, "HawkEye 360 Pathfinder Cluster Mission to identify RFI locations." June, 2020. URL: https://directory.eoportal.org/web/eoportal/satellite-missions/h/hawkeye
(92) BlackSky Global, "Global-4 Orbital Debris Assessment Report (ODAR)." FCC Licensing, 18 December, 2018.
(93) CU Aerospace, "Propulsion Unit for CubeSats." Company Website, Datasheet, 2018.
(94) Carroll, D. L., Cardin, J. M., Burton, R. L., Benavides, G. F., Hejmanowski, N., Woodruff, C., Bassett, K., King, D., Laystrom-Woodard, J., Richardson, L., Day, C., Hageman, K., and Bhandari, R. "Propulsion Unit for CubeSats (PUC)." 62nd JANNAF Propulsion Meeting, Nashville, TN, 1-5 June, 2015, Paper Tracking # 4059, 2015, Dist. A.
(95) Burton, R.L., Benavides, G.F., and Carroll, D.L. "Space Thruster using Robust Microcavity Discharge." U.S. Patent No. 9,242,747 B1, 2016.
(96) Woodruff, C., Carroll, D., King, D., Burton, R., and Hejmanowski, N. "Monofilament Vaporization Propulsion (MVP) – CubeSat propulsion system with inert polymer propellant." Small Satellite Conf., Paper # SSX18-III-09, Logan, UT, Aug. 6-9, 2018.
(97) CU Aerospace, "Monofilament Vaporization Propulsion System Solid Inert Polymer Propellant." Company Website, Datasheet, 2020.
(98) Woodruff, C., King, D., Burton, R., Bowman, J., and Carroll, D. "Development of a Fiber-Fed Pulsed Plasma Thruster for Small Satellites." Small Satellite Conference, Logan, UT, Paper # SSC19-WKVIII-06, 2019.
(99) Woodruff, C., King, D., Burton, R., and Carroll, D. "Fiber-fed Pulsed Plasma Thruster for Small Satellites." 36th International Electric Propulsion Conference (IEPC) 2019, Vienna, Austria, Paper # IEPC 2019-A899, 2019.

(100) Woodruff, C., King, D., Burton, R., and Carroll, D. “Fiber-Fed Advanced Pulsed Plasma Thruster (FPPT).” U.S. Patent # 10,570,892, Feb. 25, 2020.
(101) CU Aerospace, “Fiber-Fed Pulsed Plasma Thruster System Solid Inert Polymer Propellant.” Company Website, Datasheet, 2020.
(102) “NASA Funds Long-Standing Partners in CubeSat Development.” Press Release, University of Illinois at Urbana/Champaign, Aerospace Engineering, 9 Oct., 2019.
(103) Aurora Propulsion Technologies, “Attitude and Orbit Control System (AOCS).” Company Website, URL: https://aurorapt.fi, Datasheet, Copyright May, 2020.
(104) Werner, D. “Aurora to test deorbit tether on Momentus mission.” SpaceNews, 5 February, 2020. URL: https://spacenews.com/aurora-momentus-plasma-brake/
(105) Ziemer, J., Marrese-Reading, Colleen, Cutler, C., Dunn, C., Romero-Wolf, A., Javidnia, S., Le, T., Li, I., Barela, P., Demmons, N., Hruby, V., Slutsky, J., Thorpe, J., Maghami, P., Hsu, O., and O’Donnell, J. “In-Flight Verification and Validation of Colloid Microthruster Performance.” AIAA Propulsion and Energy Forum, Cincinnati, OH, AIAA-2018-4643.
(106) Krejci, D., Reissner, A., Seifert, B., Jelem, D., Horbe, T., Plesescu, F., Friedhoff, P., and Lai, S. “Demonstration of the IFM Nano FEEP Thruster in Low Earth Orbit.” 4S Symposium, 2018.
(107) Krejci, D., Reissner, A., Schonherr, T., Seifert, B., Saleem, Z., and Alejos, R. “Recent Flight Data from IFM Nano Thrusters in a Low Earth Orbit.” 36th IEPC, Vienna, Austria, IEPC-2019-A724.
(108) Amos, J. “ICEYE’s Small Radar Satellites Achieve Big Capability.” BBC News, 6 May, 2020, URL: https://www.bbc.com/news/science-environment-52560809
(109) Werner, D. “Key Hurdle Cleared for York Space Systems and U.S. Army Small Satellite Launch.” SpaceNews, 22 February, 2018, URL: https://spacenews.com/key-hurdle-cleared-for-york-space-systems-and-u-s-army-small-satellite-launch/
(110) Clark, S. “Rocket Lab Deploys Experimental U.S. Military SmallSats on First Night Launch.” Spaceflight Now, 5 May, 2019. URL: https://spaceflightnow.com/2019/05/05/rocket-labs-deploys-experimental-u-s-military-SmallSats-on-first-night-launch/
(111) Wörner, N. “Sensor Networks of Satellites.” ElektronikNet, 26 May, 2020. URL: https://www.elektroniknet.de/international/sensor-networks-of-satellites-176831.html
(112) Bangert, P., Kramer, A., and Schilling, K. “UWE-4: Integration State of the First Electrically Propelled 1U CubeSat.” 31st Annual AIAA/USU Conference on Small Satellites, SSC17-WK-47, 2017.
(113) Kramer, A., Bangert, P., and Schilling, K. “Hybrid Attitude Control On-Board UWE-4 Using Magnetorquers and the Electric Propulsion System NanoFEEP.” 33rd Annual AIAA/USU Conference on Small Satellites, SSC19-WKI-02, 2019.
(114) NASA, “Upcoming ELaNa CubeSat Launches.” NASA CubeSat Launch Initiative. URL: https://www.nasa.gov/content/upcoming-elana-CubeSat-launches
(115) NASA, “NASA Announces Tenth Round of Candidates for CubeSat Space Missions.” 14 March, 2019, Press Release. URL: https://www.nasa.gov/feature/nasa-announces-tenth-round-of-candidates-for-CubeSat-space-missions
(116) “Accion Systems Raises $11 Million in Series B Funding.” 5 February, 2020, Satnews. URL: https://www.satnews.com/story.php?menu=1&number=351788008
(117) N. Arthur. “Ion Thruster Produced Roll Torque.” AIAA-2019-4166.
(118) Malphrus, B. “The Lunar IceCube EM-1 Mission: Prospecting the Moon for Water Ice.” IEEE Aerospace and Electronic Systems Magazine, Vol 34, Issue 4, DOI: 10.1109/MAES.2019.2909384.
(119) Clark, P. “Lunar Ice Cube Mission: Determining Lunar Water Dynamics with a First Generation Deep Space CubeSat.” 47th Lunar and Planetary Science Conference, 2016.

(120) Hardgrove, C. "The Lunar Polar Hydrogen Mapper CubeSat Mission." IEEE Aerospace and Electronic Systems Magazine, Vol 35, Issue 3, DOI: 10.1109/MAES.2019.2950747.
(121) eoPortal, "SMART-1 (Small Mission for Advanced Research in Technology." June, 2020. URL: https://directory.eoportal.org/web/eoportal/satellite-missions/s/smart-1
(122) eoPortal, "TacSat-2 / Roadrunner." June 2020. URL: https://earth.esa.int/web/eoportal/satellite-missions/content/-/article/tacsat2
(123) de Grys, K., Mathers, A., Welander, B., and Khayms, V. "Demonstration of 10,400 Hours of Operation on a 4.5 kW Qualification Model Hall Thruster." 46th AIAA Joint Propulsion Conference, Nashville, TN, July, 2010.
(124) Sheetz, M. and Petrova, M. "Why in the next decade companies will launch thousands more satellites than in all of history." CNBC, 15 December, 2019. URL: https://www.cnbc.com/2019/12/14/spacex-oneweb-and-amazon-to-launch-thousands-more-satellites-in-2020s.html
(125) Gorbunov, A., Khodnenko, V., Khromov, A., Murashko, V., Koryakin, A., Zhosan, V., and Grikhin, G. "Vernier Propulsion System for Small Earth Remote Sensing Satellite "Canopus-V." 32nd IEPC, Wiesbaden, Germany, 2011.
(126) eoPortal, "Kanopus-V 1 (Kanous-Vulkan N1, Environmental Satellite)." June, 2020. URL: https://directory.eoportal.org/web/eoportal/satellite-missions/k/kanopus-v-1
(127) eoPortal, "Kanopus-V-IK 1 (Kanous-Vulkan-Infra-Krasny-1)." June, 2020. URL: https://directory.eoportal.org/web/eoportal/satellite-missions/k/kanopus-v-ik-1
(128) EDB Fakel, "Stationary Plasma Thrusters." Company Website, Datasheet, 2020.
(129) Gnizdor, R., Markov, A., Mitrofanova, O., and Semenenko, D. "The research of the modified SPT-70 thruster parameters and characteristics." 36th IEPC, Vienna, Austria, 2019.
(130) Hruby, P., Demmons, N., Courtney, D., Tsay, M., Szabo, J., and Hruby, V. "Overview of Busek Electric Propulsion." 36th IEPC, Vienna, Austria, 2019.
(131) Kamhawi, H., Haag, T., Benavides, G., Hickman, T., Smith, T., Williams, G., Myers, J., Polzin, K., Dankanich, J., Byrne, L., Szabo, J., and Lee, L. "Overview of Iodine Propellant Hall Thruster Development Activities at NASA Glenn Research Center." 52nd AIAA Joint Propulsion Conference, Salt Lake City, Utah, 2016.
(132) NASA TechPort, "Iodine Satellite (iSAT)." June, 2020. URL: https://techport.nasa.gov/view/91492
(133) Lev, D., Zimmerman, R., Shoor, B., Appel, L., Ben-Ephraim, M., Herscovitz, J., and Epstein, O. "Electric Propulsion Activities at Rafael in 2019." 36th IEPC, Vienna, Austria, 2019.
(134) Herscovitz, J., and Karnieli, A. "VENuS Program: Broad and New Horizons for Super-Spectral Imaging and Electric Propulsion Missions for a Small Satellite." 22nd AIAA/USU Conference on Small Satellites, Logan, Utah, 2008.
(135) Herscovitz, J., Appel, L., Barnett, D., Baron, D., Davidson, A., Gontmacher, P., Kedem, M., Lev, D., Merenstein, A., Rbinovich, L., Reiner, D., Salama, O., Amit-Shapira, Y., Shechter, Y., Shoor, B., Warshavsky, A., and Zhuravel, N. "VENuS – A Novel Technological Mission Using Electric Propulsion." 35th IEPC, Atlanta, Georgia, 2017.
(136) Herscovitz, J., Lev, D., Shoor, B., Katz-Franco, D., Berkman, S., Baron, D, and Adler, S. "VENuS – Updates on Technological Mission using the Israeli Hall Effect Thruster (IHET)." 36th IEPC, Vienna, Austria, 2019.
(137) eoPortal "VENuS (Vegetation and Environment monitoring on a New MicroSatellite)." June, 2020. URL: https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/venus
(138) SITAEL "Electric Propulsion – HT100 Hall Effect Thruster Product Sheet." Company Website, Datasheet, 2020.

(139) Misuri, T., Ducci, C., Gregucci, S., Pedrini, D., Cannelli, F., Cesari, U., Nania, F., Vicini, A., Pace, G., Magistro, F., Cenni, J., Dignani, D., Farauanu, C., Quaranta, V., Tiseo, B., Orefice, M., and Bruno, G. "SITAEL HT100 Thruster Unit, Full Ground Qualification." 36th IEPC, Vienna, Austria, 2019.
(140) Tambini, A., Antonini, F., Melega, N., Mariotti, G., Centonze, V., and Gabriele, A. "uHETsat small Power System for high demanding payloads." European Space Power Conference, 2019.
(141) Apollo Fusion, "Apollo Constellation Engine (ACE)." Company Website, https://apollofusion.com/ace.html, Copyright 2019.
(142) Astro Digital US, Inc. "Astro Digital Ignis Orbital Debris Assessment Report (ODAR) v1.0." FCC Public Database, 2019.
(143) Exotrail, "Hall effect thruster for small satellites." Company Website, Online Datasheet, May, 2020.
(144) Exotrail Press Release, "Exotrail delivers its first Hall Effect Propulsion system prototype for In-Orbit Demonstration mission." 02 October, 2019.
(145) Exotrail Press Release, "Exotrail secures contract with AAC Clyde Space to equip their spacecrafts for Eutelsat's ELO 3 and 4." 18 February, 2020.
(146) Gurciullo, A., Jarrige, J., Lascombes, P., and Packan, D. "Experimental performance and plume characterization of a miniaturized 50W Hall thruster." 36th IEPC, Vienna, Austria, 2019.
(147) ExoTerra Resource, "Halo Hall-Effect Thruster." Company Website, Datasheet, May, 2020.
(148) VanWoerkom, M., Gorokhovsky, V., Pulido, G., Pettigrew, R., and Seidcheck, A. "Test Results of ExoTerra's Halo Micro Electric Propulsion System." 36th IEPC, Vienna, Austria, 2019.
(149) NASA Press Release, "NASA Announces New Tipping Point Partnerships for Moon and Mars Technologies." 27 September, 2019.
(150) Vinoski, J. "Orbion's Plasma Rocket Thrusters Will Power AST's New Space-Based Cell Tower." Forbes, 23 July, 2020.
(151) Henry, C. "Megaconstellation startup raises $110 million to connect smartphones via satellite." SpaceNews, 5 March, 2020.
(152) Burton, R. "Pulsed Plasma Thrusters." In Encyclopedia of Aerospace Engineering (eds R. Blockley and W. Shyy). doi:10.1002/9780470686652.eae120.
(153) Kolbeck, J., Anders, A., Beilis, I., and Keidar, M. "Micro-propulsion based on vacuum arcs." Journal of Applied Physics, June, 2019, https://doi.org/10.1063/1.5081096.
(154) REGULUS, 6 May 2020, URL: https://www.t4innovation.com/wp-content/uploads/2020/05/T4i-REGULUS-Magazine.pdf
(155) Bellomo, N. "Enhancement of Microsatellites' Mission Capabilities: Integration of REGULUS Electric Propulsion Module into UniSat-7." 70th International Astronautical Congress, Washington, D.C., October, 2019.
(156) "Cube Quest Challenge NASA Facts." NASA, FS-2019-12-073-MSFC. URL: https://www.nasa.gov/sites/default/files/atoms/files/cubequest_fs_june2020_508.pdf
(157) "Three DIY CubeSats Score Rides on NASA's First Flight of Orion, Space Launch System." NASA Press Release 17-055, 8 June, 2017. URL: https://www.nasa.gov/press-release/three-diy-CubeSats-score-rides-on-nasa-s-first-flight-of-orion-space-launch-system
(158) Alhorn, D., Casas, J., Agasid, E., Adams, C., Laue, G., Kitts, C., and O'Brien, S. "NanoSail-D: The Small Satellite That Could!" SmallSat Conference, 2011.
(159) Mansell, J., Spencer, D., Plante, B., Diaz, A., Fernandez, M., Bellardo, J., Betts, B., and Nye, B. "Orbit and Attitude Performance of the LightSail 2 Solar Sail Spacecraft." AIAA 2020-2177.

(160) "CubeSail." Laboratory for Advanced Space Systems at Illinois (LASSI), Accessed 5 July, 2020. URL: https://aerospace.illinois.edu/research/research-facilities/laboratory-advanced-space-systems-illinois-lassi

(161) Johnson, L, et al. "Near Earth Asteroid Scout: Exploring Asteroid 1991VG Using a SmallSat." *Proceedings of the 70th International Astronautical Congress*, IAC-19/B4/2.

(162) "AE's Prox-1 Satellite Launches from Kennedy Space Center." Georgia Institute of Technology, 25 June, 2019. URL: https://ae.gatech.edu/news/2019/06/aes-prox-1-satellite-launches-kennedy-space-center

(163) C. Henry. "Tethers Unlimited Says Early Results of Deorbit Hardware Test Promising." SpaceNews, 23 January, 2020. URL: https://spacenews.com/tethers-unlimited-says-early-results-of-deorbit-hardware-test-promising/

(164) Clark, S. "SmallSat Companies Teaming Up on Deorbit Experiment." Spaceflight Now, 15 August, 2019. URL: https://spaceflightnow.com/2019/08/15/SmallSat-companies-teaming-up-on-deorbit-experiment/

(165) Busek Company, "Busek Micro Resistojet." Company Website, Datasheet, Copyright 2013.

(166) Hejmanowski, N. J., Woodruff, C. A., Burton, R. L., Carroll D. L., Palla, A. D., and Cardin J. M. "CubeSat High Impulse Propulsion System (CHIPS) Design and Performance." JANNAF, Phoenix, AZ, 2016, Dist. A.

(167) Hejmanowski, N. J., Woodruff, C. A., Burton, R. L., and Carroll D. L. "Electrothermal Space Thruster Heater for Decomposable Propellants." U.S. Patent # 9,909,574 B1, 2018.

(168) Hejmanowski, N. J., Woodruff, C., Burton, R.L., Carroll, D.L., and Cardin, J. "CubeSat High Impulse Propulsion System (CHIPS)." 62nd JANNAF Propulsion Meeting, Nashville, TN, 1-5 June, 2015, Dist. A.

(169) CU Aerospace, "CubeSat High Impulse Propulsion System." Company Website, Datasheet, 2019.

(170) Cifali, G., Gregucci, S., Andreussi, T., and Andrenucci, M. "Resistojet Thrusters for Auxiliary Propulsion of Full Electric Platforms." 35th International Electric Propulsion Conference, Atlanta, GA, IEPC-2017-371, 2017.

(171) Sitael, "XR Resistojet Product Family." Datasheet, Company Website, Copyright 2015.

(172) Courtney, D., Wright, P., Lafko, D., Metivier, E., and Demmons, N. "Electrospray Propulsion for Precise Attitude and Position Control." AAS 17-088, Breckenridge, CO., 2017.

(173) D. Courtney et al. "Electrospray Thrusters for Small Spacecraft Control: Pulsed and Steady State Operation." AIAA-2018-4654.

(174) Courtney, D., Wood, Z., and Fedkiw, T. "Reconstructing Electrospray Plume Current Spatial Distributions Using Computed Tomography." 36th IEPC, Vienna, Austria, IEPC-2019-A-787.

(175) D. Courtney et al. "High-Speed Transient Characterization of the Busek BET-300-P Electrospray Thruster." 36th IEPC, Vienna, Austria, IEPC-2019-A-788.

(176) Enpulsion, "IFM Nano Thruster." Company Website, Datasheet ENP2018-001.F.1, Accessed 2020.

(177) Schönherr, T., Little, B., Krejci, D., Reissner, A., and Seifert, B. "Development, Production, and Testing of the IFM Nano FEEP Thruster." 36th IEPC, Vienna, Austria, IEPC-2019-362, 2019.

(178) Krejci, D., Hugonnaud, V., Schonherr, T., Little, B., Reissner, A., Seifert, B., Kock, Q, Borras, E., and Amo, J. "Full Performance Mapping of the IFM Nano Thruster, Including Direct Thrust Measurements." *Journal of Small Satellites*, 2019, Vol. 8, No. 2, pp. 881-893.

(179) Enpulsion, "IFM Micro Thruster COTS+." Company Website, Datasheet ENP2018-002.G.1, Accessed 2020.
(180) Grimaud, L., Krejci, D., and Seifert, B. "The IFM Micro FEEP Thruster: A Modular Design for SmallSat Propulsion." 36th IEPC, Vienna, Austria, IEPC-2019-A675, 2019.
(181) Morpheus Space, "nanoFEEP and multiFEEP." Company Website, Datasheet, June, 2020. URL: https://www.morpheus-space.com/static/MSWeb/documents/M-Space%20Products.pdf.
(182) Bock, D., Spethmann, A., Trottenberg, T., Kersten, H., and Tajmar, M. "In-Plume Thrust Measurement of NanoFEEP Thruster with a Force Measuring Probe Using Laser Interferometry." 36th IEPC, Vienna, Austria, IEPC-2017-391, 2017.
(183) Accion Systems, "TILE-2-4C." Company Website, Datasheet, Copyright 2019.
(184) Accion Systems, "TILE-3-36C-1U." Company Website, Datasheet, Copyright 2019.
(185) Avant Space, "GT-50 RF Ion Thruster." Company Datasheet. URL: http://www.avantspace.com/upload/iblock/dc9/Data-sheet.pdf
(186) Kralkin, E., et al. "Exploratory Testing of a Radio-Frequency Thruster for Small Satellites." IEPC-2017-425.
(187) Busek, "BIT-3 RF Ion Thruster." Company Website, Datasheet, Copyright 2019.
(188) "All-Electric CubeSat Propulsion Technologies for Versatile Mission Application." 32nd International Symposium on Space Technology and Science (ISTS), Fukui, Japan, June, 2019, ISTS-2019-b-002.
(189) Tsay, M., Frongillo, J., Model, J., Zwahlen, J., Barcroft, C., Feng, C. "Neutralization Demo and Thrust Stand Measurement for BIT-3 RF Ion Thruster." 2017 AIAA Propulsion and Energy Forum, Atlanta, GA, July, 2017, AIAA-2017-4890.
(190) ThrustMe, "NPT30-Xe." Company Website, Datasheet, Copyright 2019.
(191) ThrustMe, "NPT30-I2 1.5U," Company Website, Datasheet, Copyright 2020.
(192) Martinez, J., Rafalskyi, D., and Aanesland, A. "Development and Testing of the NPT30-I2 Iodine Ion Thruster." 36th IEPC, Vienna, Austria, IEPC-2019-811, 2019.
(193) Leiter, H., Lauer, D., Bauer, P., Berger, M., and Rath, M. "The Ariane Group Electric Propulsion Program 2019-2020." 36th IEPC, Vienna, Austria, IEPC-2019-592, 2019.
(194) Leiter, H., Altmann, C., Lauer, D., Rath, M., Becker, F., Feili, D., and Amo, J. "A Nouvelle Neutralization Concept for RIT-μX Miniaturized Radio Frequency Ion Thruster Systems." 36th IEPC, Vienna, Austria, IEPC-2019-806, 2019.
(195) Ariane Group, "Electric Propulsion Systems and Components." Company Website, Datasheet, Accessed 2020.
(196) Leiter, H., Lotz, B., Feili, D., Tartz, M., Neumann, H., and Cara, D. "Design Development and Test of the RIT-μX Mini Ion Engine System." IEPC-2009-179.
(197) Leiter, H., Altmann, C., Porst, J., Lauer, D., Berger, M., and Rath, M. "Six Decades of thrust – The Ariane Group Radiofrequency Ion Thrusters and Systems Family." IEPC-2017-027.
(198) Apollo Fusion, "Apollo Constellation Engine (ACE) Krypton/Xenon Propulsion System." Company Website, Datasheet, Copyright 2020.
(199) Szabo, J., Tedrake, R., Metivier, E., Paintal, S., and Taillefer, Z. "Characterization of a One Hundred Watt, Long Lifetime Hall Effect Thruster for Small Spacecraft." 53rd AIAA Joint Propulsion Conference, Atlanta, Georgia, 2017.
(200) Busek, "BHT-200 Busek Hall Effect Thruster." Company Website, Datasheet, 2019.
(201) Hruby, V., Monheiser, J., Pote, B., Freeman, C., and Connolly, W. "Low Power, Hall Thruster Propulsion System." IEPC-99-092, Kitakyushu, Japan, 1999.
(202) Busek, "BHT-600 Busek Hall Effect Thruster." Company Website, Datasheet, 2016.
(203) Szabo, J., Pote, B., Tedrake, R., Paintal, S., Byrne, L., Hruby, V., Kamhawi, H., and Smith, T. "High Throughput 600 Watt Hall Effect Thruster for Space Exploration." 52nd AIAA Joint Propulsion Conference, Salt Lake City, Utah, 2016.

(204) Saevets, P., Semenenko, D., Albertoni, R., and Scremin, G. “Development of a Long-Life Low-Power Hall Thruster.” 35th IEPC, Atlanta, Georgia, 2017.
(205) Conversano, R., Goebel, D., Katz, I., and Hofer, R. “Low-Power Hall Thruster with an Internally Mounted Low-Current Hollow Cathode.” U.S. Patent No. 10,723,489, 2020.
(206) Conversano, R., Reilly, S., Kerber, T., Brooks, J., and Goebel, D. “Development of and Acceptance Test Preparations for the Thruster Component of the Ascendant Sub-kW Transcelestial Electric Propulsion System (ASTRAEUS).” 36th IEPC, Vienna, Austria, 2019.
(207) Conversano, R., Lobbia, R., Kerber, T., Tilley, K., Goebel, D., and Reilly, S. “Performance characterization of a low-power magnetically shielded Hall thruster with an internally-mounted hollow cathode.” Plasma Sources Science and Technology, Vol. 28, No. 10, 2019.
(208) Conversano, R., Barchowsky, A., Lobbia, R., Chaplin, V., Lopez-Ortega, A., Loveland, J., Lui, A., Becatti, G., Reilly, S., Goebel, D., Snyder, J., Hofer, R., Randolph, T., Mikellides, I., Vorperian, V., Carr, G., Rapinchuk, J., Villalpando, C., and Grebow, D. “Overview of the Ascendant Sub-kW Transcelestial Electric Propulsion System (ASTRAEUS).” 36th IEPC, Vienna, Austria, 2019.
(209) Lobbia, R., Conversano, R., Ortega, A., Reilly, S., Mikellides, I. “Pole Erosion Measurements for the Development Model of the Magnetically Shielded Miniature Hall Thruster (MaSMi-DM).” 36th IEPC, Vienna, Austria, 2019.
(210) Ortega, A., Mikellides, I., Conversano, R., Lobbia, R., Chaplin, V. “Plasma Simulations for the Assessment of Pole Erosion in the Magnetically Shielded Miniature Hall Thruster (MaSMi)." 36th IEPC, Vienna, Austria, 2019.
(211) Sommerville, J., Fruncek, C., King, L., Makela, J., Terhune, K., Washeleski, R., and Myers, R. “Performance of the Aurora Low-Power Hall-Effect Thruster.” 36th IEPC, Vienna, Austria, 2019.
(212) Vaudolon, J., Vial, V., Cornu, N., and Habbassi, I. “PPS-X00 Thruster Development Status at Safran.” 36th IEPC, Vienna, Austria, 2019.
(213) SITAEL “Electric Propulsion – HT400 Hall Effect Thruster Product Sheet.” Company Website, Datasheet, 2020.
(214) Ducci, C., Raiji, H., Pedrini, D., Misuri, T., and Onida, L. “SITAEL’s HT400 Hall Effect Thruster for Constellation Applications.” 36th IEPC, Vienna, Austria, 2019.
(215) Pedrini, D., Ducci, C., Misuri, T., Paganucci, F., Andrenucci, M. “Sitael Hollow Cathodes for Low-Power Hall Effect Thrusters.” IEEE Transactions on Plasma Science, Vol. 46, No. 2, February, 2018.
(216) Space Electric Thruster Systems “ST25 Hall-Effect Thruster.” Company Website, Datasheet, 2020.
(217) Petrenko, O., Tolok, S., Maslov, V., Kulagin, S., Serbin, V., Alekseenko, O., and Shcherbak, D. “Electric propulsion system SPS-25 with Hall Thruster.” 70th International Astronautical Congress (IAC),Washington D.C., October, 2019.
(218) Space Electric Thruster Systems “ST40 Hall-Effect Thruster.” Company Website, Datasheet, 2020.
(219) Krishnan, M., Velas, K., and Leemans, S. “Metal Plasma Thruster for Small Satellites.” Journal of Propulsion and Power, March, 2020, DOI: 10.2514/1.B37603.
(220) Busek “BmP-220 Technical Specifications.” Company Website, Datasheet, Copyright 2019.
(221) Jarrige, J., Packan, D., Blanchet, A., and Herrero, L. “Direct Thrust Measurement of a Vacuum Arc Thruster.” 36th IEPC, Vienna, Austria, 2019.
(222) Blanchet, A., Herrero, L., Voisin, L., Pilloy, B., and Courteville, D. “Plasma Jet Pack Technology for Nano-Microsatellites.” 36th IEPC, Vienna, Austria, 2019.

(223) Ciaralli et al. "Results of the Qualification Test Campaign of a Pulsed Plasma Thruster for CubeSat Propulsion (PPTCUP)." Acta Astronautica, Volume 121, Pages 314-322, April–May, 2016.
(224) Siddiqui, M., Cretel, C., Synowiec, J., Hsu, A., Young, J., and Spektor, R. "First Performance Measurements of the Phase Four RF Thruster." 35th IEPC, Atlanta, GA, October, 2017.
(225) Siddiqui, M. and Cretel, C. "Updated Performance Measurements and Analysis of the Phase Four RF Thruster." Joint Propulsion Conference, Cincinnati, OH, AIAA-2018-4817.
(226) Cretel, C., Ajamia, M., Thompson, D., and Siddiqui, M. "Torsional Balance Thrust Measurement Techniques for Small RF Thrusters."
(227) "Meet Maxwell." Phase Four, website, accessed 2020, URL: https://www.phasefour.io/maxwell/
(228) "REGULUS Electrical Propulsion System for Micro-satellites." T4i, datasheet. URL: https://www.t4innovation.com/wp-content/uploads/2019/10/T4i_REGULUS_datasheet_.pdf
(229) "ConstantQ Spacecraft Propulsion." Fluid & Reason, website, accessed 2020. URL: https://fluidandreason.com/constantq/
(230) "Plasma Brake Module (PBM)." Aurora, datasheet, 2020. URL: https://aurorapt.fi/wp-content/uploads/2020/05/Aurora-PBM.pdf
(231) "Terminator Tape." Tethers Unlimited, datasheet, 2020. URL: https://www.tethers.com/wp-content/uploads/2020/03/2020-Terminator-Tape.pdf

5.0 Guidance, Navigation & Control

5.1 Introduction

The Guidance, Navigation & Control (GNC) subsystem includes both the components used for position determination and the components used by the Attitude Determination and Control System (ADCS).

In Earth orbit, onboard position determination can be provided by a Global Positioning System (GPS) receiver. Alternatively, ground-based radar tracking systems can also be used. If onboard knowledge is required, then these radar observations can be uploaded and paired with a suitable propagator. Commonly, the USAF publishes Two-Line Element sets (TLE) (1), which are paired with a SGP4 propagator (2). In deep space, position determination is performed using the Deep Space Network (DSN) and an onboard radio transponder (3).

Using SmallSats in cislunar space and beyond requires a slightly different approach than the GNC subsystem approach in low-Earth orbit. Use of the Earth's magnetic field, for example, is not possible in these missions, and careful consideration of alternate ADCS designs and methods must be available. Two communication relay CubeSats (Mars Cube One, MarCO) successfully demonstrated interplanetary capability during the 2018 Insight mission to Mars (4). This interplanetary mission demonstrated both the capability of this class of spacecraft and the GNC fine pointing design for communication.

ADCS includes sensors to determine attitude and attitude rate, such as star trackers, sun sensors, horizon sensors, magnetometers, and gyros. In addition, the ADCS is often used to control the vehicle during trajectory correction maneuvers and, using accelerometers, to terminate maneuvers when the desired velocity change has been achieved. Actuators are designed to change a spacecraft's attitude and to impart velocity change during trajectory correction maneuvers. Common spacecraft actuators include magnetic torquers, reaction wheels, and thrusters. There are many attitude determination and control architectures and algorithms suitable for use in small spacecraft (5).

Miniaturization of existing technologies is a continuing trend in small spacecraft GNC. While three-axis stabilized, GPS-equipped, 100 kg class spacecraft have been flown for decades, it has only been in the past few years that such technologies have become available for micro- and nano-class spacecraft. Table 5-1 summarizes the current state-of-the-art of performance for GNC subsystems in small spacecraft. Performance greatly depends on the size of the spacecraft and values will range for nano- to micro-class spacecraft.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

Table 5-1: The State of the Art for GNC Subsystems		
Component	**Performance**	**TRL**
Reaction Wheels	0.0006 – 0.3 Nm peak torque, 0.005 – 8 N m s storage	9
Magnetic Torquers	0.1 A m^2 – 15 A m^2	9
Star Trackers	8 arcsec pointing knowledge	9
Sun Sensors	0.1° accuracy	9
Earth Sensors	0.25° accuracy	9
Inertial Sensors	Gyros: 0.15° h^{-1} bias stability, 0.02° $h^{-1/2}$ ARW Accels: 3 µg bias stability, 0.02 (m s^{-1})/$h^{-1/2}$ VRW	9
GPS Receivers	1.5 m position accuracy	9
Integrated Units	1 – 0.002° pointing capability	9
Atomic Clocks	10 – 100 Frequency Range (MHz)	5 – 6
Deep Space Navigation	Bands: X, Ka, S, and UHF	9

5.2 State-of-the-Art in GNC Subsystems

5.2.1 Integrated Units

Integrated units combine multiple different attitude and navigation components to provide a simple, single-component solution to a spacecraft's GNC requirements. Typical components included are reaction wheels, magnetometers, magnetic torquers, and star trackers. The systems often include processors and software with attitude determination and control capabilities. Table 5-2 describes some of the integrated systems currently available. Blue Canyon Technologies' XACT (figure 5.1) flew on the NASA-led missions MarCO and ASTERIA, both of which were 6U platforms, and have also flown on 3U missions (MinXSS was deployed from NanoRacks in February 2016).

Figure 5.1: BCT XACT Integrated ADCS Unit. Credit: Blue Canyon Technologies.

Table 5-2. Currently Available Integrated Systems							
Manufacturer	**Model**	**Mass (kg)**	**Actuators**	**Sensors**	**Processor**	**Pointing Accuracy**	**TRL**
AAC Clyde Space	High-Precision Attitude Determination and Control System	Unk	Unk	Unk	Unk	0.5°	7
Adcole Space	MAI-025 Micro ADCS	0.250	1 reaction wheel 3 magnetic torquers	1 magnetometer	Unk	{1°, 1°, 3°}	Unk
Adcole Space	MAI-400	0.694	3 reaction wheels 3 magnetic torquers	3-axis magnetometer 2 Earth horizon sensors	Yes	1°	9
Adcole Space	MAI-401	0.560	3 reaction wheels 3 magnetic torquers	1 star tracker 3-axis magnetometer	Unk	0.1°	7
Adcole Space	MAI-500	1.049	3 reaction wheels 3 magnetic torquers	2 star trackers 3-axis magnetometer	Yes	0.1°	7
Berlin Space Technologies	iADCS-100	0.400	3 reaction wheels 3 magnetic torquers	1 star tracker 3 gyros, 1 magnetometer, 1 accelerometer	Yes	1°	9
Blue Canyon Technologies	XACT-15	0.885	3 reaction wheels 3 magnetorquers	1 star tracker 3-axis magnetometer	Yes	0.007°	9

Blue Canyon Technologies	XACT-50	1.230	3 reaction wheels 3 magnetorquers	1 star tracker 3-axis magnetometer	Yes	0.007°	9
Blue Canyon Technologies	XACT-100	1.813	3 reaction wheels 3 magnetorquers	1 star tracker 3-axis magnetometer	Yes	0.007°	9
Blue Canyon Technologies	Flexcore	configuration dependent	3 – 4 reaction wheels 3 magnetorquers	1 star tracker 3-axis magnetometer	Yes	0.007°	9
CubeSpace	CubeADCS 3-Axis	Unk	3 reaction wheels 3 megnetic torquers	10 coarse sun sensors 1 magnetometer 1 fine sun/earth sensor	Unk	Unk	Unk
CubeSpace	CubeADCS Y-Momentum	Unk	1 reaction wheel 3 magnetic torquers	10 coarse sun sensors 1 magnetometer	Unk	Unk	Unk
KU Leuven	ADCS	0.715	3 reaction wheels 3 magnetic torquers	1 star tracker 3 gyros 3 magnetometers	Yes	0.1°	Unk
Tyvak	Inertial Reference Module (IRM)	0.610	3 reaction wheels 3 magnetorquers	2 star trackers 3 gyros	Yes	0.057° (1s)	9

5.2.2 Reaction Wheels

Miniaturized reaction wheels provide small spacecraft with a three-axis precision pointing capability and must be carefully selected based on a number of factors including the mass of the spacecraft and the required rotation performance rates. Reaction wheels provide torque and momentum storage along the wheel spin axis and require the spacecraft to counter-rotate around the spacecraft center of mass due to conservation of angular momentum from the wheel spin direction. Table 5.3 lists a selection of high-heritage miniature reaction wheels. With the exception of three units, all of the reaction wheels listed have spaceflight heritage. For example, Blue Canyon's RWp500 has been flying on NASA's CYGNSS mission since 2015, and Millennium Space Systems has 20 RWA1000s in orbit. For full three-axis control, a spacecraft requires three wheels. However, a four wheel configuration is often used to provide fault tolerance (6). Due to parasitic external torques, reaction wheels need to be periodically desaturated using an actuator that provides an external torque, such as thrusters or magnetic torquers (7).

In addition, the multiple reaction wheels are often assembled in a "skewed" or angled configuration such that there exists a cross-coupling of torques with two or more reaction wheels. While this reduces the torque performance in any single axis, it allows a redundant, albeit reduced, torque capability in more than one axis. The result is that should any single reaction wheel fail, one or more reaction wheels are available as a reduced-capability backup option.

Table 5-3. High Heritage Miniature Reaction Wheels

Manufacturer	Model	Mass (kg)	Peak Power (W)	Peak Torque (Nm)	Momentum Capacity (Nms)	# Wheels	Radiation Tolerance (krad)	TRL
AAC Clyde Space	Small Sat Reaction Wheel	1.500	Unk	0.040	Unk	Unk	10	9
Adcole Space	MAI-400	0.110	Unk	0.001	0.011	1	Unk	9
Berlin Space Technologies	RWA05	1.700	0.5	0.016	0.500	1	30	9
Blue Canyon Technologies	RWP015	0.130	1	0.004	0.015	1	40	9
Blue Canyon Technologies	RWp050	0.240	1	0.007	0.050	1	40	9
Blue Canyon Technologies	RWp100	0.330	1	0.007	0.100	1	40	9
Blue Canyon Technologies	RWp500	0.750	6	0.025	0.500	1	40	9
Blue Canyon Technologies	RW1	0.950	9	0.100	1.000	1	40	9
Blue Canyon Technologies	RW4	3.200	10	0.250	4.000	1	40	9

Blue Canyon Technologies	RW8	4.400	10	0.250	8.000	1	40	9
CubeSpace	Cube Wheel Small	0.060	0.65	0.000	0.002	1	24	9
CubeSpace	Cube Wheel Small+	0.090	2.3	0.002	0.004	1	24	9
CubeSpace	Cube Wheel Mediu m	0.150	2.3	0.001	0.011	1	24	9
CubeSpace	Cube Wheel Large	0.225	4.5	0.002	0.031	1	24	9
GomSpace	NanoT orque GSW-600	0.940	Unk	0.002	0.019	1	Unk	Unk
Millenium Space Systems	RWA1 000	0.980	Unk	0.100	0.100	Unk	Unk	9
NanoAvionics	RWO	0.137	3.25	0.003	0.020	1	20	9
NanoAvionics	4RWO	0.665	6	0.006	0.037	4	20	9
NewSpace Systems	NRWA -T005	1.2	Unk	0.01	0.050	1	10	9
NewSpace Systems	NRWA -T065	1.55	Unk	0.02	0.65	1	10	9
NewSpace Systems	NRWA -T10	5	2	0.21	10.6	1	10	9
Sinclair Interplanetary	RW-0.03	0.185	1.8	0.002	0.040	1	20	9
Sinclair Interplanetary	RW-0.003	0.050	Unk	0.001	0.005	1	10	6
Sinclair Interplanetary	RW-0.01	0.120	1.05	0.001	0.018	1	20	9
Sinclair Interplanetary	RW3-0.06	0.226	23.4	0.020	0.180	1	20	9
Vectronic Aerospace	VRW-01	1.800	25	0.025	1.000	1	20	Unk
Vectronic Aerospace	VRW-02	1.000	25	0.020	0.200	1	20	9
Vectronic Aerospace	VRW-05	1.300	25	0.025	0.500	1	20	Unk

5.2.3 Magnetic Torquers

Magnetic torquers provide control torques perpendicular to the local external magnetic field. Table 5-4 lists a selection of high heritage magnetic torquers and figure 5.2 illustrates some of ZARM Technik's product offerings. Magnetic torquers are often used to remove excess momentum from reaction wheels. As control torques can only be provided in the plane perpendicular to the local magnetic field, magnetic torquers alone cannot provide three-axis stabilization.

Figure 5.2: Magnetorquers for micro satellites. Credit: ZARM Technik.

Use of magnetic torquers beyond low-Earth orbit and in interplanetary applications need to be carefully investigated since their successful operation is dependent on a significant local external magnetic field. This magnetic field may or may not be available in the location and environment for that mission.

Table 5-4. High Heritage Magnetic Torquers

Manufacturer	Model	Mass (kg)	Power (W)	Peak Dipole (A m^2)	# Axes	Radiation Tolerance (krad)	TRL
Adcole Space	Electromagnet (Type A)	0.018	Unk	0.15	Unk	Unk	9
CubeSpace	CubeTorquer Small	0.028	Unk	0.24	Unk	20	9
CubeSpace	CubeTorquer Medium	0.036	Unk	0.66	Unk	20	9
CubeSpace	CubeTorquer Large	0.072	Unk	1.90	Unk	20	9
CubeSpace	CubeTorquer Coil	0.046	Unk	0.13	Unk	20	9
GomSpace	Nano Torque GST-600	0.156	Unk	0.31 – 0.34	3	Unk	Unk
GomSpace	NanoTorque Z-axis Internal	0.106	Unk	0.139	1	Unk	Unk
ISIS	Magnetorquer Board	0.196	1.2	0.20	3	Unk	9
MEISEI	Magnetic Torque Actuator for Spacecraft	0.5	1	12	1	Unk	9
NanoAvionics	MTQ3X	0.205	0.4	0.30	3	20	9
NewSpace Systems	NCTR-M002	0.030	0.2	0.20	1	Unk	9
NewSpace Systems	NCTR-M012	0.050	0.8	1.19	1	Unk	Unk

Sinclair Interplanetary	TQ-40	0.825	Unk	48.00	1	Unk	9
Sinclair Interplanetary	TQ-15	0.400	Unk	19.00	1	Unk	9
SpaceFlight Industries	0-1-1	0.727	Unk	15.00	1	Unk	9
Surrey Satellite Technology	MTR-5	0.500	Unk	5.00	Unk	5	9
ZARM	MT0.1-1	0.003	Unk	0.10	Unk	Unk	9
ZARM	MT1-1	0.060	Unk	1.00	Unk	Unk	9
ZARM	MT2-1	0.2	0.5	2	1	Unk	Unk
ZARM	MT5-2	0.3	0.77	5	1	Unk	Unk
ZARM	MT6-2	0.3	0.5	6	1	Unk	Unk
ZARM	MT10-2-H	0.35	1	10	1	Unk	Unk
ZARM	MT15-1	0.43	1.11	15	1	Unk	Unk

5.2.4 Thrusters

Thrusters used for attitude control are described in the Chapter 4. Pointing accuracy is determined by minimum impulse bit, and control authority by thruster force.

5.2.5 Star Trackers

A star tracker can provide an accurate, standalone estimate of three-axis attitude by comparing a digital image captured with a focal plane array detector to an onboard star catalog (8). Star trackers typically identify and track multiple stars and provide three-axis attitude (and often attitude rate) several times a second, usually provided as a quaternion. Table 5-5 lists some models suitable for use on a small spacecraft.

Table 5-5. Star Trackers Suitable for Small Spacecraft

Manufacturer	Model	Mass (kg)	Power (W)	FOV	Cross axis accuracy (3s)	Twist accuracy (3s)	Radiation Tolerance (krad)	TRL
Adcole Space	MAI-SS Space Sextant	0.282	2	Unk	5.7"	27"	75	9
Ball Aerospace	CT-2020	3.000	8	Unk	1"	1"	Unk	6

Berlin Space Technologies	ST200	0.040	0.65	22°	30"	200"	11	9
Berlin Space Technologies	ST400	0.280	0.65	15°	15"	150"	11	9
Blue Canyon Technologies	Standard NST	0.350	1.5	10° x 12°	6"	40"	40	9
Blue Canyon Technologies	Extended NST	1.300	1.5	10° x 12°	6"	40"	40	9
Creare	UST	0.840	Unk	Unk	7"	15"	40	5
CubeSpace	CubeStar	0.055	0.264	42° diameter	55.44"	77.4	Unk	8
Danish Technical University	MicroASC	0.425	1.9	Unk	Unk	Unk	Unk	9
Leonardo	Spacestar	1.600	6	20° x 20°	7.7"	10.6"	Unk	9
NanoAvionics	ST-1	0.108	1.2	21° full-cone	8"	50"	20	9
Sinclair Interplanetary	ST-16RT2	0.185	1	8° half-cone	5"	55"	Unk	9
Sodern	Auriga-CP	0.210	1.1	Unk	2"	11"	Unk	9
Sodern	Hydra-M	1.400	1	Unk	Unk	Unk	Unk	5
Sodern	Hydra-TC	1.400	1	Unk	Unk	Unk	Unkn.	5
Space Micro	MIST	0.520	4	14.5°	15"	105"	30	9
Space Micro	µSTAR-100M	1.800	5	Unk	15"	105"	100	Unk
Space Micro	µSTAR-200M	2.100	10	Unk	15"	105"	100	Unk
Space Micro	µSTAR-200H	2.700	10	Unk	3"	21"	100	Unk
Space Micro	µSTAR-400M	3.300	18	Unk	15"	105"	100	Unk
Surrey Satellite Technology	Altair HB+	1.000	Unk	Unk	10"	60"	Unk	9
Terma	HE-5AS	2.200	7	22°	3"	15"	100	9
Terma	T1	0.923	0.75	20° circular	4.5"	27"	Unk	5

Terma	T2	0.923	0.5	20° circular	10.5"	63"	Unk	5
Vectronic Aerospace	VST-41MN	0.900	2.5	14° x 14°	27"	183"	20	Unk
Vectronic Aerospace	VST-68M	0.470	3	14° x 14°	7.5"	45"	20	Unk

5.2.6 Magnetometers

Magnetometers provide a measurement of the local magnetic field and this measurement can be used to provide both estimates of attitude (9) and also orbital position. The vast majority of CubeSats use commercial-off-the-shelf (COTS) magnetometers and improve their performance with software. Table 5-6 provides a summary of some three-axis magnetometers available for small spacecraft, one of which is illustrated in figure 5.3.

Figure 5.3: NSS Magnetometer. Credit: NewSpace Systems.

Table 5-6. Three-axis Magnetometers for Small Spacecraft

Manufacturer	Model	Mass (kg)	Power (W)	Resolution (nT)	Orthogonality	Radiation Tolerance (krad)	TRL
GomSpace	NanoSense M315	0.008	Unk	Unk	Unk	Unk	Unk
MEISEI	3-Axis Magnetometer for Small Satellite	0.220	1.5	Unk	1°	Unk	9
NewSpace Systems	NMRM-Bn25o485	0.085	0.75	8	1°	10	9
NewSpace Systems	NMRM-001-485	0.067	0.55	8	1°	10	9
SpaceQuest	MAG-3	0.100	Voltage Dependant	Unk	1°	10	9
ZARM	High-Rel Fluxgate Magnetometer	0.3	1	Unk	1°	30	Unk
ZARM	AMR Magnetometer	0.06	0.3	Unk	1°	Unk	Unk

5.2.7 Sun Sensors

Sun sensors are used to estimate the direction of the Sun in the spacecraft body frame. Sun direction estimates can be used for attitude estimation, though to obtain a three-axis attitude estimate at least one additional independent source of attitude information is required (e.g., the Earth nadir vector, the direction to a star, etc). Because the Sun is easily identifiable and extremely bright, Sun sensors are often used for fault detection and recovery. However, care must be taken to ensure the Moon is not inadvertently misidentified as the sun.

Figure 5.4: Adcole Coarse Sun Sensor Detector (Cosine Type). Credit: Adcole Space.

There are several types of Sun sensors which operate on different principles, but the most common types for small spacecraft are cosine detectors and quadrant detectors. Quadrant detectors appear to be gaining popularity in the CubeSat world due to their compact size and low cost.

<u>Cosine detectors</u> are photocells. Their output is the current generated by the cell, which is (roughly) proportional to the cosine of the angle between the sensor boresight and the Sun. For that reason, at least two cosine detectors (pointing in different directions) are needed to estimate the direction to the Sun and typically four are used to obtain an unambiguous solution and for additional sky coverage. Cosine detectors are inexpensive, low-mass, simple and reliable devices but their accuracy is typically limited to a few degrees and they do require analog-to-digital converters. Figure 5.4 is an example of a cosine detector.

<u>Quadrant detectors.</u> Quadrant sun sensors typically operate by shining sun light through a square window onto a 2 x 2 array of photodiodes. The current generated by each photodiode is a function of the direction of the sun relative to the sensor boresight. The measured currents from all four cells are then combined mathematically to produce the angles to the sun.

Examples of small spacecraft sun sensors are described in table 5-7.

Table 5-7. Small Spacecraft Sun Sensors										
Manufacturer	**Model**	**Sensor Type**	**Mass (kg)**	**Peak Power (W)**	**Analog or Digital**	**FOV**	**Accuracy (3s)**	**# Measurement Angles**	**Radiation Tolerance (krad)**	**TRL**
Adcole Space	Analog Sun Detector	Cosine	0.068	Unk	Analog	Unk	0.75°	1	Unk	9
Adcole Space	MAI Sun Sensor (SmallSat)	Unk	0.0055	0.005	Analog	Unk	Unk	Unk	Unk	Unk
Adcole Space	MAI Sun Sensor (CubeSat)	Unk	0.0035	0.005	Analog	Unk	Unk	Unk	Unk	Unk
Adcole Space	Coarse Sun Sensor	Unk	0.13	0	Analog	Varies	5°	2	Unk	9
Adcole Space	Digital Sun Senser	Unk	1.279	1	Digital	±32° per axis	0.1°	2	Unk	9
Bradford Engineering	CoSS	Cosine	0.024	0	Analog	160° full cone	3°	1	Unk	Unk
Bradford Engineering	CoSS-R	Cosine	0.015	0	Analog	180° full cone	3°	1	Unk	Unk
Bradford Engineering	CSS-01, CSS-02	Cosine	0.215	0	Analog	180° full cone	1.5°	2	Unk	Unk
Bradford Engineering	FSS	Quadrant	0.375	0.25	Analog	128° x 128°	0.3°	2	10	Unk
Bradford Engineering	Mini-FSS	Quadrant	0.050	0	Analog	128° x 128°	0.2°	2	Unk	Unk
CubeSpace	CubeSense	Camera	0.030	0.2	Digital	180° full cone	0.2°	2	24	9

GomSpace	NanoSense FSS	Quadrant	0.002	Unk	Digital	{45°, 60°}	{±0.5°, ±2°}	2	Unk	Unk
Lens R&D	BiSon64-ET	Quadrant	0.024	Unk	Analog	±58° per axis	0.5°	2	Unk	Unk
Lens R&D	BiSon64-ET-B	Quadrant	0.033	Unk	Analog	±58° per axis	0.5°	2	Unk	Unk
Lens R&D	MAUS	Quadrant	Unk	Unk	Analog	±46° per axis	Unk	2	Unk	Unk
NewSpace Systems	NFSS-411	Unk	0.035	0.13	Digital	140°	0.1°	TBD	10	9
NewSpace Systems	NCSS-SA05	Unk	0.005	Unk	Analog	114°	0.5°	TBD	Unk	Unk
Solar MEMS Technologies	ISS-AX	Quadrant	0.100	Unk	Analog	{120°, 50°, 20°, 10°}	{12°, 5°, 2°, 1°}	2	Unk	Unk
Solar MEMS Technologies	ISS-DX	Quadrant	0.100	Unk	Digital	{120°, 50°, 20°, 10°}	0.4° to 0.1°	2	Unk	Unk
Solar MEMS Technologies	ISS-TX	Quadrant	0.100	Unk	Digital	{120°, 50°, 20°, 10°}	{12°, 5°, 2°, 1°}	2	Unk	Unk
Solar MEMS Technologies	nanoSSOC-A60	Quadrant	0.004	Unk	Analog	±60° per axis	0.5°	2	100	Unk
Solar MEMS Technologies	nanoSSOC-D60	Quadrant	0.007	Unk	Digital	±60° per axis	0.5°	2	30	Unk
Solar MEMS Technologies	SSOC-A60	Quadrant	0.025	Unk	Analog	±60° per axis	0.3°	2	100	Unk
Solar MEMS Technologies	SSOC-D60	Quadrant	0.035	Unk	Digital	±60° per axis	0.3°	2	30	Unk
Space Micro	CSS-01, CSS-02	Cosine	0.010	0	Analog	120° full cone	5°	1	100	9
Space Micro	MSS-01	Quadrant	0.036	0	Analog	48° full cone	1°	2	100	9

5.2.8 Horizon Sensors

Horizon sensors can be simple infrared horizon crossing indicators (HCI), or more advanced thermopile sensors that can be used to detect temperature differences between the poles and equator. For terrestrial applications, these sensors are referred to as Earth Sensors, but can be used for other planets. Examples of such technologies are described in table 5-8 and illustrated in figure 5.5.

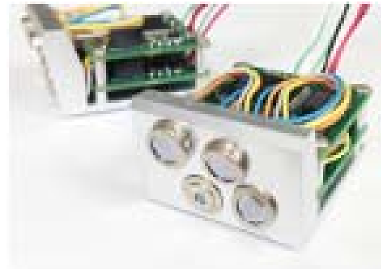


Figure 5.5: MAI-SES. Credit: Adcole Space.

In addition to the commercially-available sensors listed in table 5-8, there has been some recent academic interest in horizon sensors for CubeSats with promising results (10) (11).

Table 5-8. Commercially-Available Horizon Sensors

Manufac-turer	Model	Sensor Type	Mass (kg)	Peak Power (W)	Analog or Digital	Accuracy	# Measu-rement Angles	Rad Tolerance (krad)	TRL
Adcole Space	MAI-SES Static Earth Sensor	Static	0.033	TBD	TBD	0.25°	TBD	Unk	9
CubeSpace	CubeSense	Camera	0.030	0.200	Digital	0.2°	2	24	9
CubeSpace	CubeIR	Infrared	0.050	0.230	Digital	1.5°	2	24	Unk
Servo	Mini Digital HCI	Pyroelectric	0.050	Voltage Dependant	Digital	0.75°	Unk	Unk	9
Servo	Mini HCI	Pyroelectric	0.0115	Voltage Dependant	Unk	Unk	Unk	Unk	Unk
Servo	RH 310	Pyroelectric	1.5	1	Unk	.015°	Unk	20	Unk
Solar MEMS Technologies	HSNS	Infrared	0.120	0.150	Unk	1°	Unk	30	Unk

5.2.9 Inertial Sensing

Inertial sensing is a broad category which includes gyroscopes for measuring angular change and accelerometers for measuring velocity change.

Inertial sensors are packaged in different ways, ranging from single-axis devices (e.g., a single gyroscope or accelerometer), to packages which include multiple axes of a single device type (e.g., Inertial Reference Units are typically three gyroscopes mounted in a triad orientation to provide three-axes angular change), to Inertial Measurement Units (IMUs), which are packages which include multiple axes of both gyroscopes and accelerometers (to enable 6-DOF inertial propagation). Some vendors also offer packages that incorporate magnetometers and barometers.

Inertial sensors are frequently used to propagate the vehicle state between measurement updates of a non-inertial sensor. For example, star trackers typically provide attitude updates at 5 Hz or possibly 10 Hz. If the control system requires accurate knowledge between star tracker updates, then an IMU may be used for attitude propagation between star tracker updates.

The main gyroscope types used in modern small spacecraft are fiber optic gyros (FOGs) and MEMS gyros, with FOGs usually offering superior performance at a mass and cost penalty (12). Other gyroscope types exist (e.g., resonator gyros, ring laser gyros), but these are not common in the SmallSat/CubeSat world due to size, weight, and power (SWaP) and cost considerations.

Gyro behavior is a complex topic (13) and gyro performance is typically characterized by a multitude of parameters, but in table 5-9 we have chosen only to include bias stability and angle random walk, as these two are often the driving performance parameters. Similarly, we list bias stability and velocity random walk for accelerometers. That said, when selecting inertial sensors, it is important to consider other factors such as dynamic range, output resolution, bias, sample rate, etc.

Table 5-9. Gyros Available for Small Spacecraft

Manufacturer	Model	Sensor Type	Technology	Mass (kg)	Power (W)	Gyros				Accelerometers			
							Bias Stability		ARW		Bias Stability		VRW
						# Axes	(°/hr)	stat	(°/rt(hr))	# Axes	(μg)	stat	(m/sec)/rt(hr)
Advanced Navigation	Orientus	IMU + magnetometers	MEMS	0.025	0.325	3	3.000	TBD	0.240	3	20	TBD	0.059
AdvanTech International	AU7684	IMU	MEMS	TBD	TBD	3	10.000	TBD	0.500	3	2000	TBD	TBD
DARPA	PRIGM	IMU	MEMS	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk
Epson	M-G370	IMU	MEMS	0.010	TBD	3	0.800	av	0.060	3	10	av	0.025
Epson	M-G365	IMU	MEMS	0.010	TBD	3	1.200	av	0.080	3	8	av	0.020
Epson	M-G364	IMU	MEMS	0.010	TBD	3	2.200	av	0.090	3	50	av	0.025
Epson	M-G354	IMU	MEMS	0.010	TBD	3	3.000	av	0.200	3	70	av	0.030
Epson	M-V340	IMU	MEMS	0.001	TBD	3	3.500	av	0.170	3	50	av	0.150
Epson	M-G550	IMU	MEMS	0.081	TBD	3	3.500	av	0.100	3	TBD	Unk	TBD
Gladiator Technologies	A40	Accel	MEMS	0.015	TBD	0	N/A	Unk	N/A	1	45	TBD	0.038

Gladiator Technologies	G150Z	Gyro	MEMS	0.028	TBD	1	1.200	TBD	0.060	0	N/A	N/A	N/A
Gladiator Technologies	G300D	IRU	MEMS	0.018	0.200	3	5.000	TBD	0.168	0	N/A	N/A	N/A
Gladiator Technologies	LandMark 60LX	IMU	MEMS	0.125	0.600	3	4.000	TBD	0.096	3	10	TBD	0.016
Gladiator Technologies	LandMark 01	IMU	MEMS	0.026	0.270	3	10.000	TBD	0.210	3	55	TBD	0.053
Gladiator Technologies	LandMark 005	IMU	MEMS	0.018	0.270	3	5.000	TBD	0.168	3	45	TBD	0.044
Gladiator Technologies	LandMark 007	IMU	MEMS	0.020	0.275	3	10.000	TBD	0.210	3	2000	TBD	3.530
Gladiator Technologies	LandMark 007X	IMU	MEMS	0.020	0.275	3	10.000	TBD	0.210	3	1000	TBD	2.942
Gladiator Technologies	LandMark 60LX	IMU	MEMS	0.115	0.550	3	3.000	TBD	0.096	3	25	TBD	0.024
Gladiator Technologies	LandMark 65	IMU	MEMS	0.115	0.600	3	7.000	TBD	0.120	3	10	TBD	0.021

Gladiator Technologies	MRM60	IMU	MEMS	0.120	1.000	3	3.000	TBD	0.096	3	25	TBD	0.024
Honeywell	MIMU	IMU	RLG	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk
Honeywell	HG1930	IMU	MEMS	0.159	3.000	3	20.000	1σ	0.175	3	10	1σ	0.300
Honeywell	HG1700	IMU	RLG	0.726	8.000	3	1.000	1σ	0.125	3	1000	1σ	TBD
Inertial Sense	µIMU	IMU + magnetometers +barometer	MEMS	0.011	0.340	3	10.000	max	0.150	3	40	max	0.070
InertialLabs	IMU-P "Tactical" Standard A	IMU	MEMS	0.070	0.800	3	1.000	rms	0.200	3	5	rms	0.015
KVH	1725 IMU	IMU	FOG	0.700	8.000	3	1.000	1σ	0.017	3	100	1σ	0.071
KVH	1750 IMU	IMU	FOG	0.700	8.000	3	0.100	1σ	0.012	3	10	1σ	0.014
KVH	1775 IMU	IMU + magnetometers	FOG	0.700	8.000	3	0.100	1σ	0.012	3	50	1σ	0.071
KVH	CG-5100	Unk	Unk	2.270	15.000	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk
KVH	DSP-1760	IRU	FOG	0.600	8.000	3	0.100	1σ	0.120	0	N/A	Unk	N/A
KVH	DSP-3000	Gyro	FOG	0.270	3.000	1	1.000	1σ	0.067	0	N/A	Unk	N/A
KVH	DSP-3100	Gyro	FOG	0.200	3.000	1	1.000	1σ	0.067	0	N/A	Unk	N/A
KVH	DSP-3400	Gyro	FOG	0.300	3.000	1	1.000	1σ	0.067	0	N/A	Unk	N/A
KVH	DSP-4000	Gyros	FOG	2.360	9.000	2	3.000	1σ	0.067	0	N/A	Unk	N/A

L3	CIRUS	Gyros	FOG	15.400	40.000	3	0.000	1σ	0.100	0	N/A	Unk	N/A
LORD Sensing	3DM-CV5-10	IMU	MEMS	0.011	0.500	3	8.000	TBD	0.450	3	80	TBD	0.059
LORD Sensing	3DM-CX5-10	IMU	MEMS	0.008	0.300	3	8.000	TBD	0.300	3	40	TBD	0.015
LORD Sensing	3DM-GX5-10	IMU	MEMS	0.017	0.300	3	8.000	TBD	0.300	3	40	TBD	0.015
MEMSENSE	MS-IMU3020	IMU + magnetometer	MEMS	0.020	0.500	3	1.060	typ	0.220	3	14.8	typ	0.078
MEMSENSE	MS-IMU3025	IMU + magnetometer	MEMS	0.025	0.850	3	0.960	typ	0.150	3	3.7	typ	0.008
MEMSENSE	MS-IMU3030	IMU + magnetometer	MEMS	0.025	1.350	3	0.550	typ	0.114	3	3.7	typ	0.028
MEMSENSE	MS-IMU3050	IMU + magnetometer	MEMS	0.090	2.500	3	0.300	typ	0.065	3	2.6	typ	0.020
NewSpace Systems	Stellar Gyro	IRU	Image-based rotation estimate	0.100	0.200	3	N/A		N/A	0	N/A	Unk	N/A
Northrop Grumman	LN-200S	IMU	FOG, SiAc	0.750		3	1.000		0.070	3	Unk	Unk	Unk
Northrop Grumman	LN-200S	IMU	FOG	0.750	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk

Northrop Grumman	µFORS-3U	Gyro	FOG	0.150	2.300	1	0.050	1σ	0.080	0	N/A	Unk	N/A
Northrop Grumman	µFORS-6U	Gyro	FOG	0.150	2.300	1	0.050	1σ	0.047	0	N/A	Unk	N/A
Northrop Grumman	µFORS-36m	Gyro	FOG	0.137	2.500	1	18.000	1σ	1.000	0	N/A	Unk	N/A
Northrop Grumman	µFORS-1	Gyro	FOG	0.110	2.250	1	1.000	1σ	0.100	0	N/A	Unk	N/A
Northrop Grumman	µIMU-I-SP	IMU	MEMS	0.680	8.000	3	6.000	1σ	0.300	3	3000	rms	0.147
Northrop Grumman	µIMU-I-HP	IMU	MEMS	0.680	8.000	3	3.000	1σ	0.150	3	1500	rms	0.041
Northrop Grumman	µIMU-IC-SP	IMU	MEMS	0.680	8.000	3	6.000	1σ	0.300	3	3000	rms	0.147
Northrop Grumman	µIMU-IC-HP	IMU	MEMS	0.680	8.000	3	9.000	1σ	0.150	3	1500	rms	0.041
Northrop Grumman	µIMU-M-SP	IMU	MEMS	0.680	8.000	3	9.000	1σ	0.450	3	3000	rms	0.147

Northrop Grumman	µIMU-M-HP	IMU	MEMS	0.680	8.000	3	4.500	1σ	0.230	3	1500	rms	0.041
NovAtel	IMU-HG1900	IMU	MEMS	2.500	8.000	3	1.000	TBD	0.090	3	700	TBD	Unk
NovAtel	IMU-µIMU-IC	IMU	MEMS	2.570	11.000	3	6.000	TBD	0.300	3	3000	TBD	0.250
NovAtel	OEM-IMU-ADIS-16488	IMU	MEMS	0.048	3.600	3	6.000	TBD	0.300	3	1000	TBD	0.029
NovAtel	OEM-IMU-EG370N	IMU	MEMS	0.010	0.100	3	0.800	TBD	0.060	3	10	TBD	0.025
NovAtel	OEM-HG1900	IMU	MEMS	0.460	3.000	3	5.000	TBD	0.090	3	700	TBD	Unk
NovAtel	OEM-HG1930	IMU	MEMS	0.200	3.000	3	2.000	TBD	0.125	3	3000	TBD	Unk
NovAtel	OEM-IMU-HG4930P	IMU	MEMS	0.200	3.000	3	Unk	TBD	Unk	3	Unk	TBD	Unk
NovAtel	OEM-IMU-STIM300	IMU	MEMS	0.055	3.600	3	0.500	TBD	0.150	3	50	TBD	0.060
Sensonor	STIM202	IRU	MEMS	0.055	1.500	3	0.400	TBD	0.150	0	N/A	TBD	N/A
Sensonor	STIM210	IRU	MEMS	0.052	1.500	3	0.300	TBD	0.150	0	N/A	TBD	N/A

Sensonor	STIM300	IMU	MEMS	0.055	2.000	3	0.300	TBD	0.150	3	50	TBD	0.070
Sensonor	STIM318	IMU	MEMS	0.057	2.500	3	0.300	TBD	0.150	3	3	TBD	0.015
Sensonor	STIM277H	IRU	MEMS	0.052	1.500	3	0.300	TBD	0.150	0	N/A	TBD	N/A
Sensonor	STIM377H	IMU	MEMS	0.055	2.000	3	0.300	TBD	0.150	3	50	TBD	0.070
Sensonor	STIM308	IMU	MEMS	0.055	2.000	3	0.300	TBD	0.150	3	50	TBD	0.070
Silicon Sensing Systems	CRS02	Gyro	MEMS	0.025	Unk	1	Unk		Unk	0	N/A	TBD	N/A
Silicon Sensing Systems	CRS03	Gyro	MEMS	0.025	Unk	1	3.500	rms	0.100	0	N/A	TBD	N/A
Silicon Sensing Systems	SiRRS01-01	Gyro	MEMS	0.035	TBD	1	5.000	TBD	0.380	0	N/A	TBD	N/A
Surrey Satellite Technology	MIRAS-01	IRU	MEMS	2.800	Unk	3	10.000	TBD	0.600	0	N/A	Unk	N/A
Systron Donner	SDI50x-AE00	IMU	MEMS	0.590	5.000	3	1.000	1σ	0.020	3	100	1σ	0.059
Systron Donner	SDI50x-BE00	IMU	MEMS	0.590	5.000	3	1.500	1σ	0.020	3	200	1σ	0.059

Systron Donner	SDI50x-CE00	IMU	MEMS	0.590	5.000	3	2.000	1σ	0.020	3	200	1σ	0.071
Systron Donner	BEI GyroChip II	Gyro	MEMS	0.050	TBD	1	180.000	TBD	TBD	0	N/A	Unk	N/A
Systron Donner	BEI GyroChip	Gyro	MEMS	0.060	TBD	1	7.200	TBD	TBD	0	N/A	Unk	N/A
Thales	InterSense NavChip Series 3 Class A	IMU	MEMS	0.003	0.135	3	4.000	TBD	0.180	3	6	TBD	0.020
Thales	InterSense NavChip Series 3 Class B	IMU	MEMS	0.003	0.135	3	5.000	TBD	0.180	3	40	TBD	0.030
Thales	InterSense NavChip	IMU	MEMS	0.003	0.135	3	5.000	TBD	0.180	3	40	TBD	0.030
Thales	InterSense InertiaCube4	IRU	MEMS	0.011	TBD	3	TBD	TBD	TBD	0	N/A	Unk	N/A
VectorNav	VN-100	IMU + magnetometers +barometer	MEMS	0.015	0.220	3	10.000	max	0.210	3	40	max	0.082
VectorNav	VN-110	IMU + magnetometers	MEMS	0.125	2.500	3	1.000	max	0.054	3	10	max	0.024
Xsens Technologies	MTi-610	IMU	MEMS	0.009	0.530	3	8.000	TBD	0.420	3	10	TBD	0.035

5.2.10 GPS Receivers

For low-Earth orbit spacecraft, GPS receivers are now the primary method for performing orbit determination, replacing ground-based tracking methods. Onboard GPS receivers are now considered a mature technology for small spacecraft, and some examples are described in table 5-10. There is a new generation of chip-size COTS GPS solutions, for example the NovaTel OEM 719 board has replaced the ubiquitous OEMV1.

GPS accuracy is limited by propagation variance through the exosphere and the underlying precision of the civilian use C/A code (14). GPS units are controlled under the Export Administration Regulations (EAR) and must be licensed to remove COCOM limits (15).

However, past experiments have demonstrated the ability of using a weak GPS signal at GSO, and potentially soon to cislunar distances (16) (17). Development and testing in this fast-growing area of research and development may make onboard GPS receivers more commonly available in the near future.

Table 5-10. GPS Receivers for Small Spacecraft

Manufacturer	Model	Mass (kg)	Power (W)	Accuracy (m)	Radiation Tolerance (krad)	TRL
APL	EGNS	0.4	Unk	3	20	6
Eurotech	COM-1289	0.85	Unk	1.2	Unk	Unk
General Dynamics	Explorer	1.2	Unk	15	100	9
General Dynamics	Viceroy-4	1.1	Unk	5	100	9
Novatel	OEM615	0.021	1.6	1.5	Unk	9
SkyFox Labs	piNAV-NG	0.024	Unk	10	Unk	9
Surrey Satellite Technology	SGR-05U	0.04	0.8	10	5	9
Surrey Satellite Technology	SGR-05P	0.055	1	10	11	9
Surrey Satellite Technology	SGP-07	0.45	1.6	10	5	9
Surrey Satellite Technology	SGR-Ligo	0.09	0.5	5	5	5
Surrey Satellite Technology	SGR-10	0.95	5	10	10	9
GomSpace	GPS-kit	0.031	1.3	1.5	Unk	Unk

5.2.11 Deep Space Navigation

In deep space, navigation is performed using radio transponders in conjunction with the Deep Space Network (DSN). As of 2020, the only deep space transponder with flight heritage that is suitable for small spacecraft is the JPL-designed and General Dynamics-manufactured Small Deep Space Transponder (SDST). JPL has also designed IRIS V2, which is a deep space transponder that is more suitable for the CubeSat form factor. Table 5-11 details these two radios, and the SDST is illustrated in figure 5.6. IRIS V2, derived from the Low Mass Radio Science Transponder (LMRST), flew on the MarCO CubeSats and is scheduled to fly on INSPIRE (18).

Figure 5.76 General Dynamics SDST. Credit: General Dynamics.

Table 5-11. Deep Space Transponders for Small Spacecraft						
Manufacturer	**Model**	**Mass (kg)**	**Power (W)**	**Bands**	**Radiation Tolerance (krad)**	**TRL**
General Dynamics	SDST	3.2	19.5	X, Ka	50	9
JPL	IRIS V2.1	1.2	35	X, Ka, S, UHF	15	9

5.2.12 Atomic Clocks

Atomic clocks have been used on larger spacecraft in low-Earth orbit for several years now, however integrating them on small spacecraft is relatively new. The conventional method for spacecraft navigation is a two-way tracking system of ground-based antennas and atomic clocks. The time difference from a ground station sending a signal and the spacecraft receiving the response can be used to determine the spacecraft's location, velocity, and (using multiple signals) the flight path. This is not a very efficient process, as the spacecraft must wait for navigation commands from the ground station instead of making real-time decisions, and the ground station can only track one spacecraft at a time, as it must wait for the spacecraft to return a signal (19). In deep space navigation, the distances are much greater from the ground station to spacecraft, and the accuracy of the radio signals needs to be measured within a few nanoseconds.

JPL's Deep Space Atomic Clock (DSAC) project plans to launch a prototype of a miniaturized, low-mass (16 kg) atomic clock based on mercury-ion trap technology which underwent demonstration testing in the fall of 2017. The project aims to produce a <10 kg configuration in the second generation. The DSAC was launched in 2019 as a hosted payload on General Atomic's Orbital Test Bed spacecraft aboard the U.S. Air Force Space Technology Program (STP-2) mission (20), and has been extended for in-orbit demonstration through August 2021.

More designers of small spacecraft technology are developing their own version of atomic clocks and oscillators that are stable and properly synchronized for use in space. They are designed to fit small spacecraft, for missions that are power and volume limited or require multiple radios.

Table 5-12. Atomic Clocks and Oscillators for Small Spacecraft							
Manufacturer	**Model**	**Dimensions (mm)**	**Mass (kg)**	**Power (W)**	**Frequency Range**	**Rad Tolerance**	**TRL**
AccuBeat	Ultra Stable Oscillator	120 x 120 x 120	Unk	3.8 W	Unk	Unk	6
Bliley Technologies	Miniature Half-DIP Package Low Power OCXO	Up to 12 x 12 x 10	Unk	135 – 180 mW at steady state	10 MHz to 60 MHz	Unk	6
Bliley Technologies	Iris Series 1"x1" OCXO for LEO	19 x 11 x 19	Unk	1.5 W at steady state	10 MHz to 100 MHz	Unk	6
Microsemi	9635QT	33 x 33 x 33	Unk	Unk	Unk	Unk	6
Microsemi	Miniature Atomic Clock (MAC)	51 x 51 x 18	0.1	8	10 MHz	Unk	Unk
Microsemi	Space Chip Scale Atomic Clock (CSAC)	41 x 35 x 11	0.035	0.12	10 MHz	20	9

5.3 On the Horizon

Technological progress in the area of guidance, navigation, and control is slow. Given the high maturity of existing GNC components, future developments in GNC are mostly focused on incremental or evolutionary improvements, such as decreases in mass and power, and increases in longevity and/or accuracy. This is especially true for GNC components designed for deep space missions, where small spacecraft missions have only very recently been demonstrated. However, in a collaborative effort between the Swiss Federal Institute of Technology and Celeroton, there is progress being made on a high-speed magnetically levitated reaction wheel for small satellites (figure 5.7). The idea is to eliminate mechanical wear and stiction by using magnetic bearings rather than ball bearings. The reaction wheel implements a dual hetero/homopolar, slotless, self-bearing, permanent-magnet synchronous motor (PMSM). The fully active, Lorentz-type magnetic bearing consists of a heteropolar self-bearing motor that applies motor torque and radial forces on one side of the rotor's axis, and a homopolar machine that exerts axial and radial forces to allow active control of all six degrees of freedom.

Figure 5.7: High-speed magnetically levitated reaction wheel. Credit: Celeroton AG.

It is capable of storing 0.01 Nm of momentum at a maximum 30,000 rpm, applying a maximum torque of 0.01 Nm (21).

Another interesting approach to measuring angular velocity is the Stellar Gyro from NewSpace Systems. This sensor estimates angular rates from star images taken by a camera; one advantage of this approach is that it avoids the problem of gyro drift. Of course, such a sensor does require a clear view of the sky.

5.4 Summary

Small spacecraft GNC is a mature area, with many previously flown, high TRL components offered by several different vendors. Progress in developing integrated units will offer simple, single vendor, modular devices for ADCS, which will simplify GNC subsystem design. Other areas of GNC have potential for additional improvements as more research is being conducted. For example, a team at the University of Michigan is developing a multi-algorithmic hybrid ADCS system for CubeSats that can implement multiple estimation and control algorithms (22). Another team from Johns Hopkins University is conducting ground simulations of docking, charging, relative navigation, and deorbiting for a fully robotic CubeSat (23).

The rising popularity of SmallSats in general, and CubeSats in particular, means there is a high demand for components, and engineers are often faced with prohibitive prices. The Space Systems Design Studio at Cornell University is tackling this issue for GNC with their PAN nanosatellites. A paper by Choueiri et al. outlines an inexpensive and easy-to-assemble solution for keeping the ADSC system below $2,500 (25). Lowering the cost of components holds exciting implications for the future, and will likely lead to a burgeoning of the SmallSat industry.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

References

(1) Shepherd, L. C. G. and Shepherd, A. F. S. C.: *“Space Surveillance Network.”* Shared Space Situational Awareness Conference. Olorado Springs. 2006.

(2) Vallado, D A, et al.: *“Revisiting spacetrack report 3."* 2006.

(3) Thornton, C L and Border, J S: "*Radiometric Tracking Techniques For Deep-Space Navigation."* s.l. : John Wiley & Sons,, 2003.

(4) JPL. MarCO: Mission Overview. *CubeSat.* [Online] 2020. [https://www.jpl.nasa.gov/CubeSat/missions/marco.php.

(5) Wertz, J. R.: "*Spacecraft attitude determination and control."* Springer Science & Business Media. *Vol. 73.* 2012,

(6) Jin, J, Ko, S and Ryoo, C K: *“Fault Tolerant Control For Satellites With Four Reaction Wheels.”* vol. 16, no. 10, pp. 1250–1258. 2008.

(7) Kulczycki, R. and Wisniewski, P.: *“Slew Maneuver Control For Spacecraft Equipped With Star Camera And Reaction Wheels.”* Vol. 13, no. 3, pp. 349–356. 2005.

(8) Spratling, B. B. and Mortari, D.: *“A Survey On Star Identification Algorithms.”* Vol. 2, no. 1, pp. 93–107. 2009.

(9) Psiaki, M L, Martel, F and Pal, P K.: *“Three-Axis Attitude Determination Via Kalman Filtering Of Magnetometer Data.”* Vol. 13, no. 3, pp. 506–514. 1990.

(10) Wessels, J H.: "Infrared Horizon Sensor for CubeSat Implementation." *Masters Thesis, Stellenbosch University.* 03 2018.

(11) Pelemeshko, A, et al.: "*High-Precision Cubesat Sun Sensor Coupled With Infrared Earth Horizon Detector."* IOP Conf. Ser.: Mater. Sci. Eng. Vol. 734. pp. 0121-8. 2020,

(12) Greenheck, D, et al.: *"Design and Testing of a Low-Cost MEMS IMU Cluster for SmallSat Applications."* 2014. 28th Annual AIAA/USU Conference on Small Satellites.

(13) Merhav, S.: *Aerospace Sensor Systems and Applications.* Springer New York, 1998.

(14) Montenbruck, O. et al.: *"Precision Spacecraft Navigation Using A Low-Cost GPS Receiver."* Vol. 16, no. 4, pp. 519–529. 2014.

(15) *"Foreign Availability Determination Procedures And Criteria."* Office of the Federal Register. Title 15 Part 768.7. 2015.

(16) Jeffery Foust: "GPS in Space." *MIT Technology Review.* [Online] 01 2002. https://www.technologyreview.com/2002/01/01/275613/gps-in-space/.

(17) Adam Hadhazy: "Cosmic GPS." *Aerospace America.* [Online] 05 2020. https://aerospaceamerica.aiaa.org/features/cosmic-gps/.

(18) Aguirre, F. H.: *"X-Band Electronics For The INSPIRE Cubesat Deep Space Radio."* 2015. IEEE Aerospace Conference.

(19) Baird, D.: "NASA Tests Atomic Clock for Deep Space Navigation." [Online] 2018. https://www.jpl.nasa.gov/news/news.php?feature=7053.

(20) Cornwell, D.: "NASA's Deep Space Atomic Clock and Optical Communications Program for PNT Applications." [Online] 2016. [Cited: June 19, 2018.] https://www.gps.gov/governance/advisory/meetings/2016-12/cornwell.pdf.

(21) JW, Kolar, et al.: "*High-Speed Magnetically Levitated Reaction Wheels For Small Satellites."* Anacapri, Capri: 23rd International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2016), 2016.

(22) Lee, D Y, Kuevor, P. and Culter, J.: "Multi-algorithmic Hybrid Attitude Determination and Control System of the CubeSat 'CADRE'." [Online] 2016. https://digitalcommons.usu.edu/smallsat/2016/S2CDH/2/.

(23) Mishra, S., Basescu, M. and Kobilarov, M.: "Laboratory Validation of Vision Based Grasping, Guidance and Control with Two Nanosatellite Models." [Online] 2016. https://digitalcommons.usu.edu/smallsat/2016/S5GuidCont/6/.

(24) Gunter, B. C., et al.: "The Ranging and Nanosatellite Guidance Experiment (RANGE)." [Online] 2016. https://digitalcommons.usu.edu/smallsat/2016/S5GuidCont/3/.

(25) Choueiri, M N, Bell, M and Peck, M A.: "Cost-Effective and Readily Manufactured Attitude Determination and Control System for NanoSatellites." *AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech Forum.* 2018.

6.0 Structure, Mechanisms, and Materials

6.1 Introduction

Since the 2018 edition of this report, there have been expanded offerings for commercial-off-the-shelf (COTS) structures, and likewise an expansion of custom machined, composite, and even printed structures used, or proposed for use, on small spacecraft missions. This chapter refers to small spacecraft structures with a focus on 1U – 16U platforms. Specifically, those components designed to transmit loads through the spacecraft to the interface of the launch and deployment system. Such structures must also provide attachment points for payloads and associated components. These assemblies are typically classified as the primary structure. In contrast, secondary structures are all the other structures (like solar panels, thermal blankets etc.), that only need to be self-supporting. When a primary structure fails it is usually catastrophic. While failure of a secondary structure typically does not affect the integrity of the spacecraft, it can have a significant impact on the overall mission. These structural categories serve as a good reference, but can be hard to distinguish for small spacecraft that are particularly constrained by volume. This is especially true for CubeSats, as the capabilities of these spacecraft have expanded but the volume afforded by the standard dispensers (by definition) have not. Therefore, it is imperative that structural components be as volume-efficient as possible.

The primary structural components need to be multi-functional in order to achieve this volume efficiency. Such functions may include thermal management, radiation shielding, pressure containment, and even strain actuation. These are often assigned to secondary structural components in larger spacecraft.

Important to any discussion of small spacecraft structure is the selection of materials. Requirements for physical properties, such as density, thermal expansion, radiation resistance, and mechanical properties, such as modulus, strength, and toughness, must be satisfied. The manufacture of a typical structure involves both metallic and non-metallic materials, each offering advantages. Metals tend to be more homogeneous and isotropic, meaning properties are similar at every point and in every direction. Non-metals, such as composites, are inhomogeneous and anisotropic by design, meaning properties can be tailored to directional loads. In general, the choice is governed by the operating environment of the spacecraft, while ensuring adequate margin for launch and operational loading. Deliberations must include more specific issues, for example thermal balance and thermal stress management. Payload or instrument sensitivity to outgassing and thermal displacements must also be considered.

Structural design is not only affected by different subsystems and launch environments, but also the spacecraft application, for example there are different configurations for a spin-stabilized and 3-axis stabilized systems. Instrumentation also places requirements on the structure and can require mechanisms, such as a deployable boom to create enough distance between a magnetometer and the spacecraft to minimize structural effects on the measurement.

An overview of radiation effects and some mitigation strategies is also included in this chapter because radiation exposure can impact the structural design of small spacecraft. With the number of small spacecraft operating out of low-Earth orbit with increased radiation exposure, mission planners may also want to consider risk mitigation strategies associated with specific radiation environments. This includes both interplanetary missions, where solar radiation dominates, and polar low-Earth orbit (PLEO) missions, where solar radiation risk increases over the poles. In addition, as solar maximum approaches in 2025 (1) with an increased number of solar particle events (SPEs), mission planners will need to consider many orbital environments.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

6.2 State-of-the-Art

Two general approaches are common for primary structures in the small spacecraft market: COTS structures and custom machined or printed components. It is not surprising that most COTS offerings are for the CubeSat market. Often the COTS structures can simplify the development of a small spacecraft, but only as the complexity of the mission, subsystems, and payload requirements fall within the design intent of a particular COTS structure. The custom machined structures enable greater flexibility in mission specific system and payload design. The typical commercial structure has been designed for low-Earth orbit applications and limited mission durations, where shielding requirements are confined to radiation protection from the Van Allen Belts.

6.2.1 Primary Structures

There are now several companies that provide CubeSat primary structures (often called frames or chassis). Most are machined from aluminum alloy 6061 or 7075 and are designed with several mounting locations for components to allow flexibility in spacecraft configuration. This section highlights several approaches taken by various vendors in the CubeSat market. Of the offerings included in the survey, 1U, 3U and 6U frames are most prevalent, where a 1U is nominally a 10 x 10 x 10 cm structure. However, 12U frames are becoming more available. As there are now dispensers for the 12U CubeSat structure, there is an additional standard for CubeSat configurations. This trend has followed the development path of the 6U CubeSat structure, and the standard for the exact dimensional constraints of the spacecraft will be set once a 12U dispenser has been space-qualified.

Monocoque Construction

PUMPKIN, INC.

Figure 6.1: The 6U Supernova Structure Kit. Credit: Pumpkin, Inc.

In the structural monocoque approach taken by Pumpkin for their 1U – 3U spacecraft, loads are carried by the external skin in an attempt to maximize internal volume. Pumpkin, Inc. provides several COTS CubeSat structures intended as components of their CubeSat Kit solutions, ranging in size from sub-1U to the larger 6U – 12U SUPERNOVA structures (2). Pumpkin offerings are machined from Al 5052-H32 and can be either solid-wall or skeletonized.

Pumpkin has developed the SUPERNOVA, a 6U and 12U structure that features a machined aluminum modular architecture. The 6U structure (figure 6.1), is designed to integrate with the Planetary Systems Corporation (PSC) Canisterized Satellite Dispenser, and accommodates the PSC Separation Connector for power and data during integration (2).

AAC CLYDE SPACE CS CUBESAT STRUCTURE

AAC Clyde Space also offers a monocoque CubeSat structure from 1U – 3U. The 1U chassis has a total mass of 0.155 kg and dimensions of 100 x 100 x 113.5 mm. The 2U structure has a mass of 0.275 kg and dimensions of 100 x 100 x 227 mm. The 3U structure has a mass of 0.394 kg and dimensions of 100 x 100 x 340.5 mm. AAC Clyde Space standardized their components to make the spacecraft easier to reconfigure than other COTS structures, as both 1U and 3U structures interface with all standard deployment PODs, including NanoRacks (3). The 3U structure is seen in figure 6.2.

Figure 6.2: 3U CS Structure. Credit: AAC Clyde Space.

Modular Frame Designs

NANOAVIONICS MODULAR FRAME

NanoAvionics has developed what it calls “standardized frames and structural element” that, when assembled, form the primary structure for 1U to 12U spacecraft. The 1U, 2U and 3U form factors have masses from 0.090 kg, 0.172 kg, and 0.254 kg, respectively. A modular 3U structure from NanoAvionics is shown in figure 6.3. These components are intended to be modular, made from 7075 aluminum, and like many COTS CubeSat structures, compliant with the PC/104 form factor (4).

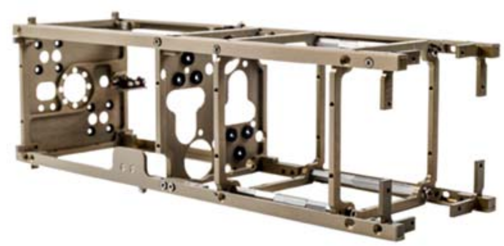


Figure 6.3: NanoAvionics Small Satellite Structures. Credit: NanoAvionics.

INNOVATIVE SOLUTIONS IN SPACE (ISIS)

ISIS offers a wide array of CubeSat structures, with the largest being a 16U structure. Several of their 1U, 2U, 3U and 6U structures have been flown in low-Earth orbit, see table 6-1 for more information on these structures.

Table 6-1: ISIS CubeSat Structures

Structure	Dimensions (mm)	Primary Structure Mass (kg)	Primary + Secondary Structure Mass (kg)	TRL Status in LEO environment
1U	100 x 100 x 114	0.1	0.2	9
2U	100 x 100 x 227	0.16	0.2	9
3U	100 x 100 x 341	0.24	0.3	9
6U	100 x 226 x 340.5	0.9	1.1	9
8U	226 x 226 x 227	1.3	1.9	6
12U	226.3 x 226 x 341	1.5	2.0	7
16U	226.3 x 226.3 x 454	1.75	2.25	6

Multiple mounting configurations can be considered to allow a high degree of creative flexibility with the ISIS design. Detachable shear panels allow for access to all of the spacecraft's electronics and avionics, even after final integration (5).

GOMSPACE

GomSpace provides full turn-key solutions for small satellite systems. They offer modular nanosatellite structures from 1 – 6U with strong flight heritage. The 6U (figure 6.4) has a 4U payload allocation, mass of 8 kg, and propulsive configuration capabilities. The 3U structure was first deployed from the International Space Station (ISS) in 2015, and two 6U systems were deployed in early 2018. The 7075 aluminum structure weighs 1.06 kg (6).

Figure 6.4: 6U nanosatellite structure. Credit: GomSpace.

ENDUROSAT

EnduroSat provides 1U, 1.5U, 3U, 6U CubeSat structures that range in dimension from 100 x 100 x 113.5 mm to 100 x 226.3 x 366 mm (1U – 6U). Material for all EnduroSat structures is made of Aluminum 6061-T651 (see table 6-2 for complete list). All of the listed structures have undergone environmental qualification including vibrational, thermal and TVAC testing while the 1U structure and 3U structure also have flight heritage.

Table 6-2: EnduroSat CubeSat Structures

Structure	Dimensions (mm)	Primary Structure Mass (kg)	Material	TRL Status
1U	100 x 100 x 114	< 0.1	Al 6061 or 7075	9
1.5U	100 x 100 x 170.2	0.11	Al 6061 or 7075	6
3U	100 x 100 x 340	< 0.29	Al 6061	9
6U	100 x 226 x 366	< 1	Al 6061	6

Card Slot System

COMPLEX SYSTEMS & SMALL SATELLITES (C3S)

C3S has developed a 3U CubeSat structure (figure 6.5) that uses a backplane PCB for bus communication, which provides independent assembly order, simplifies the stack-up tolerances, and uses space-grade interface connectors. These benefits include (8):

• High reliability electronic, structural and thermal connections
• Access to individual cards and units during integration and testing
•Simplified stack-up tolerances
• Dedicated and independent thermal interfaces for all cards

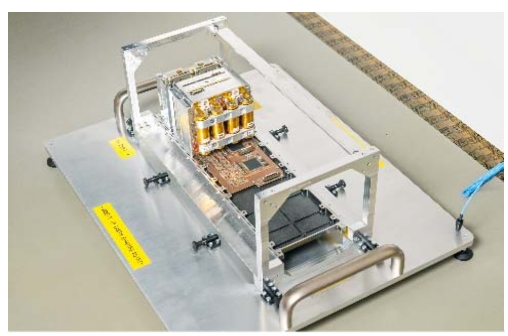


Figure 6.5: C3S 3U CubeSat Structure. Credit: Complex Systems & Small Satellites.

6.2.2 Custom Primary Structures

A growing development in building custom small satellites is the use of detailed interface requirement guidelines. These focus on payload designs with the understanding of rideshare safety considerations for mission readiness and deployment methods. Safety considerations include safety switches, such as the remove before flight pins and foot switch, and requirements that the spacecraft remain powered-off while stowed in the deployment dispensers. Other safety requirements often entail anodized aluminum rails and specific weight, center of gravity, and external dimensions for a successful canister or dispenser deployment. The required interface documents originate with the rideshare integrator for the specific dispenser being used with the launch vehicle. The launch vehicle provider typically provides the launch vibrational conditions. The NASA CubeSat Launch Initiative (CSLI) requires CubeSat or SmallSat systems be able to withstand the General Environmental Verification Standard (GEVS) vibration environment of approximately 10 Grms over a 2-minute period. The NASA CLSI rideshare provides electrical safety recommendations for spacecraft power-off requirements during launch and initial deployment. The detailed dispenser or canister dimensional requirements provide enough information, including CAD drawings in many cases, to enable a custom structural application. Table 6-3 is a sample of dispenser and canister companies that provide spacecraft physical and material requirements for integration.

Table 6-3: Spacecraft Physical Dimension and Weight Requirements from Deployers

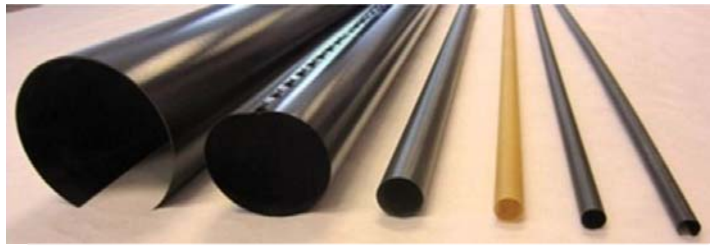
Manufacturer	U	Requirements	Available Documents
Tyvak Railpod III, 6U NLAS, 12U Deployer	3U, 6U, 12U	Dimensions, Weight, Rail	Interface Control Documentation
Planetary Sciences Corporation	3U, 6U, 12U	Dimensions, Weight, Tabs	Interface Guide, CAD Drawings
ISIPOD ISIS CubeSat Shop	1U, 2U, 3U, 4U, 6U, 8U, 12U, 16U	Dimensions, Weight, Rail	Follows CubeSat Standard

6.2.3 Mechanisms

There are several companies offering mechanisms for small spacecraft. Although not exhaustive, this section will highlight a few devices for release actuation, component pointing, and boom extension, which represent the state-of-the-art for the CubeSat market. Please refer to the Deorbit Systems chapter for deployable mechanisms used for deorbit devices.

CTD: Deployable Booms

Composite Technology Development (CTD) has developed a composite boom called the Stable Tubular Extendable Lock-Out Composite (STELOC), that is rolled up or folded for stowage and deploys using stored strain energy. The slit-tube boom, shown in figure 6.6 employs an innovative interlocking SlitLock™ edge feature along the tube slit that greatly enhances stability. The boom can be fabricated in many custom diameters and lengths, offers a small stowed volume, and has a near-zero coefficient of thermal expansion (CTE) (9). This technology has flown in low-Earth orbit.



AlSat-1N: AstroTube Deployable Boom

Oxford Space Systems collaborated with the Algerian Space Agency to develop the AstroTube deployable boom (figure 6.7) that was recently demonstrated in low-Earth orbit on a 3U CubeSat called AlSat-1N. It is the longest retractable boom that has been deployed and retracted on the 3U CubeSat platform. It incorporates a flexible, composite structure for the 1.5 m-long boom element, and a novel deployment mechanism for actuation. When retracted, the boom is housed within a 1U volume and has a total mass of 0.61 kg (10).

Figure 6.7: The flexible composite member that is employed on the AstroTube. Credit: Oxford Space Systems.

ROCCOR: Deployable Booms

ROCCOR has developed several different deployable booms that have a wide range of applications on small spacecraft. The Roll Out Composite (ROC) Boom can be deployed with antennas and instruments. This boom is 1 – 5 m in length and is made out of carbon fiber composite shells that use a passive spring to unroll the device.

The Triangle Rollable and Collapsible (TRAC) Boom, originally developed for AFRL, can be as long as 7 m. The CubeSat ROC Boom Deployer is awaiting a launch opportunity to reach TRL 7. This deployer has a volume of 1 x 1 x 1.5U, a length of up to 1.5 m, and a total mass of < 1 kg.

NASA: Deployable Composite Boom (DCB)

NASA Langley Research Center (LaRC) has developed DCBs through the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program and a joint effort with the German Aerospace Center. DCBs have high bending and torsional stiffness, packaging efficiency, thermal stability, and a low weight of less than 25% compared to metallic booms. The Advanced Composite Solar Sail project (ACS3) will demonstrate DCB technology for solar sailing applications. The DCB/ACS3 7 m boom technology is extensible to 16.5 m deployable boom lengths (figure 6.8).

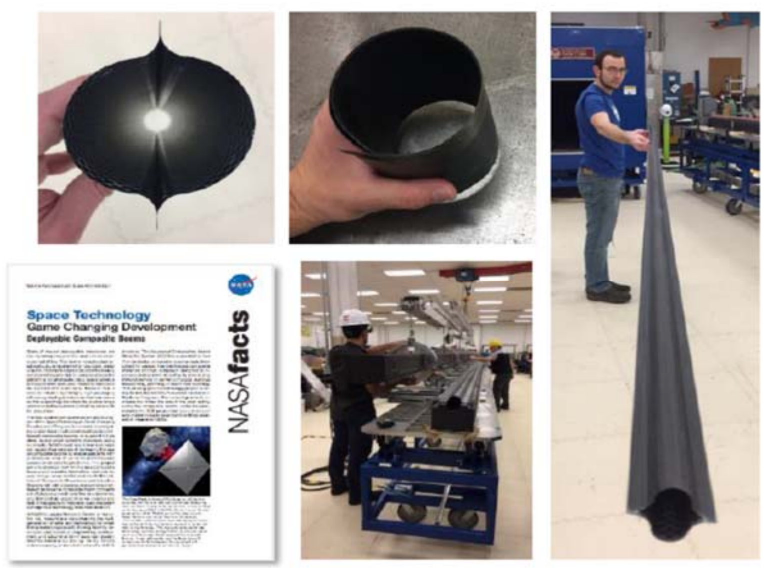


Figure 6.8: NASA Deployable Composite Boom (DCB) Technology. Credit: NASA.

RSat-P and RECS: Robotic Arms

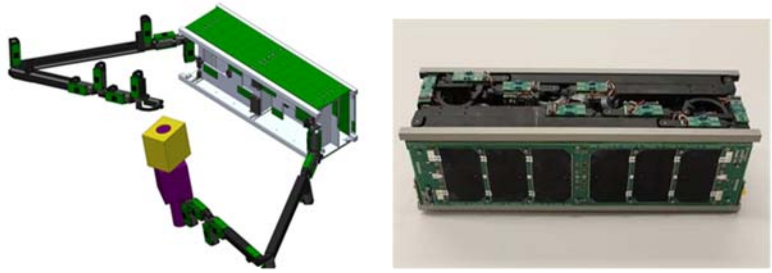


Figure 6.9: Robotic Experimental Construction Satellite (RECS). Credit: The Naval Academy.

Repair Satellite-Prototype (RSat-P) is a 3U CubeSat that is part of the Autonomous On-orbit Diagnostic System (AMODS) built by the US Naval Academy Satellite lab to demonstrate capabilities for in-orbit repair systems. RSat-P uses two 60 cm extendable robotic arms with the ability to maneuver around a satellite to provide images and other diagnostic information to a ground team. RSAT-P launched with the ELaNaXIX Mission in December 2018 and was lost during initial deployment. The robotic development has continued with the Naval Academy Satellite Team for Autonomous Robotics (NSTAR) Robotic Experimental Construction Satellite (RECS), a 3U CubeSat, which will demonstrate the robotic arm capabilities in the ISS microgravity environment in late 2021. The RECS robotic arms were built using 3D Windform print technology. Figure 6.9 shows the robotic arms from RSAT CubeSat heritage that are being developed further for RECS.

Tethers Unlimited, Inc.: 3 DOF Gimbal Mechanism

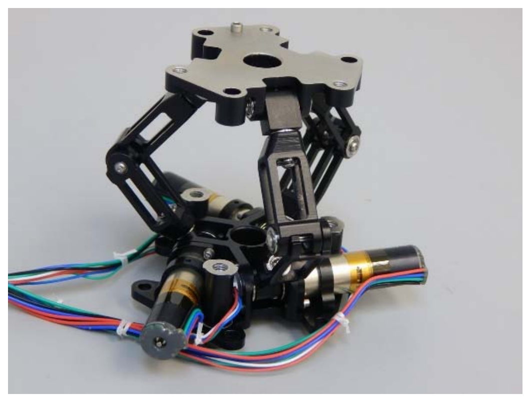


Figure 6.10: COBRA-HPX. Credit: Tethers Unlimited, Inc.

Tethers Unlimited offers a three degrees of freedom (3DOF) gimbal mechanism called the Compact On-Board Robotic Articulator (COBRA) that has two available configurations. A few of the varying specifications are found in table 6-4, and the HPX configuration is shown in figure 6.10. This mechanism provides accurate and continuous pointing for sensors and thrusters (11).

Five COBRA gimbals have been deployed on orbit over the past year, providing precision pointing for optical and high frequency RF satellite crosslinks on private small spacecraft missions.

Table 6-4: Tethers Unlimited COBRA Specifications

	COBRA-UHPX	COBRA-HPX
Mass (kg) (with launch locks)	0.491	0.276
Stowed diameter footprint (mm)	165	113
Deployed Height (excl. launch locks)	85.5	73.5
Operating Temperature Range (°C)	-35 to +70	-35 to +70
Power Consumption	Load Dependent	2.4 W
Payload Capacity	0.5 kg in 1G	1.2 kg in zero-G
Actuator	22 mm BLDC Motor	12 mm Stepper Motor
TRL in LEO	9	9

The KRAKEN robotic arm is modular, with high-dexterity (up to 7 DOF) and will enable CubeSats to perform challenging missions, such as in-orbit assembly, satellite servicing, and debris capture. The standard configuration is 1 m arm that can stow in a 190 x 270 x 360 mm volume and the mass is 5 kg (12). The TRL for this system is 5, assuming a low-Earth orbit environment.

The COBRA-Bee carpal-wrist mechanism for NASA'S Astrobee robot, a small, free-flying robot that assists astronauts aboard the ISS. The COBRA-Bee gimbal can enable Astrobee to precisely point and position sensors, grippers, and other tools (13). COBRA-Bee has the capability to provide this precise multi-purpose pointing and positioning capability in a small-scale, tightly integrated COTS product, with an interface to support third-party sensors, end-effectors, and tools.

Honeybee: Solar Panel Drive Actuator

Honeybee, in cooperation with MMA, has developed a CubeSat Solar Array Drive Actuator (SADA) that accommodates ±180° single-axis rotation for solar array pointing, can transfer 100 W of power from a pair of deployed panels, and features an auto sun-tracking capability (14). Honeybee also offers the unit in a slip-ring configuration for continuous rotation. Table 6-5 highlights a few key specifications for this actuator.

Table 6-5: Honeybee CubeSat SADA Specifications	
Mass (slip ring option)	0.18 kg
Backlash	< 3°
Operating Temperature Range (°C)	-30 to +85
Size	100 x 100 x 6.5 mm
Radiation Tolerance	10 kRad
Wire Wrap7 channels per wing	@ 1.4 A per channel
Slip Ring10 channels per wing	@ 0.5 A per channel
TRL in LEO	6

Ensign-Bickford Aerospace & Defense

EBAD’s TiNi product line has several field resettable release mechanisms available for the small spacecraft market, but perhaps the most relevant to the CubeSat market is the Frangibolt Actuator (particularly the FD04 mini-frangibolt model) and the ML50 Microlatch, due to their small size and power specifications.

The Frangibolt operates by applying power to a Copper-Aluminum-Nickel memory shape alloy cylinder which generates force to fracture a custom notched #4 fastener in tension. The Frangibolt is intended to be reusable by re-compressing the actuator using a custom tool and replacing the notched fastener (15), and It has operated in low-Earth orbit on pumpkin CubeSat buses. The

ML50 Micro Latch is designed to release loads up to 50 lbf (222.4 N) and capable of supporting forces up to 100 lbf (445 N) during maximum launch conditions. Standard interface uses a 4 – 40 thread to attach a bolt or stud to the releasable coupling nut. Field resetting of the device is done simply by ensuring no more power is being sent to the device, placing the coupler back on the device, and hand pressing until the coupler engages with the ball locks (16). Figure 6.11 shows a model of the FD04 Frangibolt actuator and a picture of the ML50 microlatch and table 6-6 describes a few key specifications of both mechanisms.

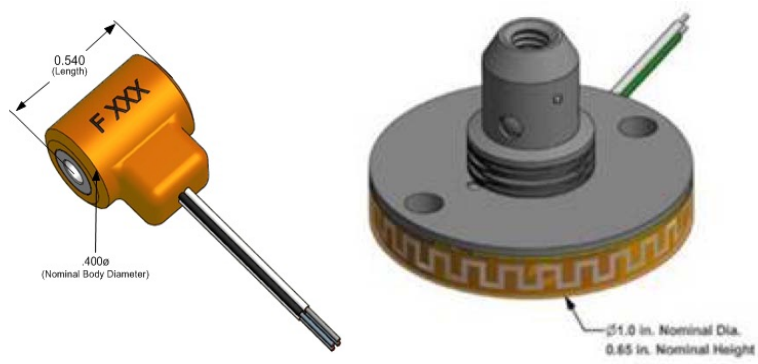


Figure 6.11: (left) TiNi Areospace Frangibolt Actuator and (right) ML50 microlatch. Credit: Ensign-Bickford Aerospace & Defense.

Table 6-6: Ensign-Bickford Aerospace & Defense Release Mechanisms			
TiNi FD04 Frangibolt Actuator		**ML50 Specifications**	
Mass (kg)	0.007	**Mass (kg)**	0.015
Power C	15 W @ 9 VD	**Power/Operational Current**	1.5 A to 3.75 A
Operating Temperature Range (°C)	-50 to +80	**Operating Temperature Range (°C)**	-50°C to +60
Size	13.72 x 10.16 mm	**Max Release Load**	222.4 N
Holding Capacity	667 N	**Max Torque**	106 N mm
Function Time Typically	20 sec @ 9 VDC	**Function Time Typically**	120 ms @ 1.75A (23°C)
Life	50 cycles MIN	**Life**	50 cycles MIN
TRL in LEO	9	**TRL in LEO**	6

6.2.4 Additive Manufacturing Materials

The use of additive manufacturing for spacecraft primary structures has long been proposed, but only recently has this process been adopted by flight missions. However, it is important to note that additive manufacturing has become common for small spacecraft secondary structural elements for many years. Typically, the advantage of additive manufacturing is to free the designer from constraints imposed by standard manufacturing processes, and allow for monolithic structural elements with complex geometry. In practice, additive manufacturing has its own set of geometric constraints, but when understood and respected, the designer can approach a design challenge with a larger tool set than has been available in the past.

Table 6-7: Accura Bluestone Specifications	
Density	1.78 g cm^{-3}
Color	Blue
Glass Transition (Tg)	78 – 81°C
Tensile Strength	66 – 68 MPa
Tensile Modulus	7600 – 11700 MPa
Flexural Strength	124 – 154 MPa
Outgassing, TML	low
TRL in LEO	6

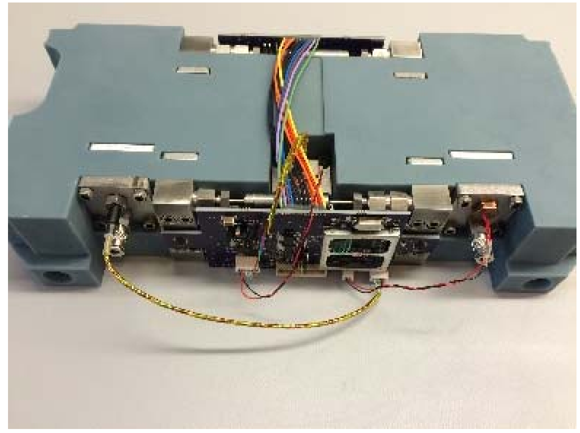


Figure 6.12: Illustration of the BioSentinel cold gas attitude control thruster. Credit: Lightsey et al. (2019).

Accura Bluestone

3D Systems Corporation has developed a stereolithographically fabricated composite material that shows promise for spacecraft structures. This material is currently being used as the main structural component for nozzles, tubing, and storage of the cold-gas propulsion system shown in figure 6.12, originally developed at the University of Texas Austin and now being developed for several missions at Georgia Institute of Technology. Table 6-7 shows a summary of material properties published by 3D Systems (17). The 3D printed attitude thruster designed for BioSentinel, a 6U interplanetary spacecraft that will be launched with Artemis I in 2021, is made from Accura Bluestone (18).

Windform Materials

CRP Technology is using selective laser sintering (SLS) technology for their carbon filled polyamide-based material, called Windform XT 2.0. The Windform material has been tested under VUV radiation exposure and did not show any signs of degradation (19). Table 6-8 shows a summary of material properties published by CRP Technology. TuPOD is a nanosatellite that was launched in September 2016 and was constructed by CRP USA using the Windform XT 2.0. The successful operation of TuPOD is exciting to the small satellite world because its innovative 3D structure is the only one of its kind.

Table 6-8: Windform XT2.0 Specifications	
Density	1.097 g cm^{-3}
Color	Black
Melting Point	179.3°C
Tensile Strength	83.84 MPa
Tensile Modulus	8928.20 MPa
Resistivity, Surface	< 10^8 Ohm
Outgassing, TML	0.53%
TRL in LEO	9

A new milestone in the PocketQube arena has been recently marked by using Windform XT 2.0 (figure 6.13). For the first time several 1P PocketQubes space-ready,

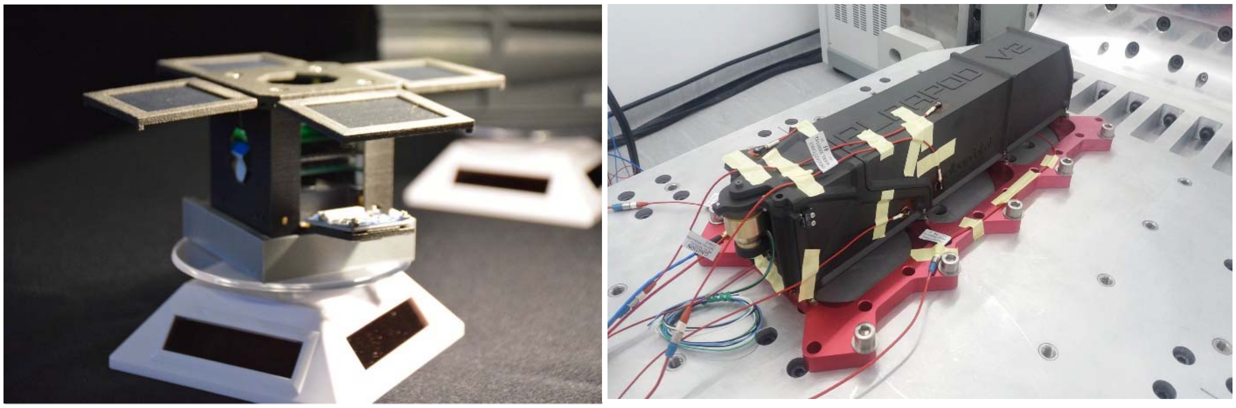


Figure 6.13: (left) Discovery 1P PocketQubes and (right) 3D printed AlbaPod 2.0 using Windform XT2.0. Credit: (left) Mini-Cubes and (right) Alba Orbital.

named Discovery, have been entirely 3D printed using this Carbon-reinforced composite material and Laser Sintering process (manufacturer: CRP USA). CRP Technology built an updated, orbit-ready version of a PocketQube satellite deployer, AlbaPod 2.0, using Windform XT 2.0.

Additive Manufacturing Facility (AMF)

In 2016, Made in Space introduced a permanent manufacturing facility, the Additive Manufacturing Facility (AMF) shown in the top image of figure 6.14, which provides hardware manufacturing services to NASA and the U.S. National Laboratory onboard the ISS. The AMF is the first commercially available manufacturing service in space, enabling several in-orbit manufacturing capabilities and providing research opportunities for terrestrial and space-based 3D printing applications, such as CubeSats (20). The MakerSat mission is a proof-of-concept that will use the AMF to demonstrate additive manufacturing in microgravity, by assembling and deploying a CubeSat from the ISS. MakerSat-0, launched in August 2018, operated for nine months in SSO low-Earth orbit to monitor characteristics of different plastics in the vacuum of space (21). This first flight was in preparation of MakerSat-1, a CubeSat that was manufactured entirely on the ISS see in the lower image in figure 6.14, and released into orbit February 2020. It has provided insights into the robustness of the 3D-printed components (22).

Figure 6.14: (top) Additive Manufacturing Facility onboard the ISS and (bottom) the MakerSat-1 CubeSat. Credit: Made in Space.

6.2.5 Radiation Effects and Mitigation Strategies

Shielding from the Space Environment

Radiation Shielding has been described as a cost-effective way of mitigating the risk of mission failure due to total ionizing dose (TID) and internal charging effects on electronic devices. In space mission analysis and design, the average historical cost for adding shielding to a mission is below 10% of the total cost of the spacecraft. The benefits include reducing the risk of early total ionizing dose electronics failures. Some of the key CubeSat and SmallSat commercial electronic semiconductor parts include processors, voltage regulators, and memory devices, which are key components in delivering of science and technology demonstration data.

Shielding the spacecraft is often the simplest method to reduce both a spacecraft's ratio of total ionizing dose to displacement damage dose (TID/DDD) accumulation, and the rate at which single events (SEEs) occur if used appropriately. Shielding involves two basic methods: shielding with the spacecraft's pre-existing mass (including the external skin or chassis, which exists in every case whether desired or not), and spot/sector shielding. This type of shielding, known as passive shielding, is only very effective against lower energy radiation, and is best used against high particle flux environments, including the densest portions of the Van Allen belts, the Jovian magnetosphere, and short-lived solar particle events. In some cases, increased shielding is more detrimental than if none was used, owing to the secondary particles generated by highly penetrating energetic particles. Therefore, it is important to analyze both the thickness and type of materials used to shield all critical parts of the spacecraft. Due to the strong omni-directionality of most forms of particle radiation, spacecraft need to be shielded from the full 4π steradian celestial sphere. This brings the notion of "shielding-per-unit-solid-angle" into the design space, where small holes or gaps in shielding are often only detrimental proportionally to the hole's solid angle as viewed by the concerned electrical, electronic and electro-mechanical (EEE) components. Essentially, completely enclosing critical components should not be considered a firm design constraint when other structural considerations exist.

Inherent Mass Shielding

Inherent mass shielding consists of using the entirety of the pre-existing spacecraft's mass to shield sensitive electronic components that are not heavily dependent on location within the spacecraft. This often includes the main spacecraft bus processors, power switches, etc. Again, the notion of "shielding-per-unit-solid-angle" is invoked here, where a component could be well shielded from its "backside" (2π steradian hemisphere) and weakly shielded from the "front" due to its location near the spacecraft surface. It would only then require additional shielding from its front to meet operational requirements. The classic method employed here is to increase the spacecraft's structural skin thickness to account for the additional shielding required. This is the classic method largely due to its simplicity, where merely a thicker extrusion of material is used for construction. The disadvantage to this method is the material used, very often aluminum, is mass optimized for structural and surface charging concerns and not for shielding either protons/ions or electrons. Recent research has gone into optimizing structural materials for both structural and shielding concerns, and is currently an active area of NASA's Small Business Innovation Research (SBIR) program research and development.

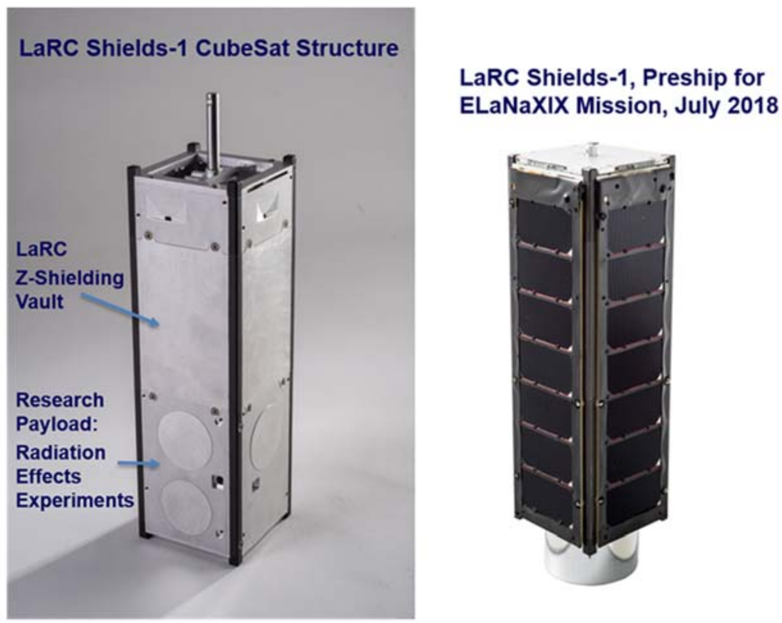
The process to determine exactly how much inherent shielding exists involves using a reverse ray tracing program on the spacecraft solid model from the specific point(s) of interest. After generating the "shielding-per-unit-solid-angle" map of the critical area(s) of the spacecraft, a trade study can be performed on what and where best to involve further additional shielding.

Numerous CubeSat and SmallSat systems use commercial, processors, radios, regulators, memory, and SD Cards. Many of these products rely on silicon diodes and metal oxide semiconductor field effect transistors (MOSFETS) in these missions. A comprehensive NASA guidance document on the use of commercial electronic parts was published for the ISS orbit, which is a low-Earth orbit where the predominant radiation source is the South Atlantic Anomaly. The hardness of commercial parts was noted as having a range from 2 – 10 kRad (45). For typical thin CubeSat shielding of 0.20 cm (0.080 in) aluminum, yearly trapped dose is 1383 Rad; with an additional estimated 750 Rad from solar particle events, the total dose increases to 2133 Rad for the ELaNaXIX Mission environment at 85 degrees inclination and 500 km circular orbit (table 6-

9). Adding a two-fold increase for the trapped belt radiation uncertainty brings the total radiation near the TID lifetime of many commercial parts, even before estimating a SPE TID contribution. The uncertainty of radiation model results of low-earth orbit below 840 km has been estimated as at least two-fold; Van Allen Belt models are empirical and rely on data in the orbital environment (27). The NASA Preferred Reliability Series, "Radiation Design Margin Requirements" also recommends a radiation design margin of 2 for reliability. Currently, the Aerospace Corporation proton (AP) and Aerospace Corporation electron (AE) Models do not have radiation data below 840 km, and radiation estimates are extrapolated for the lower orbits. For spacecraft interplanetary trajectories near the sun or Earth, the radiation contributions from SPEs will be higher than low-Earth orbit, where there is some limited SPE radiation protection by the Van Allen Belts. By reducing the total ionizing dose on commercial parts, the mission lifetimes can be increased by reducing the risk of electronic failures on sensitive semiconductor parts.

Shields-1 Mission, Radiation Shielding incorporated into CubeSat Structural Design

Shields-1 has operated in polar low-Earth orbit and was launched through the ELaNaXIX Mission in December 2018. The Shields-1 mission increased the development level of atomic number (Z) Grade Radiation Shielding with an electronic enclosure (vault) and Z-grade radiation shielding slabs with aluminum baselines experiments (figure 6.15). Preliminary results in table 6-9 show a significant reduction in total ionizing dose in comparison to typical modeled 0.20 cm (0.080 in) aluminum structures sold by commercial CubeSat providers. The 3.02 g cm^{-2} Z-Shielding vault has an over 18 times reduction in total ionizing dose compared to modeled 0.20 cm aluminum shielding.



Shields-1 structure and Final Preship Picture with LaRC Z-Shielding Vault and Experiment, Solar Panels and Thermal Radiator

Figure 6.15: Shields-1 Z-shielding structure and final Preship picture, ELaNaXIX Mission. Credit: NASA.

Z-shielding enables a low volume shielding solution for CubeSat and SmallSat applications where reduced volume is important. AlTiTa, Z–shielding, at 2.08 g cm^{-2} reduces the dose from a SPE by half when compared to a standard 0.2 cm aluminum structure (figure 6.16). NASA has innovated "Methods of Making Z-Shielding" with patents in preparing different structural shieldings, from metals to hybrid metal laminates and thin structural radiation shielding, to enable low-volume integrated solutions with CubeSats and SmallSats.

Table 6-9. Shields-1 Experimental Total Ionizing Dose Measurements in PLEO				
Shielding	**Areal Density (g/cm2)**	**Thickness (cm)**	**Trapped Belts TID Total (Rad (Si)/Year)**	**SPE King Sphere Model, (Rad (Si))**
Al	0.535	0.198	1383+/-47 #	750+/-5
Al	1.26	0.465	**90.9 +/-2.7 (SL)**	432 +/- 7
Al	1.69	0.624	**84.3 +/-2.5 (SL)**	345 +/- 9
Al	3.02	1.11	**73.6 +/-3.2 (SL)**	183 +/- 11
AlTi	1.33	0.378	**89.7 +/-2.7 (SL)**	451 +/- 6
AlTiTa20	2.08	0.429	**84.3 +/-2.5 (SL)**	338 +/- 6
AlTiTa40	3.02	0.483	**81.9 +/-3.4 (SL) 75.6+/-3.2 (Vault)**	253 +/- 6

Table 6-9. Shields-1 Experimental total ionizing dose measurements in PLEO in comparison to typical 0.20 cm aluminum shielding commercially available for CubeSats and SPE additional contributions to dose. ***Bold values*** *Shields-1 experimental results. SL = Slab, Vault = Z-Shielding electronics enclosure. # sphere Space Environment Information System (SPENVIS) Multi-layered Shielding Simulation Software (MULASSIS) AP8 Min AE8 Max modeled results. SPE King Sphere Model SPENVIS MULASSIS modeled results.*

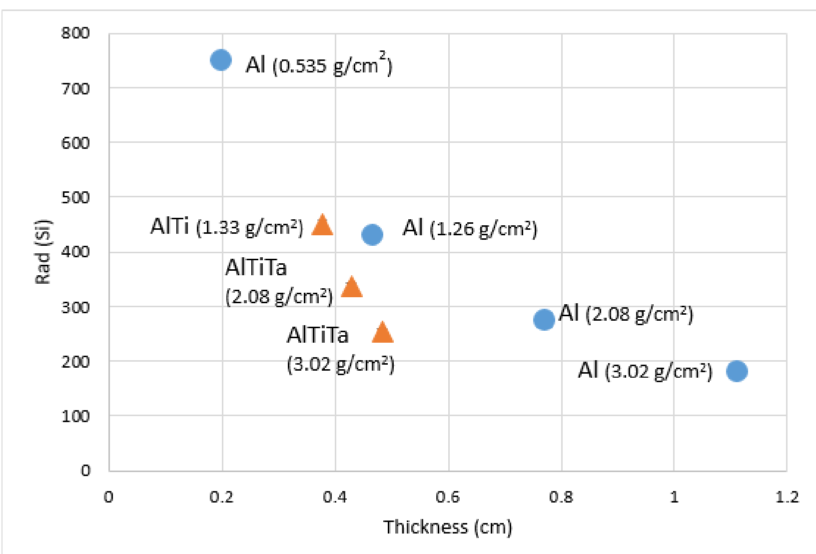


Figure 6.16: SPE Contribution to TID in PLEO, King Sphere Model, ELaNaXIX Shields-1 orbit. Credit: NASA.

Ad Hoc Shielding

There are two types of ad hoc shielding used on spacecraft: spot shielding, where a single board or component is covered in shield material (often conformally), and sector shielding, where only critical areas of the spacecraft have shielding enhancement. These two methods are often used in concert as necessary to further insulate particularly sensitive components without unnecessarily increasing the overall shield mass and/or volume. Ad hoc shielding is more efficient per unit mass than inherent mass shielding because it can be optimized for the spacecraft's intended radiation environment while loosening the structural constraints. The most recent methods include: multiple layer shields with layer-unique elemental atomic numbers which are layered advantageously (often in a low-high-low Z scheme), known as “graded-Z” shielding, and advanced low-Z polymer or composite mixtures doped with high-Z, metallic micro-particles. Low-Z elements are particularly capable at shielding protons and ions while generating little secondary radiation, where high Z elements scatter electrons and photons much more efficiently. Neutron shielding is a unique problem, where optimal shield materials often depend on the particle energies involved. Commercial options include most notably Tethers Unlimited’s VSRS system for small spacecraft, which was specifically designed to be manufactured under a 3D printed fused filament fabrication process for conformal coating applications (a method which optimizes volume and minimizes shield gaps).

Charge Dissipation Coating

The addition of conformal coatings over finished electronic boards is another method to mitigate electrostatic discharge on sensitive electronic environments. Arathane, polyurethane coating materials, and HumiSeal acrylic coatings have been used to mitigate discharge and provide limited moisture protection for electronic boards. This simple protective coating over sensitive electronic boards support mission assurance and safety efforts. Charge dissipation films have decreased electrical resistances in comparison to standard electronics and have been described by NASA as a coating that has volume resistivities between $10^8 – 10^{12}$ ohm-cm. In comparison, typical conformal coatings have volume resistivities from $10^{12} – 10^{15}$ ohm-cm.

LUNA Innovations, Inc. XP Charge Dissipation Coating

The XP Charge Dissipation Coating has volume resistivities in the range of $10^8 – 10^{12}$ ohm-cm (table 6-9) and is currently developing space heritage through the NASA MISSE 9 mission and Shields-1. The XP Charge Dissipation Coatings were developed through the NASA SBIR program from 2010 to present for extreme electron radiation environments, such as Outer Planets, medium Earth and geostationary orbits, to mitigate charging effects on electronic boards.

The LUNA XP Charge Dissipation Coating has reduced resistance compared to typical commercial conformal coatings as shown in table 6-10, which reduces surface charging risk on electronic boards. LUNA XP Coating (figure 6.17) on an electronic board has transparency for visual parts inspection. For extreme radiation environments a combination of radiation shielding and charge dissipation coating reduces the ionizing radiation that contributes to charging and provides a surface pathway for removing charge to ground.

Table 6-10: XP Charge Dissipation Coating and Commercial Conformal Coating Resistivity Comparisons

Material	Volume Resistivity (Ohm-cm)
XP Charge Dissipation Coating	$10^8 – 10^{12}$, 4.7 x 10^9 at 25°C
Arathane 5750 A/B	9.3 X 10^{15} at 25°C, 2.0 X 10^{13} at 95°C
Humiseal 1B73	5.5 x 10^{14} Ohms (Insulation Resistance per MIL-I-46058C)

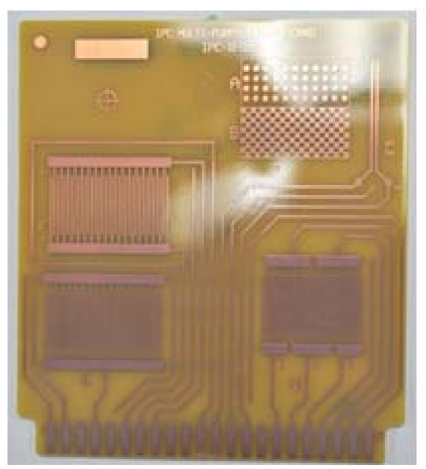


Figure 6.17: Transparent LUNA XP Charge Dissipation Coating on an Electronic Board. Credit: LUNA Innovations, Inc.

6.3 Summary

The Structures, Materials, and Mechanisms chapter has been revised to include custom structure references with the dimensional and material requirements of for integrating deployment systems. The chapter has been updated with current status of structures, materials, and mechanisms for small satellite missions. Mechanisms section has been updated with new technology. A radiation environment section has been revised with radiation shielding considerations for orbits and solar maximum with references for commercial parts and radiation design margin. State-of-the-art radiation shielding and charge dissipation materials have been updated.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

References

(1) Space Weather Prediction Center. Solar Cycle 25 Forecast Update. [Online] 12 19, 2019. https://www.swpc.noaa.gov/news/solar-cycle-25-forecast-update.

(2) Pumpkin Space Systems. CubeSat Kit Structures. *Pumpkin Space Systems.* [Online] 2017.

(3) AAC Clyde Space. CS 3U CubeSat Structure. *AAC Clyde Space.* [Online] 2018.

(4) NanoAvionics. NanoAvionics Structural Components. *NanoAvionics.* [Online] 2018.

(5) Innovative Solutions In Space. Flight proven platforms. [Online] 2020. https://www.isispace.nl/cubesat-platforms/.

(6) GomSpace. GomSpace's fourth Demonstration Mission is Successfully Launched – intended to Pioneer the Advanced. [Online] 2018. https://gomspace.com/news/gomspaces-fourth-demonstration-mission-is-suc.aspx.

(7) Endurosat. Cubesat-3u-structure. [Online] 2017. [Cited: July 15, 2018.] https://www.endurosat.com/products/cubesat-3u-structure/.

(8) Complex Systems & Small Satellites. C3S CubeSat Structure. *Complex Systems & Small Satellites - Datasheet.* [Online] 2018.

(9) Composite Technology Development. STELOC Composite Booms. *Composite Technology Development - Datasheet.* [Online] 2018.

(10) Reveles, J., et al:. "In-Orbit Performance of AstroTube: AlSat Nano's Low Mass Deployable Composite Boom Payload." 31st Annual AIAA/USU Conference of Small Satellites Logan, UT. 2017.

(11) Tethers Unlimited, Inc. Cobra Gimbal Datasheet. 2019.

(12) Tethers Unlimited. KRAKEN Robotic Arm. [Online] 2020. https://www.tethers.com/robotic-arm/.

(13) NASA. COBRA-Bee Carpal-Wrist Gimbal for Astrobee. [Online] February 2017. [Cited: July 18, 2018.] https://www.sbir.gov/sbirsearch/detail/1426639.

(14) Honeybee Robotics. CubeSat Solar Array Drive Assembly. *Honeybee Robotics.* [Online] 2018.

(15) Ensign-Bickford Aerospace & Defense. TiNi™ Mini Frangibolt® Actuator: Small, SImple, Powerful. [Online] 2020. https://www.ebad.com/tini-mini-frangibolt.

(16) 3D Systems Inc. Accura Bluestone Technical Data. *3D Systems Inc.* [Online] 2015.

(17) Stevenson, T. and Lightsey, G.: *"Design and Characterization of a 3D Printed Attitude Control Thruster for an Interplanetary 6U CubeSat.*" 30th Annual AIAA/USU Conference on Small Satellites, Logan, UT. 2016.

(18) CRP Technology. Vacuum Ultraviolet Light Exposure of Windform SP and Windform LX 3.0. *CRP Technology.* [Online] 2018.

(19) Made In Space. Additive Manufacturing Facility. *Made In Space.* [Online] 2018.

(20) Grim, B., et al.: "MakerSat: A CubeSat Designed for In-Space Assembly." 30th Annual AIAA/USU Conference on Small Satellites, Logan, UT. 2016.

(21) Made in Space. Satellite Parts 3D Printed On ISS Deployed in Functioning Satellite. [Online] 03 2020. https://madeinspace.us/blog/2020/03/02/satellite-parts-3d-printed-on-iss-deployed-in-functioning-satellite/.

(22) Ensign-Bickford Aerospace & Defense. Developed Specifically for “New Space” Applications. [Online] 2020. https://www.ebad.com/tini-micro-latch/.

(23) NASA. "MITIGATING IN-SPACE CHARGING EFFECTS —A GUIDELINE." October 19, 2017. https://ccmc.gsfc.nasa.gov/RoR_WWW/SWREDI/2018/nasa-hdbk-4002a_revalidated.pdf.

(24) Chase Corporation. "HumiSeal® 1B73 Acrylic Conformal Coating Technical Data Sheet." https://chasecorp.com/humiseal1/wp-content/uploads/sites/12/2018/10/1B73-TDS.pdf

(25) NASA. "Deployable Composite Booms (DCB)." January 30, 2020. https://gameon.nasa.gov/projects/deployable-composite-booms-dcb/

(26) Luna Inc. " Luna coating provides radiation protection in space." February 13, 2018. https://lunainc.com/blog/luna-coating-provides-radiation-protection-space

(27) Innovative Solutions in Space. "CubeSat Deployers -- Datasheet." 2020. https://www.cubesatshop.com/wp-content/uploads/2016/07/ISIS-CubeSat-deployers-Brochure-v2-compressed.pdf

(28) Planetary Systems Corporation. "Canisterized Satellite Dispenser." 2020. https://www.planetarysystemscorp.com/product/canisterized-satellite-dispenser/

(29) Knight, A. N., T.R. Tetterton, A.J. Engl, P.M. Sinkovitz, B.J. Ward, J.S. Kang, "Design and Development of On-orbit Servicing CubeSat-class Satellite", 34h AIAA/USU Conf. on Small Sat SSC20-V-01, 1-6 August 2020, Logan, UT.

(30) Langer, M and Boumeester. "Reliability of CubeSats – Statistical Data, Developers' Beliefs and the Way Forward", 30th Annual AIAA/USU Conference on Small Satellites, August 2016, Logan, UT, SSC16-X-2, 1-12.

(31) U.S. Patent No. 10,600,52212, 24 March 2020, "Method of Making Thin Atomic (Z) Grade Shields", D.L. Thomsen III.

(32) U.S. Patent No. 10,039,217, 31 July 2018, "Methods of Making Z-Shielding." D.L. Thomsen III, R.J. Cano, B.J. Jensen, S.J. Hales, and J.A. Alexa.

(33) U.S. Patent No. 8,661,653, 4 March 2014, "Methods of Making Z-Shielding." D.L. Thomsen III, R.J. Cano, B.J. Jensen, S.J. Hales, and J.A. Alexa.

(34) Vampola, A. L. "The Space Particle Environment", NASA/SDIO Space Environmental Effects on Materials Workshop, NASA Conference Proceedings 3035, part 2, NASA Langley Research Center, Hampton, VA June 28 – July 1, 1988, pg. 367.

(35) Wertz, J. R., W. J. Larson. "Space Mission Analysis and Design, Third Edition." Space Technology Library, Space Technology Series, Hawthorne, CA: Microcosm Press and New York: Springer, 1999, p.976.

(36) Vette, J. I., The AE-8 Trapped Electron Model Environment, NSSDC/WDC-A-R&S 91-24, 1991a.

(37) Vette, J. I., The NASA/National Space Science Data Center Trapped Radiation Environment Model Program (1964-1991), NSSDC/WDC-A-R&S 91-29, 1991b.

(38) Wenberg, D. L., B. P. Keegan, M. E. Lange, E. A. S. Hanlon, and J. S. Kang. 2016. "RSat Flight Qualification and Test Results for Manipulable Robotic Appendages Installed on 3U CubeSat Platform." 30th Annual AIAA/USU Conference on Small Satellites. Logan, UT.

(39) Thomsen, D.L., "Shields-1 Preliminary Radiation Shielding Dosimetry in Polar Low Earth Orbit", Committee on Space Research (COSPAR), Small Satellites for Sustainable Science and Development, Herzliya, Israel, 7 November 2019.

(40) Thomsen III, D.L., W. Kim, and J.W. Cutler. "Shields-1, A SmallSat Radiation Shielding Technology Demonstration", 29th AIAA/USU Conf. on Small Sat., SSC15-XII-9, August 2015.

(41) Sawyer, D. M., and J. I. Vette, AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum, NSSDC/WDC-A-R&S 76-06, 1976.

(42) NASA Preferred Reliability Series PD 1258, "Space Radiation Effects on Electronic Components in Low Earth Orbit", August 1996.

(43) NASA Preferred Reliability Series PD 1260, "Radiation Design Margin Requirement", May 1996.

(44) Hastings, D., H. Garrett, "Spacecraft Environment Interactions." New York, NY: Cambridge University Press, 1996, p.292.

(45) NASA PE 1258, "Space Radiation Effects on Electronic Components in Low-Earth Orbit

7.0 Thermal Control

7.1 Introduction

All spacecraft components have a range of allowable temperatures that must be maintained in order to meet survival and operational (function/performance) requirements during all mission phases. Temperatures are regulated throughout a spacecraft with passive and/or active thermal management techniques. Given the increased interest in small spacecraft over the last decade, "miniaturized" application of these thermal management methods were advanced to ensure adequate thermal control techniques are available for SmallSats.

While traditional thermal control techniques have been well demonstrated on large spacecraft, these existing techniques sometimes require additional development for application for small spacecraft applications. Application of these techniques/technologies to large-scale spacecraft is still considered state-of-the-art for the purposes of this review, but may be less than a Technology Readiness Level (TRL) value of 9 for small spacecraft applications. Typically, for small spacecraft form factors, thermal control challenges stem from four intrinsic properties of these spacecraft:

- low thermal mass
- limited external surface area
- limited volume
- limited power (for active control)

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that TRL designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

7.2 State-of-the-Art

7.2.1 Passive Systems

Passive thermal control requires no input power for thermal regulation of a spacecraft. This can be achieved using several methods and is highly advantageous to spacecraft designers, especially for the CubeSat form factor, as passive thermal control systems are associated with low cost, volume, weight, and risk, and due to their simplicity have been shown to be highly reliable. The integration of Multi-Layer Insulation (MLI), thermal coatings/surface finishes, heat pipes, sunshades, thermal straps and louvers are some examples of passive methods to achieve thermal control in a spacecraft.

Other "passive" methods include spacecraft design methodologies that help manage thermal loads. These can include structural and electrical design elements that help improve heat transfer via conduction, thereby reducing (or maintaining) component temperatures.

Examples of these include:

- thermally isolated structural joints where multiple washers with low thermal conductivity are stacked between fasteners and joined surfaces to limit heat transfer via conduction in specific places and;
- circuit board designs that include copper layers connected by vias that conduct heat away from electrical components through the boards to their connectors/structural connection points (using the thermal mass of the structural bus).

Table 7-1 is a list of the current state-of-the-art passive thermal techniques applicable for small spacecraft.

Table 7-1: Passive Thermal Systems		
Manufacturer	**Product**	**TRL in LEO Environments**
Sheldahl, Dunmore, Aerospace Fabrication and Materials	MLI Materials	9
AZ Technology, MAP, Astral Technology Unlimited, Inc., Dunmore Aerospace, AkzoNobel Aerospace Coatings, Parker-Lord	Paint	9
Sheldahl, Dunmore, Aerospace Fabrication and Materials	Selective Surface and Metallized Tape Coatings	9
Bergquist, Parker Chomerics, Aerospace Fabrication and Materials, AIM Products LLC	Thermal Gap Fillers and Conductive Gaskets	9
Sierra Lobo, Aerospace Fabrication and Materials	Sun Shields	4 – 7
Space Dynamics Laboratory, Thermal Management Technologies, Aavid Thermacore, Technology Applications, Inc., Thermotive Technology	Flexible Thermal Straps	7
Thermal Management Technologies, Active Space Technologies	Storage Units	7
NASA Goddard Space Flight Center	Thermal Louvers	7
Starsys	Thermal switches	7 – 9
Aerospace Fabrication and Materials, Thermal Management Technologies	Deployable Radiators	6
Aavid Thermacore, Inc. and Advanced Cooling Technology, Inc.	Passive Heat Pipes	7

Films, Coatings, and Thermal Insulation

In a vacuum, heat is transferred by two means: radiation and conduction. The internal environment of a fully enclosed small satellite is usually dominated by conductive heat transfer, while heat transfer to/from the outside environment is driven via thermal radiation. Thermal radiation heat transfer is controlled by using materials that have certain specific radiative properties, namely: solar absorptivity (implying wavelengths in the range of ~0.3 – 3 µm) and, IR (infrared) emissivity (~3 – 50 µm). Solar absorptivity governs how much of the incident solar flux a spacecraft absorbs, while IR emissivity determines how well a spacecraft emits its thermal energy to space, relative to a perfect blackbody emitter, and what fraction of thermal radiation from IR sources (e.g., the Earth, Moon) are absorbed by that spacecraft surface. These properties are optical surface properties of a material and can be modified by adding specialized coatings, surface finishes, or adhesive tapes with their own specific coatings.

One example, BioSentinel, a 6U spacecraft in development at NASA Ames Research Center (ARC) that is currently slated to be launched as a secondary payload on the Artemis I mission (2021), makes extensive use of metallized tape coatings and second-surface silvered FEP tapes from Sheldahl to control its external thermal radiative properties and overall energy balance (1).

Thermal insulation is used as a thermal radiation barrier from incoming solar or IR flux and/or to prevent undesired radiative heat dissipation. Commonly used to maintain temperature ranges for electronics and batteries in-orbit, or more recently, for biological payloads, thermal insulation is usually in the form of MLI blankets. However, the use of metallized tapes is also common for small spacecraft applications.

MLI is delicate and performance drops drastically if compressed (causing a thermally conductive “short circuit”), so it should be used with caution or avoided altogether on the exterior of small satellites that fit into a deployer (e.g., P-POD, NLAS). MLI blankets can also pose a potential snagging hazard in these tight-fitting, pusher-spring style deployers. Additionally, MLI blankets tend to drop efficiency as their size decreases and the specific way they are attached has a large impact on their performance.

Due to this, MLI generally does not perform as well for small spacecraft (more specifically CubeSat form factors) as on larger spacecraft. Surface coatings are typically less delicate and are more appropriate for the exterior of a small spacecraft that will be deployed from a dispenser. Lastly, internal MLI blankets that do not receive direct solar thermal radiation can often be replaced by a variety of low emissivity tapes or coatings that perform equally well in that context, using less volume and at a potentially lower cost. Second-surface silvered FEP tapes offer excellent performance as radiator coatings, reflecting incident solar energy while simultaneously emitting spacecraft thermal energy efficiently, but the tapes must be handled carefully to maintain optical properties and they don’t always bond well to curved surfaces.

Dunmore Aerospace Corporation has produced MLI blanket materials specifically for small spacecraft and have included them in their *Satkit*. *Satkit* provides Dunmore’s STARcrest MLI materials precut into the CubeSat form-factor (e.g. 1U). These MLI materials consist of DE330, DE076, DM116, and DM100 MLI films. These materials are constructed from previously flown MLI, but *Satkit* is TRL 6. Dunmore also offers polyimide film tape and MLI tape designed to insulate wires and cables on a SmallSat and is TRL 7.

The alteration of the solar absorptance and IR emittance of a surface material by applying matte paint is another passive method of thermal control. While black paint will absorb the majority of incident thermal radiation in the solar and IR spectrums, white paint limits how much heat is absorbed from the incident solar due to its low solar absorption/IR emittance ratio (2). Tape is another known useful thermal coating resource; it is easy to both apply and remove, is relatively inexpensive, and has a longer usable lifetime than paint (3).

AZ Technology, MAP, Astral Technology Unlimited, Inc., Parker-Lord, Inc., Sheldahl, and AkzoNobel Aerospace Coatings manufacture thermal coatings (paint and tape) for aerospace use that has been demonstrated on multiple small spacecraft missions. Most manufacturers have catalogs and/or guidebooks that provide detailed product information and application guidance (for example, Sheldahl provides “The Red Book,” see references for link) and greatly aid design selection. Some examples of small spacecraft using thermal coatings include Picard (150 kg) which used white SG12FD paint on the Sun pointing face. However, coatings/paints like Parker-Lord’s Aeroglaze 306/307 are expensive and require extensive and highly specialized processes to apply. Variations in that process can affect the thermal performance of the coating. For most small spacecraft projects to date, adhesive tapes (e.g., silver Teflon) or other standard surface finishes (e.g., polishing, anodize, alodine) have been the preferred choices.

Sunshields

The use of a sunshield, or sunshade, is common for spacecraft thermal control, although only recently has this been implemented on small spacecraft to improve thermal performance. Sierra Lobo developed a deployable sunshield that has flown on CryoCube-1, which was launched on Dragon CRS-19 in February 2020. In low-Earth orbit, this sunshield can support a multiple month-long duration lifetime and can provide temperatures below 100 K and below 30 K with additional active cooling (4). Figure 7.1 displays the design of the sunshield used on CryoCube-1.

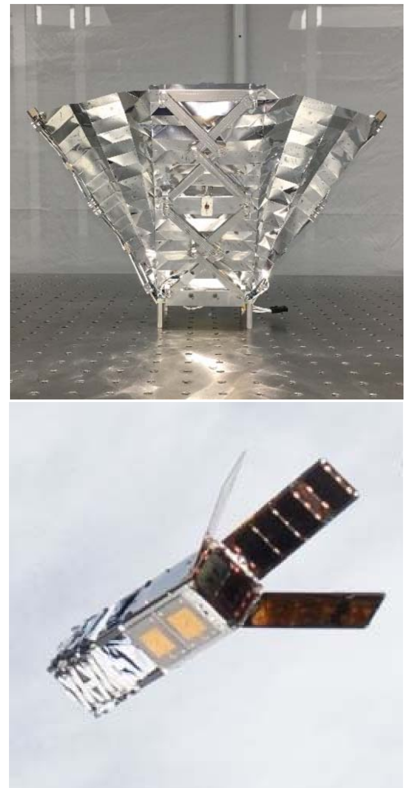


Figure 7.1: (top) Deployed Sunshield on CryoCube-1 and (bottom) CryoCube-1 in orbit with shield stowed. Credit: (top) Sierra Lobo and (bottom) NASA.

Thermal Straps – Passive

Recently, flexible thermal straps have become a convenient way to control temperature on small spacecraft, as the required mass for the strap is reduced and there is reduced stiffness between components. Flexible thermal straps can be used to allow for passive heat transfer to a thermal sink and can be customized to any particular length required.

Space Dynamics Laboratory (SDL) pioneered solderless flexible thermal straps that contain no solder, epoxy, or other filler materials to maximize thermal performance. With a strap fabrication process optimized for contamination control, SDL offers thermal straps made from aluminum foils (1145, 99.99% pure, and 99.999% pure), copper foils and braids (OFHC, ETP), and Pyrolytic Graphite Sheet (PGS). Straps with more than two end blocks and multiple material combinations have been produced, many having flight heritage on large spacecraft. Figure 7.2 shows a comparison of the as-tested conductance for the same strap geometry fabricated with three different foil materials. These results can be scaled for small

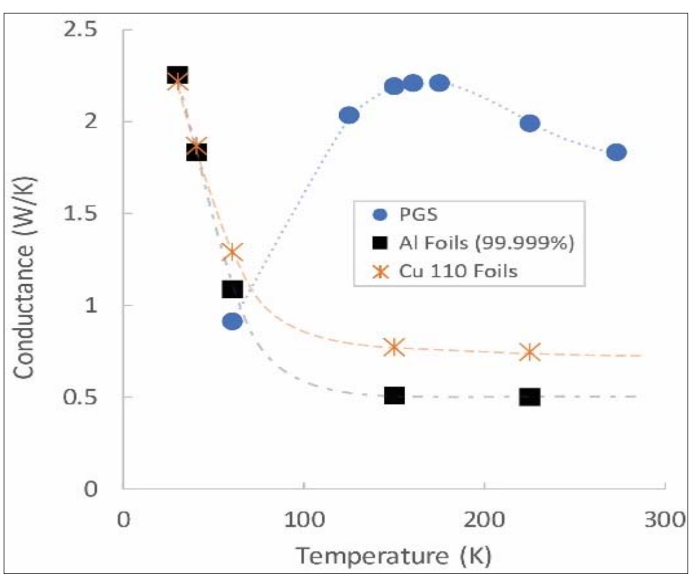


Figure 7.2: (right) A single thermal strap design with high purity aluminum foils, high purity copper foils, and PGS in aluminum end blocks and (left) their respective measured thermal conductance. The dashed lines connecting data points are based on material thermal conductivity curves. Credit: Space Dynamics Laboratory.

satellites to assist in material selection. SDL has supplied Utah State University with a PGS strap for the Active Thermal Architecture (ATA) project, a follow on to the ACCS project referenced in the cryocooler section.

Thermal Management Technologies has developed standard flexible thermal straps available in thin aluminum or copper foil layers or a copper braid (figure 7.3); custom accommodations can be fabricated and tested (5). The status for small spacecraft application is TRL 7.

Figure 7.3: Flexible Thermal Straps. Credit: Thermal Management Technologies.

Thermal straps are also being manufactured in materials other than the traditional aluminum and copper. Aavid Thermacore has designed lightweight thermal k-Core straps use k-Technology in solid conduction to supply a natural conductive path without including structural loads to the system. These have greater conduction efficiency compared to traditional aluminum straps (6), as the k-Core encapsulated graphite facilitates heat dissipation in high-power electronics. This technology has been fully designed and tested, and is TRL 5 for small spacecraft application.

Technology Applications, Inc. has specialized in testing and developing Graphite Fiber Thermal Straps (GFTS), with flight heritage on larger spacecraft missions (Orion and Spice). GFTS, shown in figure 7.4, are known to be extremely lightweight and highly efficient and thermally conductive with unmatched vibration attenuation (7). While this technology has not been demonstrated on a small spacecraft, the fittings can only be made so small and most of the straps fall into a very typical size range with the end fitting thickness at a minimum of 0.10 – 0.30 in, with a thinner flexible section.

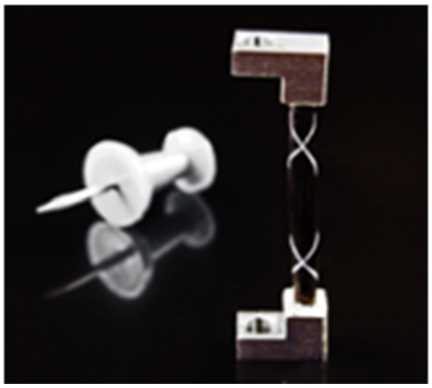


Figure 7.4: Graphite Fiber Thermal Straps (GFTS). Credit: Technology Applications, Inc.

Thermotive Technology developed the Two Arm Flexible Thermal Strap (TAFTS) that is currently flying on JPL's Portable Remote Imaging Spectrometer (PRISM) instrument. Space infrared cameras require extremely flexible direct cooling of mechanically-sensitive focal planes. The design of TAFTS uses three "swaged terminals and a twisted section" that allows for significant enhanced elastic movement and elastic displacements in three planes, while a more conventional strap of the same conductance offers less flexibility and asymmetrical elasticity (8). While infrared cameras have flown on small spacecraft missions, the TAFTS design has not been employed on a SmallSat.

The Pyrovo Pyrolytic Graphite Film (Pyrovo PGF) thermal straps offered at Thermotive have already flown in optical cooling applications for high altitude cameras and avionics on larger spacecraft. Pyrovo PGF straps use pyrolytic graphite wrapped in a HEPA filter-vented 4m thick aluminized mylar blanket, and have no exposed graphite. The specific thermal conductivity of this material has been shown to be 10x better than aluminum and 20x better than copper, as seen in figure 7.5 (9). These straps flew on JPL's ASTERIA CubeSat in 2017 and is planned to be used on the Mars 2020 rover mission.

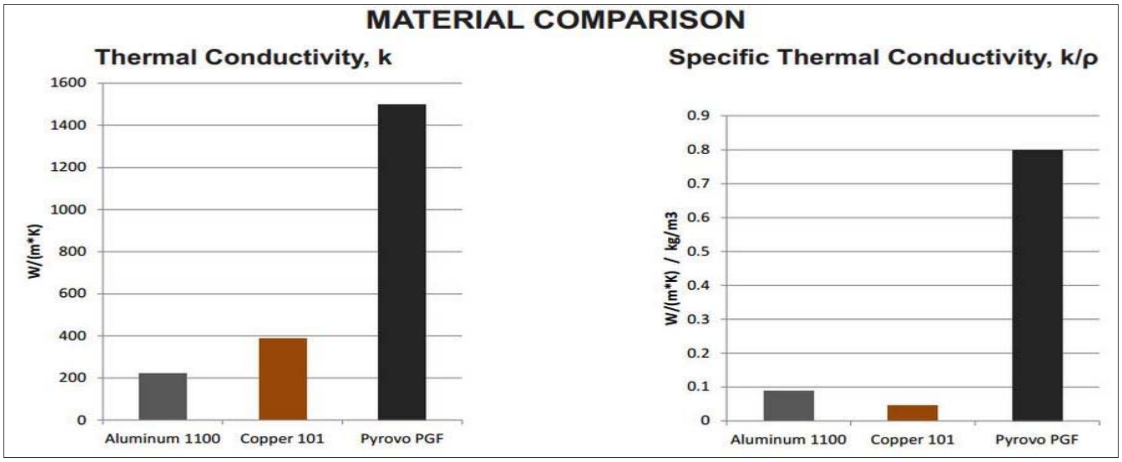


Figure 7.5: Pyrovo PGF Material Comparison. Credit: Thermotive Technology.

Thermal Louvers

Although commonly defined as active thermal control, here we consider louvers as a passive thermal control component because the designs considered do not require a power input from the spacecraft. Full-sized louvers for larger spacecraft have high efficacy for thermal control; however, their integration on small spacecraft has been challenging. Typical spacecraft louvers are associated with a larger mass and input power, which are both limited on small spacecraft. NASA Goddard Space Flight Center (GSFC) has developed a passive thermal louver that uses bimetallic springs to control the position of the flaps: when temperature of the spacecraft rises, the bimetallic properties of the springs create expansion, opening the louvers and modifying the average emissivity of the exterior surface. Similarly, when the spacecraft cools and the flaps close, the exterior surface returns to the previous emissivity (10). The louvers were developed for a 6U CubeSat, Dellingr, which was released from the NanoRacks CubeSat Deployer on the ISS into low-Earth orbit in late 2017 (11), and has a demonstrated thermal dissipation of 14 W. This louver design is illustrated in figure 7.6.

Figure 7.6: Passive Thermal Louver on 6U CubeSat Dellingr. Credit: NASA GSFC.

Deployable Radiators

Similar to thermal louvers, using deployable radiators on small spacecraft is challenging due to volumetric constraints. While paint has been widely used to create efficient radiator surfaces on larger spacecraft, the relatively limited available external surface area on SmallSats that already have body-mounted solar cells reduces the potential for creating dedicated radiative surfaces on SmallSats. For a system that requires a large amount of heat dissipation, a passive deployable radiator that is lightweight and simple in design would greatly enhance thermal performance by increasing the available radiative surface area. There has been steady development in this technology the last five years and the capability of a radiator design on a SmallSat has improved the TRL to 5.

Thermal Management Technologies has developed thermally efficient deployable radiators for small spacecraft that integrate an isothermal radiator surface with a high-conductance hinge for higher thermal efficiency. This radiator design employs a thermally conductive hinge that allows for minimal temperature gradients between the radiator and spacecraft, thus the radiator can operate near spacecraft temperatures, see figure 7.7 for radiator design. The radiating surface uses graphite composite material for mass reduction and increased stiffness, where the typical radiator uniformity is less than 0.1°C W^{-1} m^{-1}. This technology is currently in the development and testing phase (12).

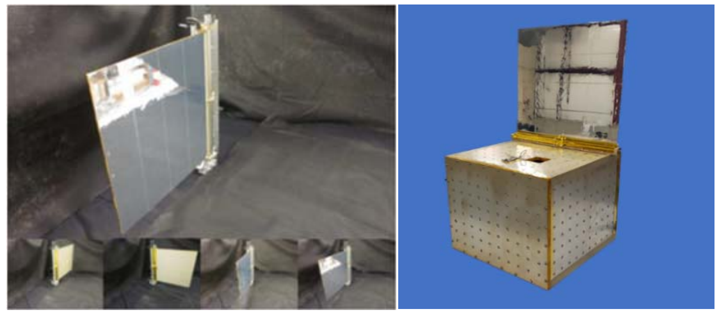


Figure 7.7: (left) 100W Deployable Radiator, and (right) Radiator shown on ESPA structure. Credit: Thermal Management Technologies.

The design of a flexible deployable radiator for small spacecraft was developed and tested by Shoya Ono, Hosei Nagano, and colleagues from Kaneka Corporation and JAXA in 2015. This design can deploy or stow the radiation area to control heat dissipation depending on environmental temperatures. It has an overall volume of 0.5 x 360 x 560 mm and 0.287 kg total mass. The fin is passively stowed and deployed by an actuator that consists of a shape memory alloy and bias spring. To increase radiator size and thermal conductivity, multiple layers of Kaneka Graphite Sheets (KGS) are used for the fin material. The rear surface of the fin is insulated with MLI to reduce the amount of heat dissipation under cold conditions. Deployment and stowage tests were conducted in a thermostatic chamber, and the thermal performance test was conducted under vacuum conditions, where it was shown that the half-scaled radiator dissipated 54 W at 60°C (13).

Thermotive is researching the Folding Elastic Thermal Surface (FETS), a deployable passive radiator for hosted payload instruments and CubeSats. Originally conceived as a thermal shield and cover for a passive cooler (cryogenic radiator) on JPL's MATMOS mission, this proposed concept is being modified as a deployable radiator for small spacecraft (14)

Deployable Solar Arrays

Deployable solar arrays may also provide a thermal design advantage as solar cells mounted away from the body of a small satellite allow for optimized surface coatings to provide improved thermal control as well as improved cooling of the array. A typical solar cell ε/α ratio may approach unity making heat rejection difficult in hot attitudes with direct or reflected solar flux incident upon the spacecraft. Also, deployed solar arrays would be able to radiate off a high emissivity/low solar absorptance backside for improved thermal management of the array.

Heat Pipes

Heat pipes are an efficient passive thermal transfer technology, where a closed-loop system transports excess heat via temperature gradients, typically from electrical devices to a colder surface, which is often either a radiator itself, or a heat sink that is thermally coupled to a radiator. Traditional heat pipes are cylindrical in shape, like those used on BIRD (92 kg), but there are also flat plates made of rectangular stainless steel tubing sandwiched between two aluminum plates and charged with a working fluid inside (15). SDS-4, a 50 kg small spacecraft, successfully incorporated this flat plate design developed at JAXA.

Roccor manufactures a conformable micro heat pipe thermal management solution based on proprietary “FlexCool” technology for small satellites that is a cross between a heat pipe and a thermal strap (16). The conformable micro heat pipe has flown on the TechEdSat 10, a 6U CubeSat deployed from the ISS.

Thermal Storage Units/Phase-Change Devices

Thermal storage units can be used in various applications for passively storing thermal energy for component protection or for future energy use. Thermal Management Technologies has developed a phase-changing thermal storage unit (TSU) that considers desired phase-change temperatures, interfaces, temperature stability, stored energy, and heat removal methodologies (figure 7.8). A complete fabrication of this device will allow the user to control temperature peaks, stable temperatures and/or energy storage. Active Space Technologies also has storage units under development that integrate online design support and high cryogenic enthalpy. The first storage units that flew in 2018 were developed at Thermal Management Technologies. For these systems on small spacecraft, the TRL is 7.

Figure 7.8: CubeSat Thermal Storage Unit. Credit: Thermal Management Technologies.

Phase-change thermal storage solutions are sometimes used to prevent or mitigate thermal run-away propagation within lithium-ion battery packs. The Kurl Technology Group (17) has developed a vaporizing thermal runaway shield with a thermal energy dissipation of 1.7 MJ kg^{-1} at 100°C.

Heat Switches

Heat (or thermal) switches are devices that can switch between being good thermal conductors or good thermal insulators as needed to control the temperature of heat producing components. The switch effectively provides either a high or low thermal coupling between a heat producing component and a low temperature sink as needed to maintain temperature of the component. Heat switches differ from thermostats in that they passively modulate a thermal coupling while thermostats modulate heater circuits (18). Typical heat switches may provide a conduction ratio of 10:1 with a technology goal of 100:1 (19). This technology is rated at TRL 7 – 9.

7.2.2 Active Systems

Active thermal control methods rely on input power for operation and have been shown to be more effective (20) in maintaining tighter temperature control for components with stricter temperature requirements or higher heat loads. Typical active thermal devices used on large-scale spacecraft include electrical resistance heaters, cryocoolers, and the use of thermoelectric coolers. Until spacecraft designers are able to miniaturize existing actively controlled thermal techniques and reduce either their power requirements or increase available spacecraft power, the use of active thermal systems in small spacecraft will be limited.

Small spacecraft designers are keen to use active thermal systems for temperature sensitive devices (such as batteries, cameras and electronics). In such cases where a complete passive system is not sufficient for thermal management, electrical resistance heaters, thermoelectric coolers, and cryocoolers are attached to specific equipment to maintain operational temperatures.

For the current state-of-the-art in active thermal technologies applicable on small spacecraft, see table 7-2.

Table 7-2: Active Thermal Systems		
Manufacturer	**Products**	**TRL in LEO Environment**
Minco Products, Inc., Birk Mfg., and All Flex Flexible Circuits, LLC., Fralock, Tayco Engineering, Inc.	Electrical Heaters	9
Ricor-USA, Inc., Creare, Sunpower Inc., Northrop Grumman, NASA Jet Propulsion Lab, and Lockheed Martin Space Systems Company	Mini Cryocoolers	6
Marlow, TE Technology, Inc.	Thermoelectric Coolers (TEC)	9

Heaters

On small spacecraft, electrical resistance heaters are typically used to maintain battery temperature during cold cycles of the orbit, and are controlled by a thermostat or temperature sensor. 1U CubeSats Compass-1, MASAT-1, and OUTFI-1 required an electrical heater attached to the battery in addition to passive control for the entire spacecraft system to maintain thermal regulation in eclipses (21). As biological payloads are becoming more common on small spacecraft, the biology have their own specified temperature requirements. NASA Ames Research Center (ARC) biological nanosats (GeneSat, PharmaSat, O/OREOS, SporeSat, EcAMSat, and BioSentinel) all use actively-controlled resistance heaters for precise temperature maintenance for their biological payloads, with closed-loop temperature feedback to maintain temperatures.

Cryocoolers

Cryocoolers are refrigeration devices designed to cool around 100K and below. A summary of cryocooler systems is given in figure 7.9 and a detailed review of the basic types of cryocoolers and their applications is given by Radebaugh (22). In figure 7.10, the first two systems (a) and (b) are recuperative cycles, and (c), (d), and (e) are regenerative cycles.

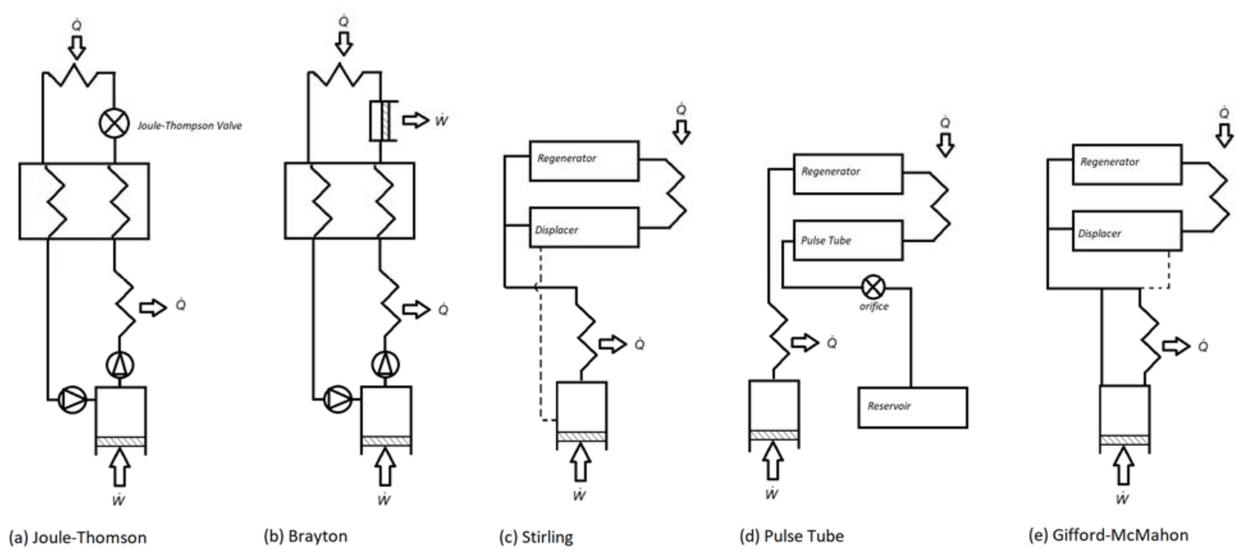


Figure 7.9: A comparison of cryocooler types. Credit: NASA.

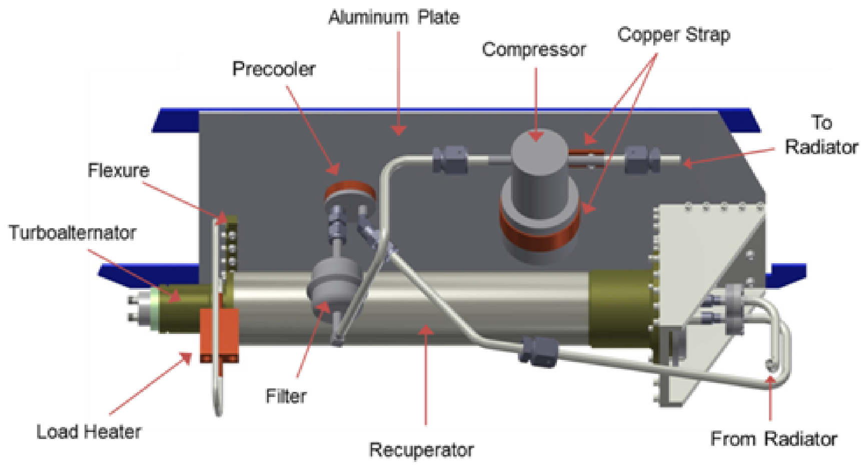


Figure 7.10: Configuration of primary mechanical UPL cryocooler components. Credit: Creare, Inc.

Cryocoolers are used on instruments or subsystems requiring cryogenic cooling, such as high precision IR sensors. The low temperature improves the dynamic range and extends the wavelength coverage. Further, the use of cryocoolers is associated with longer instrument lifetimes, low vibration, high thermodynamic efficiency, low mass, and supply cooling temperatures less than 50K (23). Instruments such as imaging spectrometers, interferometers and MWIR sensors require cryocoolers to function at extremely low temperatures.

Cryocooler – Miniaturized Examples

Creare developed an Ultra-Low Power (ULP) single-stage, turbo-Brayton cryocooler (figure 7.10) that operates between a cryogenic heat rejection temperature and the primary load temperature. The cryocooler includes a cryogenic compressor, a recuperative heat exchanger, and a turboalternator. The continuous flow nature of the cycle allows the cycle gas to be transported from the compressor outlet to a heat rejection radiator at the warm end of the cryocooler and from the turboalternator outlet to the object to be cooled at the cold end of the cryocooler (24). This cryocooler is designed to operate at cold end temperatures of 30 to 70K, with loads of up to 3 W, and heat rejection temperatures of up to 210K by changing only the charge pressure and turbo machine operating speeds. This technology has competed testing and fabrication and is TRL 6.

A unique type of cryocooler, a reverse turbo-Brayton cryocooler that produces negligible vibration, is also being developed by Creare. This technology uses a continuous flow of gas to transport heat from the active elements of the cryocooler to the objects to be cooled and to heat rejection surfaces.

Performance specifications of current units that have been demonstrated at TRL 5+ are:

- 7W at 70K (TRL 9)
- 5W at 65K
- 4W at 35K
- 300mW at 35K with a 150K heat rejection temperature
- 2W at 70K plus 20 W at 120K
- 300mW at 10K plus 2 W at 70K
- 20W at 90K.

Ricor-USA, Inc. developed the K562S, a rotary Sterling mini micro-cooler. It has a cooling capacity of 200 mW at 95 K and 300 mW at 110K. It has been used in several small gimbals designed for military applications. Ricor also developed K508N a Sterling ½ W micro cooler that has cooling capacity 500 mW at 77 K and 700 mW at 77K that is suitable for use on a small spacecraft. These coolers, shown in figure 7.11, are TRL 6 for small spacecraft applications.

Sunpower, Inc. developed the CryoTel DS1.5 Sterling Cryocooler featuring a dual-opposed-piston pressure wave generator and a separate cold head to minimize exported vibration and acoustic noise, and has a nominal heat lift of 1.4 W at 77K using 30 W power with a 1.2 kg mass (25). Sunpower also offers MT-F, a mini-cooler that has a nominal heat lift of 5 W at 77K, using 80 W power with a total mass of 2.1 kg. So far, these units (figure 7.12) have not been used in small spacecraft applications, but, given their size and performance, are candidates.

Figure 7.11: (left) K508N 1/2 W Micro Cooler, and (right) K562S Mini-cooler. Credit: Ricor-USA.

Figure 7.12: (left) CryoTel DS1.5 1.4 W Cryocooler and (right) CryoTel MT-F 5 W Cryocooler. Credit: Sunpower, Inc.

Northrop Grumman designed a Micro Pulse Tube cooler that is a split-configuration cooler that incorporates a coaxial coldhead connected via a transfer line to a vibrationally balanced linear compressor. This micro compressor has been scaled from a flight proven, high efficiency cooler (HEC) compressor although it has not operated on a SmallSat and the TRL is 6. The cooler has an operational range of 35 to 40K and a heat rejection temperature of 300K, using 80 W of input power, has 750 mW refrigeration at 40K, and a total mass of 7.4 kg (26).

Lockheed Martin Space Systems Company has engineered a pulse tube micro-cryocooler (figure 7.13), a simplified Sterling cryocooler, consisting of a compressor driving a coaxial pulse tube coldhead. The unit has a mass of 0.345 kg for the entire thermal mechanical unit, and is compact enough to be packaged in a ½U CubeSat (27). After qualification testing, the microcooler is at TRL 6 and is compatible with small spacecraft missions.

Figure 0.13: TRL6 Microcryocooler. Cryocooler Credit: Lockheed Martin Space Systems Company.

Thales Cryogenics has also developed a Linear Pulse Tube (LPT) cryocooler that has gone through extensive testing by JPL. The Thales LPT9510 cryocooler has an operating temperature range of -40 to 71°C, an input power of <85 W, and a total unit mass of 2.1 kg. The unit has no flight heritage but has undergone extensive testing and is TRL 6 (28).

Active Thermal Architecture – NASA Small Spacecraft Technology Program

The ATA project is an advanced design effort to develop active thermal control technologies for small satellites in support of future advanced missions in deep space, helio-physics, earth science, and communications. The ATA project is led by the Center for Space Engineering at Utah State University (CSE, USU) and funded by the NASA Small Satellite Technology (SST) Program in partnership with the JPL.

The ATA is a 1U two-stage active thermal control system targeted at 6U CubeSat form factors and above. The first stage consists of a Mechanically Pumped Fluid Loop (MPFL). A micro-pump circulates a working fluid between an internal integrated heat exchanger and a deployed tracking radiator. The second stage is a miniature tactical cryocooler, which directly provides cryogenic cooling to payload instrumentation. The conceptual operation of the ATA system is shown below in figure 7.14.

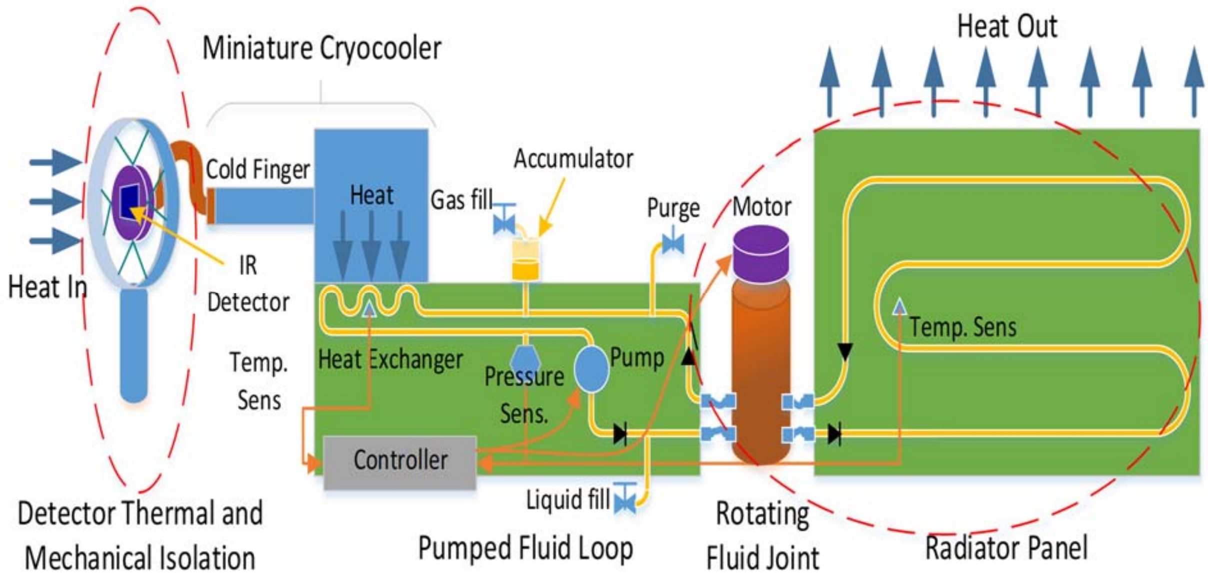


Figure 7.14: Conceptual operation of the ATA thermal control system. Credit: CSE/USU/ NASA/JPL.

Ultrasonic Additive Manufacturing techniques were used to simplify and miniaturize the ATA system by embedding the MPFL fluid channels directly into the integrated HX, CubeSat chassis, and the external radiator. The ATA system also features a dual rotary fluid union design, and an integrated geared micro-motor which allows for the two-stage deployment and solar tracking of the ATA radiator. As an active system the ATA also features passive vibration isolation and jitter cancellation technologies such as a floating wire-rope isolator design, particle damping, flexible PGS thermal links and a custom Kevlar isolated cryogenic electro-optical detector mount. Figure 7.15 shows some of the developed technologies as well as the ground-based prototype CubeSat. Ultimately, the ATA technology is suited for the thermal control of high-powered spacecraft subsystems or the general thermal maintenance of a CubeSat's environment.

7.3 On the Horizon

Traditional thermal control technologies cannot always be integrated immediately into small spacecraft platforms. Any technology, whether it is based on standard or novel methods has to address the issues created by a small spacecraft's lack of thermal mass, available surface area, internal volume, and power.

As mentioned in the introduction of this chapter, the technology that is demonstrated on larger spacecraft may need to be altered slightly to be compatible with small spacecraft, and will not automatically be assessed at TRL 9 for small spacecraft application. This section discusses some technologies being proposed and developed for small spacecraft thermal control that are not yet ready for space flight. However, small spacecraft have always provided a proving ground for technology development and a low-cost approach to test new technology for flight. Given this,

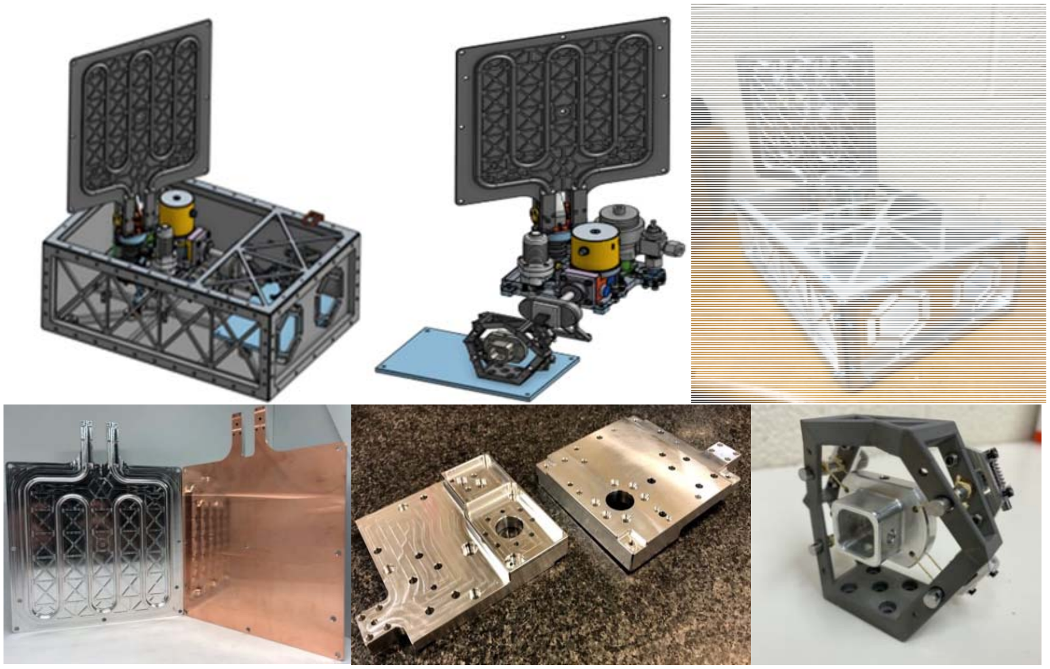


Figure 7.15: From top left: ATA CubeSat prototype, 1U ATA subsystem, ATA prototype, UAM radiator with copper backing, UAM heat exchanger, Kevlar isolated Cryogenic Electro-optical prototype mount. Credit: CSE/USU/NASA/JPL.

creative solutions should be encouraged whether they are based on existing technologies or truly something "new under the sun."

7.3.1 Fluid Loops

A pumped fluid loop is capable of achieving heat transfer between multiple locations via forced fluid convective cooling. Mechanically pumped fluid loops are not of interest to small spacecraft engineers as they are associated with high power consumption and mass. Lockheed Martin Corporation is developing a circulator pump for a closed cycle Joule Thomson cryocooler (figure 7.16). With an overall mass of 0.2 kg, it can circulate gas as part of a single-phase or two-phase thermal management system using 1.2 W of electrical power and can manage around 40 W of spacecraft power as a single-phase loop, or several hundred Watts of spacecraft power as part of a 2-phase loop (29). The compressor went through applicable testing with a compression efficiency of 20 – 30% in a 2016 study (30). This design is TRL 4.

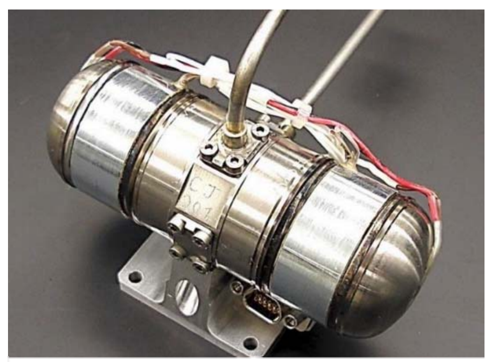


Figure 7.16: JT Compressor. Credit: Lockheed Martin Corporation.

7.3.1 Multi-functional Thermal Structures

A newer development in passive thermal control for small spacecraft are multi-functional thermal structures. These integrate thermal control capabilities directly into the structure. This is particularly advantageous for small spacecraft due to strict mass and volume constraints. Currently, Thermal Management Technologies has developed such systems that incorporate heat-spreading technologies that improve the ability to radiate waste heat. They incorporate features such as low mass, high stiffness/strength, and integrated heat pipes. Thermal Management Technologies currently has designs for 6U, 12U, ½ ESPA and Aerospace proposed Launch-U sized structures (figure 7.17), with custom sizes available. This new technology is at TRL 4.

Figure 7.17: ½ ESPA structure with IR image during evaluation; 12U structure Credit: Thermal Management Technologies.

7.4 Summary

As thermal management on small spacecraft is limited by mass, surface area, volume and power constraints, traditional passive technologies, such as MLI, paints/coatings/surface thermal finishes, and metallic thermal straps, still dominate thermal design. Active technologies, such as thin flexible resistance heaters have also seen significant use in small spacecraft, including some with advanced closed-loop control. Technologies that have to date only been integrated on larger spacecraft are being designed, evaluated, and tested for small spacecraft. Passive louvers that have successfully flown on 6U Dillengr are paving the way for thermal deployable components, while deployable radiators and various types of composite thermal straps are still undergoing testing for small spacecraft.

Technology in active thermal control systems has started expanding to accommodate volume and power restrictions of a smaller spacecraft; cryocoolers are being designed to fit within 0.5U volume that will allow small spacecraft to use optical sensors and imaging spectrometers. Thermal storage units are being developed that will better control heat dissipation, in addition to storing energy for future use.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email.

References

(1) Benton, Josh. *Personal Correpsondence*. 2018.

(2) A. Anvari, F. Farhani, and K. S. Niaki: "*Comparative Study on Space Qualified Paints Used for Thermal Control of a Small Satellite."* 2009.

(3) Soulage, M. *Personal Correspondence.* 2013.

(4) Sierra Lobo. *CryoCube-1.* 2014.

(5) Thermal Management Technologies. *Flexible Thermal Straps.* 2015.

(6) Thermacore. *Thermal Straps: Efficient Cooling without Structural Loading.* 2015.

(7) Technology Applications Inc. *Graphite Fiber Thermal Straps (GFTS).* 2015.

(8) E. Urquiza, C. Vasquez, J. Rodriguez, and B. V. Gorp: "*Development And Testing Of An Innovative Two-Arm Focal-Plane Thermal Strap (TAFTS)".* 2012.

(9) Thermotive. Products. [Online] 2014.

(10) NASA Goddard Space Flight Center. *Dellingr.* 2014.

(11) NASA. NASA Begins Checkout of Dellingr Spacecraft Designed to Improve Robustness of CubeSat Platforms. [Online] November 2017.

(12) Thermal Management Technologies. *Thermally Efficient Deployable Radiators.* 2020.

(13) Ono, S, et al.: "*Thermophysical Properties of a High-thermal-conductive Graphite Sheet and Application to a Deployable/Stowable Radiator."* 43rd International Conference on Environmental Systems. Vail. 2013.

(14) Urquiza, Eugenio, et al.: "Folding Elastic Thermal Surface — FETS. *Tech Briefs.* [Online] 07 2013. https://www.techbriefs.com/component/content/article/tb/pub/techbriefs/mechanics-and-machinery/16598.

(15) Nakamura, Y.: "*Small Demonstration Satellite-4 (SDS-4): Development, Flgith Results, and Lessons Learned in JAXA's Microsatellite Project."* 2013.

(16) ROCCOR. Engineering impactful solutions for thermal management systems. *Thermal Products.* [Online] 2020. https://www.roccor.com/thermal_products/.

(17) Kurl Technology. Hydra Absorbs Heat And Shields Battery Pack Cells From Entering Into Thermal Runaway Propagation. *Kurl Technology, Hydra Thermal Run Away Shield.* [Online] 2020. https://kulrtechnology.com/hydra-thermal-runaway-shield/.

(18) Gilmore, David. *Spacecraft Thermal Control Handbook, Volume I, Fundamental Technologies, Chapter 10: Heat Switches.* 2002.

(19) NASA. NASA Technology Roadmaps TA14: Thermal Management Systems, July 2015. [Online] 2015. https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_14_thermal_management_final.pdf.

(20) Hogstrom, K.: "*State-of-the-Art Thermal Analysis Methods and Validations for Small Spacecraft."* 2013.

(21) D. Hengeveld, J. Braun, E. Groll, and A. Williams: "*Review of Modern Spacecraft Thermal Control Technologies and Their Application to Next-Generation Buildings."* 2010.

(22) *Refrigeration for superconductors.* Radebaugh. 2004, IEEE, pp. 1719 - 1734 .

(23) R. Hon, C. Kesler, and D. Sigurdson: "*Integrated Testing of a Complete Low Cost Space Cryocooler System."* 2009.

(24) M. V. Zagarola, R. W. Hill, J. R. Gagne, and R. W. Kaszeta: "*Ultra Low Power Cryo-Refrigerator for Space Applications."* 2012.

(25) Sunpower Inc. *CryoTel® DS 1.5 - Datasheet.* 2015.

(26) D. Durand, E. Tward, G. Toma, and T. Nguyen: "*Efficient High Capacity Space Microcooler."* 2014.

(27) Nast, J. Olson and T. *Lockheed Martin Microcryocooler.* 2013.

(28) Thales Cryogenics. *LPT9510 1400 mW / 18 mm slip-on.* 2018.

(29) Champagne, P.: "*Development of a J-T Micro Compressor."* 2015.

(30) Thermal Management Technologies. *Isothermal, compact, energy dense phasechange thermal storage units for thermal management.* 2015.

(31) Sheldahl. "The Red Book". [Online] 2020. https://www.sheldahl.com/sites/default/files/2020-02/RedBook_0.pdf.

8.0 Command and Data Handling

8.1 Introduction

Current trends in small spacecraft Command and Data Handling (C&DH) appear to be following those of previous, larger scale C&DH subsystems. The current generation of microprocessors can easily handle the processing requirements of most C&DH subsystems, and will likely be sufficient for use in spacecraft bus designs for the foreseeable future. Cost is likely a primary factor for selecting a C&DH subsystem design from a given manufacturer. The ability to spread non-recurring engineering costs over multiple missions, and to reduce software development through reuse, are desirable factors in a competitive market. Heritage designs are desirable for customers looking to select components with proven reliability for their mission. As small satellites move from the early CubeSat designs with short-term mission lifetimes to potentially longer missions, radiation tolerance also comes into play when selecting parts. These distinguishing features, spaceflight heritage and radiation tolerance, are the primary differentiators in the parts selection process for long-term missions verses those which rely heavily on commercial-off-the-shelf (COTS) parts. Experimental missions typically focused on low-cost, easy-to-develop systems that take advantage of open source software and hardware to provide an easy entry into space systems development, especially for hobbyists or those who lack specific spacecraft expertise.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

8.2 State-of-the-Art

Since the publication of the earlier editions of this report, several CubeSats using COTS components and integrated systems have successfully flown in the low-Earth orbit environment with short mission durations of typically less than one year. However, significant differences in mission requirements between short-term experimental missions and long-term high reliability missions can impact how state-of-the-art is perceived for flight units. As spacecraft manufacturers begin to use more space qualified parts, they find that those devices lag their COTS counterparts by several generations in performance, but may be the only means to meet the radiation requirements placed on the system.

A variety of C&DH developments for CubeSats have occurred due to in-house development, new companies that specialize in CubeSat avionics, and the use of parts from established companies who provide spacecraft avionics for the space industry in general. Presently there are a number of commercial vendors who offer highly integrated systems that contain the on-board computer, memory, electrical power system (EPS), and the ability to support a variety of Input & Output (I/O) for the CubeSat class of small spacecraft.

While parallel developments are impacting the growth of CubeSats, vendors with ties to the more traditional spacecraft bus market are increasing C&DH processing capabilities within their product lines. In-house designs for C&DH units are being developed by some spacecraft bus vendors to better accommodate small vehicle concepts. While these items generally exceed CubeSat form factors in size, they can achieve similar environmental performance and may be useful in small satellite systems that replicate more traditional spacecraft subsystem distribution. In anticipation of extended durations in low-Earth orbit and deep space missions, vendors are now incorporating radiation hardened or radiation tolerant designs in their CubeSat avionics packages to further increase the overall reliability of their products.

As CubeSats become larger and SmallSats become smaller, technology maturation and miniaturization will further increase capabilities. The MarCO mission was the first CubeSat to operate in deep space, and in late 2021 Artemis I will release seven 6U spacecraft into lunar orbit, and five 6U spacecraft that will demonstrate a variety of technologies in deep space.

8.2.1 Form Factor

The CompactPCI and PC/104 form factors continue generally to be the industry standard for CubeSat C&DH bus systems, with multiple vendors offering components that can be readily integrated into space rated systems. Overall form factors should fit within the standard CubeSat dimension of less than 10 x 10 cm. The PC/104 form factor was the original inspiration to define standard architecture and interface configurations for CubeSat processors. But with space at a premium, many vendors have been using all available space exceeding the formal PC/104 board size. Although the PC/104 board dimension continues to inspire CubeSat configurations, some vendors have made modifications to stackable interface connectors to address reliability and throughput speed concerns. Many vendors have adopted the use of stackable "daughter" or "mezzanine" boards to simplify connections between subsystem elements and payloads, and to accommodate advances in technologies that maintain compatibility with existing designs. A few vendors provide a modular package which allows users to select from a variety of computational processors.

The form factors used in more traditional spacecraft designs frequently follow "plug into a backplane" VME standards. 3U boards offer a size (roughly 100 x 160 mm) and weight advantage over 6U boards (roughly 233 x 160 mm) if the design can be made to fit in the smaller form factor. It should be noted that CubeSats also use "U" designations, but these refer to the volume of the vehicle based on initial CubeSat standards of 1U (10 x 10 x 30 cm), 3U (10 x 10 x 30 cm), and 6U (10 x 20 x 30 cm). Some small spacecraft bus designers consider using just a single board C&DH unit as a means of saving weight.

8.2.2 On-Board Computing

Highly Integrated On-Board Computing Products

A variety of vendors are producing highly-integrated, modular, on-board computing systems for small spacecraft. These C&DH packages combine microcontrollers and/or FPGAs with various memory banks, and with a variety of standard interfaces for use with the other subsystems on board. The use of FPGAs and software-defined architectures also gives designers a level of flexibility to integrate uploadable software modifications to adapt to new requirements and interfaces. Table 8-1 summarizes the current state-of-the-art of these components. Since traditional CubeSat designs are based primarily on COTS parts, spacecraft vendors often try to use parts that have radiation tolerance or have been radiation-hardened (rad-hard), as noted in the pedigree column in table 8-1. The vehicle column shows which spacecraft classification corresponds to each on-board unit; "general satellite" classification refers to larger SmallSat platforms (i.e. larger than CubeSats). It should be noted that while some products have achieved TRL 9 by virtue of a space-based demonstration, what is relevant in one application may not be relevant to another, and different space environments and/or reliability considerations may result in lower TRL assessments. Some larger, more sophisticated computing systems have significantly more processing capability than what is traditionally used in SmallSat C&DH systems, however the increase in processing power may be a useful tradeoff if payload processing and

C&DH functions can be combined (note that overall throughput should be analyzed to assure proper functionality under the most stressful operating conditions).

Table 8-1: Sample of Highly Integrated On-board Computing Systems

Manufacturer	Product	Processor	Pedigree	Vehicle	TRL	Reference
GomSpace	Nanomind A3200	Atmel AT32UC3C MCU	COTS	CubeSat	Ukn	(1)
ISIS	iOBC	ARM 9	COTS	CubeSat	9	(2)
Pumpkin	PPM A1	TI MSP430F1612	COTS	CubeSat	9	(3)
	PPM A2	TI MSP430F1611	COTS	CubeSat	9	
	PPM A3	TI MSP430F2618	COTS	CubeSat	9	
	PPM B1	Silicon Labs C8051F120	COTS	CubeSat	9	
	PPM D1	Microchip PIC24FJ256GA110	COTS	CubeSat	9	
	PPM D2	Microchip PIC33FJ256GP710	COTS	CubeSat	9	
	PPM E1	Microchip PIC24FJ256GB210	COTS	CubeSat	9	
Xiphos	Q7S	Xilinx Zynq 7020 Arm 9	COTS w/SEE mitigation	Nano-, Micro- and SmallSats	9	(4)
	Q8S	Xilinx Ultrascale+ ARM Cortex-A53	COTS w/SEE mitigation	Nano- Micro- and SmallSats	8	(5)
BAE	RAD750	RAD750	rad-hard	General Satellite	9	(6)
	RAD5545	RAD5545	rad-hard by design	General Satellite	Ukn	(7)
AAC Clyde Space	Kryten-M3	SmartFusion Cortex-M3	COTS	CubeSat	Ukn	(8)
	Sirius OBC	SmartFusion Cortex-M3	COTS w/SEE mitigation	CubeSat	Ukn	(9)
Innoflight	cfc-300	Xilinx Zynq ARM Cortex A9	COTS	CubeSat	Ukn	(10)
	cfc-400	Xilinx Zynq Ultrascale+	COTS	CubeSat	Ukn	(11)

	cfc-500	Xilinx Kintex Ultrascale+ NVIDIA TK1	COTS	CubeSat	Ukn	(12)
Space Micro	CSP	Xilinx Zynq-7020 Dual ARM Core	COTS	CubeSat	Ukn	(13)
NanoAvionics	SatBus 3C2	STM32 ARM Cortex M7	COTS	CubeSat	9	(14)
MOOG	G-Series Steppe Eagle	AMD G-Series compatible	Rad Hard by design	General Satellite	Ukn	(15)
	V-Series Ryzen	AMD V-Series compatible	Rad Hard by design	General Satellite	Ukn	
SEAKR	Athena-3 SBC	PowerPC e500	Ukn	General Satellite	9	(16)
	Medusa SBC	PowerPC e500	Ukn	General Satellite	9	
	RCC5	Virtex 5 FX-130T	Ukn	General Satellite	9	

System developers are gravitating towards ready-to-use hardware and software development platforms that can provide seamless migration to higher performance architectures. As with non-space applications, there is a reluctance to change controller architectures due to the cost of retraining and code migration. Following the lead of microcontrollers and FPGA vendors, CubeSat avionics vendors are now providing simplified tool sets and basic, cost-effective evaluation boards.

Two such example units have been identified which may be able to support small satellite designs beyond the CubeSat form factors (see table 8-2). Spacecraft bus vendors may also have preferred sources for C&DH units, such as those developed in-house, although that information is not available in the public literature.

Table 8-2: Sample of Small C&DH Units

Vendor	Unit	Mass	Power	Processor	MIPs	References
Moog	C&DH Avionics unit	< 3 kg	25 W	BRE 440	266	(17)
SEAKR	C&DH Gen 3	5.4 kg	14 W	LEON	25	(16)

Radiation-Hardened Processors and FPGAs

Several radiation-hardened embedded processors have recently become available. These are being used as the core processors for a variety of purposes including C&DH. Some of these are the Vorago VA10820 (ARM M0) and the VA41620 and VA41630 (ARM M4); Cobham GR740 (quad core LEON4 SPARC V8) and the BAE 5545 quad core processor. These have all been radiation tested to at least 50 kRad total ionizing dose (TID).

Xilinx and Microchip (formerly Microsemi), leaders in the space-grade FPGA market, have both released new radiation-tolerant FPGA families in the past year rated to 100 kRad TID. The Xilinx RT Kintex UltraScale, a 20 nm device, has 726 k logic cells and supports 12.5 Gbps serial data transmission. The Microchip RT PolarFire is a 28 nm device with 481k logic cells and up to 10.3125 Gbps data transmission. These both offer far more capability than either company's previous families of rad-tolerant FPGA (Xilinx Virtex-5 and Microchip RTG4) and may be adopted for more complex payload data processing needs than merely C&DH use. The Kintex UltraScale is integrated within the Innoflight CFC-500 and Moog Steppe Eagle and Ryzen, listed in the table above.

Open Source Platforms

A number of open source hardware platforms hold promise for small spacecraft systems. Arduino boards consist of a microcontroller with complementary hardware circuits, called shields. The Arduino platform uses Atmel microcontrollers; therefore, developers can exploit Atmel's development environment to write software. The ArduSat spacecraft used the Arduino platform and successfully engaged the public to raise funding on Kickstarter.

BeagleBone has also emerged as a popular open source hardware platform. BeagleBone contains an ARM processor and supports OpenCV, a powerful open source machine vision software tool that could be used for imaging applications. BeagleSat is an open source CubeSat platform based on the BeagleBone embedded development board. It provides a framework and tool set for designing a CubeSat from the ground up, while expanding the CubeSat community and bringing space to a broader audience.

Raspberry Pi is another high-performance open source hardware platform capable of handling imaging, and potentially, high-speed communication applications (18). Raspberry Pi microcontrollers have been shown to be able to accommodate NASA standard core Flight Software and are available in multiple, demonstrated embodiments (19).

Several vendors have developed and implemented C&DH solutions using the Xilinx ZYNQ family of processors. This processor offers single to quad core ARM processing at GHz speeds with built-in FPGA. Although not directly radiation hardened, several radiation mitigation factors have been implemented. These systems typically have been developed on open source Linux OS.

Intel has entered the market with their Edison system. The dual-core x86-64 system on a chip (SoC) was targeted at "Internet of Things" applications, but Edison has proven to be very well suited for advanced CubeSat development—a novel use that Intel has embraced.

Arduino has become known for being beginner friendly and making the world of microcontrollers more approachable for software designers. Though it presents a relatively familiar set of APIs to developers, it does not run its own operating system. On the other hand, the BeagleBone Black, Raspberry Pi, and Intel Edison are full-featured embedded Linux systems running Angstrom, Raspbian, and Yocto Linux kernels out of the box respectively. This broadens the range of developer tool options, from web-based interfaces to Android and Python environments. Not only does this further ease the learning curve for novice developers, but it allows the full power of a Linux system to be harnessed in computation tasks.

8.2.3 Memory and Electronic Components

The range of on-board memory for small spacecraft is wide, typically starting around 32 kB and increasing with available technology. For C&DH functions, on-board memory requires high reliability. A variety of different memory technologies have been developed for specific traits, including Static Random Access Memory (SRAM), Dynamic RAM (DRAM), flash memory (a type of electrically erasable, programmable, read-only memory), Magnetoresistive RAM (MRAM), Ferro-Electric RAM (FERAM), Chalcogenide RAM (CRAM) and Phase Change Memory (PCM). SRAM is typically used due to price and availability. A chart comparing the various memory types and their performance is shown in table 8-3.

Table 8-3. Comparison of Memory Types

Feature	SRAM	DRAM	Flash	MRAM	FERAM	CRAM/ PCM
Non-volatile	No	No	Yes	Yes	Yes	Yes
Operating Voltage, ±10%	3.3 – 5 V	3.3 V	3.3 & 5 V	3.3 V	3.3 V	3.3 V
Organization (bits/die)	512 k x 8	16 M x 8	16 M x 8; 32 M x 8	128 k x 8	16 k x 8	Ukn
Data Retention (@ 70°C)	N/A	N/A	10 years	10 years	10 years	10 years
Endurance (Erase/Write cycles)	Unlimited	Unlimited	10^6	1013	1013	1013
Access Time	10 ns	25 ns	50 ns after page ready; 200 s write; 2 ms erase	300 ns	300 ns	100 ns
Radiation (TID)	1 Mrad	50 krad	30 krad	1 Mrad	1 Mrad	1 Mrad
SEU rate (relative)	Low-nil	High	Nil (cells); Low (device electronics)	Nil	Nil	Nil
Temperature Range	Mil-std	Industrial	Commercial	Mil-std	Mil-std	Mil-std
Power	500 mW	300 mW	30 mW	900 mW	270 mW	Ukn
Package	4 MB	128 MB	128 – 256 MB	1 MB	1.5 MB (12 chip package)	Ukn

There are many manufacturers that provide a variety of electronic components that have high reliability and are space rated (see table 8-4). A visit to any of their respective websites will show their range of components and subsystems including processors, FPGAs, SRAM, MRAM, bus interfaces, Application Specific Integrated Circuits (ASICs), and Low-Voltage Differential Signaling (LVDS).

Table 8-4: Sample of Space-Rated Electronics Manufacturers

Apogee Semiconductor *(USA)*	Honeywell *(USA)*	STMicroelectronics *(Switzerland)*
BAE Systems *(UK)*	Intel *(USA)*	Texas Instruments *(USA)*
Moog Broad Reach *(USA)*	Renesas *(Japan)*	3D Plus *(USA)*
Space Micro, Inc. *(USA)*	SEAKR *(USA)*	Xilinx *(USA)*
Cobham (Aeroflex, Gaisler) *(Sweden)*	Microchip *(USA)*	Vorago Technologies *(USA)*

8.2.4 Bus Electrical Interfaces and I/O

CubeSat class spacecraft continue to use interfaces that are common in the microcontroller or embedded systems world. Highly integrated systems, especially SoC, FPGA and ASICs, will typically provide several interfaces to accommodate a wide range of users and to ease the task of interfacing with peripheral devices and other controllers. Some of the most common interfaces are listed below with a brief description:

- Serial Communication Interfaces (SCI): RS-232, RS-422, RS-485 etc.
- Synchronous Serial Communication Interface: I2C, SPI, SSC and ESSI (Enhanced Synchronous Serial Interface)
- Universal Serial Bus (USB)
- Multimedia Cards (SD Cards, Compact Flash etc.)
- Networks: Ethernet, LonWorks, etc.
- Fieldbuses: CAN-Bus, LIN-Bus, PROFIBUS, etc.
- Timers: PLL(s), Capture/Compare and Time Processing Units
- Discrete IO: General Purpose Input/Output (GPIO)
- Analog to Digital/Digital to Analog (ADC/DAC)
- Debugging: JTAG, ISP, ICSP, BDM Port, BITP, and DB9 ports
- SpaceWire: a standard for high-speed serial links and networks
- High-speed data: RapidIO, XAUI, SERDES protocols are common in routing large quantities of mission data in the gigabit per second speeds

8.2.5 Radiation Mitigation and Tolerance Schemes

Deep space and long duration low-Earth orbit missions will require developers to incorporate radiation mitigation strategies into their respective designs. The CubeSat platform has traditionally used readily available COTS components. Use of COTS parts has allowed for low-cost C&DH development, while also allowing developers to take advantage of state-of-the-art technologies in their designs. Many of the component and system vendors also provide radiation hardened (rad-hard) equivalent devices as well. While there are many commercially available rad-hard components, using these components impacts the overall cost of spacecraft development. In order to keep costs as reasonable as possible, C&DH developers will need to address appropriate use of rad-hard components, along with other radiation mitigation techniques for developing an overall radiation tolerant design as discussed in the following section.

For space applications, radiation can damage electronics in two ways. TID is the amount of cumulative radiation received and single event effects (SEEs) are disturbances created by single particles hitting the electronics (20). Total dose is measured in kilorads and can affect transistor performance. Single Event Upsets (SEU) can affect the logic state of memory. A Single Event Latch-up (SEL) can affect the output transistors on Complementary Metal Oxide Semiconductors (CMOS) logic, potentially causing a high-current state. This section summarizes techniques used to mitigate system failures caused by radiation effects.

8.2.6 Memory

FRAM is a non-volatile random-access memory that is persistent like Flash memory. FRAM memory cells are latched using a Lead-Zirconium-Titanium oxide (PZT) film structure, which is more likely to maintain state during a single event effect than traditional capacitive latches found in RAM (21) (22).

MRAM is another type of non-volatile random-access memory that is persistent. It is different than FRAM and others in that it has virtually unlimited read and write cycle endurance. MRAM has been built into some processors (TI MSP430FR) as well as separate chips.

8.2.7 Imaging

Charge Couple Devices (CCD) and CMOS are image sensors that are useful in radiation environments. However, CCDs are preferred in space applications, while the CMOS detectors are a newer technology for rad hardened image sensors (23) (24) (25) (26).

8.2.8 Protection Circuits

Watchdog Timers

Watchdog timers are often used to monitor the state of a processor. A watchdog timer is a hardware circuit, external or internal to the processor, which resets the processor when the timer expires unless refreshed by the processor. If the processor jumps to an erroneous memory location through a single-event upset or a software exception, the watchdog timer resets the processor to restore operations (27).

Communication Watchdog Timer

A dedicated communication watchdog timer circuit can monitor commands and responses to determine if the system is locked up. Such a circuit resets power after a specific number of failed transmissions.

Overcurrent Protection

Single Event Latch-up (SEL) can cause device failure due to an elevated current state. Hardware and software overcurrent protection can be implemented to watch for elevated current levels and then issue a power reset to the offending circuit. The sampling frequency for software overcurrent protection must be sufficient to detect and reset the subsystem before the elevated current causes permanent damage. For hardware protection, a shunt resistor and bypass diode can be used in conjunction to filter voltage and current spikes for rad hardened devices.

Power Control

Since many components are more prone to radiation effects when powered on, a candidate mitigation strategy is to power off devices when they are not operationally needed.

8.2.9 Memory Protection

Error-Correcting Code Memory

Error-Correcting Code (ECC) memory is capable of detecting and correcting bit errors in RAM and flash memory. In general, ECC works by storing a checksum for a portion of the memory. This checksum can be used to simply mark a portion of memory unstable. Additional processing can use the memory and checksums to correct single and sometimes multi-bit errors. The memory controller is responsible for managing the ECC memory during read and write operations (28).

Software Error Detection and Correction

Bit errors can be detected and corrected using software. In general, Error Detection and Correction (EDAC) algorithms use three copies of the memory to detect and correct bit discrepancies. Software routinely “scrubs” the memory, compares each of the three stored memory values, selects the majority value, and corrects the erroneous memory location. Software EDAC can be performed at the bit or byte level. Memory lifetime needs to be considered for software EDAC implementations, since every correction increases the write count to a memory location.

8.2.10 Communication Protection

Shared Bus Switching

Another option is to decouple the clock and data lines so that each peripheral has its own pair. Additional data lines can be used on the master controller. Alternatively, an external FPGA could be used to assign a unique clock/data pair to each peripheral and, optionally, include a method as a way to reconfigure those assignments in flight.

Cyclic Redundancy Check

Cyclic Redundancy Check (CRC) is a common method for detecting memory or communication errors. Parity is a single-bit implementation of a CRC where the bit of summary information is calculated by the XOR of the data to be communicated or stored to memory. For communication channels, a CRC is calculated prior to sending the message, and is appended to the message stream in a known location. When the message is received, the CRC is calculated again and compared to the previously generated CRC appended to the data stream. For memory, the CRC is calculated prior to writing the data to memory. When the data is read out, a new CRC is calculated and compared to the previously generated CRC. CRCs help detect data corruption but cannot be used to correct the defective data.

Forward Error Correction

Forward Error Correction (FEC) transmits redundant data to help the receiver recover corrupted data. In its simplest form, FEC could transmit three bits for every bit of data and then vote to restore the original data. More efficient algorithms balance the data overhead with the correction accuracy (27).

8.2.11 Parallel Processing and Voting

Triple Modular Redundancy

Single-event upsets can interrupt discrete logic, including processing. Triple Modular Redundancy (TMR) is a fault mitigation technique where logic is replicated three times, and the output of the logic is determined by a majority vote.

Firmware Protection

Many spacecraft subsystems include a processor to handle and optimize operations. These processors require firmware which is written into onboard program memory. Like data memory, program memory is also susceptible to single-event upsets and device failure. To counter this issue, a bootloader may be used to check the validity of the firmware and provide a mechanism for uploading new versions. Additionally, multiple copies of the firmware may be stored in memory in case the primary version is corrupt.

8.2.12 Open Source Spacecraft Software

Open source software offers spacecraft developers a way to accelerate software development, improve quality, and leverage lessons learned from prior missions.

Linux

Linux is currently supported by several spacecraft avionics providers including Space Micro and Tyvak Nano-Satellite Systems. Additional software modules are needed for space applications. Such modules may include memory scrubbing, a safe mode controller, watchdog functionality, and other reliability services (23).

core Flight System and core Executive

The core Flight System (cFS) and core Executive (cFE) is a set of applications, application framework and runtime environment developed by NASA GSFC. cFE includes core services like messaging, timekeeping, events, and table-driven commanding and configuration (29) (30).

Command and Control of Space Systems

Command and Control of Space Systems (COSMOS) is a tool developed by Ball Aerospace that provides a framework for operating and testing an embedded system. The tool includes modules for telemetry display, plotting, scripting, logging, and configuration table management (21).

8.3 On the Horizon

Many C&DH systems will continue to follow trends set for embedded systems. Short duration missions in low-Earth orbit will continue to take advantage of advances made by industry leaders who provide embedded systems, technologies, and components. In keeping with the low-cost, rapid development theme of CubeSat-based missions, many COTS solutions are available for spacecraft developers.

While traditional C&DH processing needs are relatively stagnant, as small satellites are being targeted for flying increasingly data-heavy payloads (i.e. imaging systems) there is new interest in advanced on-board processing for mission data. Typically, these higher performance functions would be added as a separate payload processing element outside of the C&DH function. Automotive and smartphone industries have pushed the energy efficiency of embedded Graphics Processor Units (GPUs) – processors optimized for matrix multiplication and thus ideal for image processing and machine learning algorithms – and the space industry is looking to adopt these technologies for space applications (29). Small satellite vendors Innoflight and Moog have on-board computing products with integrated GPUs, though neither have flown yet.

8.4 Summary

System level solutions are in demand and a majority of the small spacecraft bus developers use hardware typically employed in the embedded systems and control world. As a result, there are many sources for CubeSat systems, subsystems and components from vendors who provide complete spacecraft bus avionics solutions, which include on-board computing, memory, electronic power supply, and engineering development systems. As CubeSat development and application continues to evolve, there are a wide range of avionics systems and components available to address the needs of a wide range of professional and amateur small spacecraft developers.

Designing and fabricating avionics systems for harsh radiation environments is mitigated by a combination of shielding, derating, and controlling operating conditions for cumulative ionization and displacement damage effects that cause gradual degradation in electronic devices. Small spacecraft will need to address impacts of radiation in deep space missions and extended duration missions in low-Earth orbit. Several processor manufacturers and board level integrators are addressing the need for rad-hard and radiation tolerant designs. Some board level integrators have also undertaken radiation testing of their integrated systems. Many providers of integrated systems are using rad-hard processors or FPGAs from vendors such as Xilinx, Microchip, and Cobham. Processing performance is typically not a driver for C&DH subsystems, which allows spacecraft designers to use less expensive, commercial radiation tolerant parts that do not push state-of-the-art performance. Payload demands are more likely to push state-of-the-art electronics with mission data processing requirements.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

References

(1) GomSpace. NanoMind A3200 - Datasheet. [Online] 2019. https://gomspace.com/shop/subsystems/command-and-data-handling/nanomind-a3200.aspx.

(2) ISIS. ISIS On board computer - Datasheet. [Online] 2019. https://www.isispace.nl/wp-content/uploads/2016/02/IOBC-Brochure-web-compressed.pdf.

(3) Pumpkin Space Systems. "Processor-specific CubeSat Kit™ Components." *Pumpkin Products/Store.* [Online] 2020. https://www.pumpkinspace.com/store/c19/Processor-specific_CubeSat_Kit%E2%84%A2_Components.html.

(4) Xiphos. Q7S Specifications - Datasheet. [Online] 2020. http://xiphos.com/wp-content/uploads/2015/06/XTI-2001-2020-e-Q7S-Spec-Sheet.pdf.

(5) Xiphis. Q8S SPECIFICATIONS - Datasheet. [Online] 2020. http://xiphos.com/wp-content/uploads/2020/06/XTI-2001-2025-f-Q8S-Rev-B-Spec-Sheet-1.pdf.

(6) BAE Systems. "RAD750 3U CompactPCI single-baord computer." *BAE Systems: Space product literature.* [Online] 2008. https://www.baesystems.com/en-us/our-company/inc-businesses/electronic-systems/product-sites/space-products-and-processing/radiation-hardened-electronics.

(7) BAE Systems. "RAD5545 Space VPX single-board computer." *BAE Systems: Space products literature.* [Online] 2017. https://www.baesystems.com/en-us/our-company/inc-businesses/electronic-systems/product-sites/space-products-and-processing/radiation-hardened-electronics.

(8) AAC Clyde Space. Command & Data Handling KRYTEN-M3 - Datasheet. [Online] 2020. https://www.aac-clyde.space/assets/000/000/179/AAC_DataSheet_Kryten_original.pdf?1600342763.

(9) AAC Clyde Space. Command & Data Handling Sirius OBC LEON3FT - Datasheet. [Online] 2020. https://www.aac-clyde.space/assets/000/000/181/AAC_DataSheet_Sirius_OBC_-_updated_tables_original.pdf?1599046187.

(10) Innoflight. CFC-300: Compact Flight Computer - Datasheet. [Online] 2020. https://www.innoflight.com/product-overview/cfcs/cfc-300/.

(11) Innoflight. CFC-400: Compact Flight Computer - Datasheet. [Online] 2020. https://www.innoflight.com/product-overview/cfcs/cfc-400/.

(12) Innoflight. CFC-500: Compact On-Board Computer - Datasheet. [Online] 2020. https://www.innoflight.com/product-overview/cfcs/cfc-500/.

(13) Space Micro. CubeSat Space Processor (CSP). Datasheets. [Online] 2019. https://www.spacemicro.com/assets/datasheets/digital/slices/CSP.pdf.

(14) Nanoavionics. CubeSat On-Board Computer - Main Bus Unit SatBus 3C2 - Datasheet. [Online] 2020. https://nanoavionics.com/CubeSat-components/CubeSat-on-board-computer-main-bus-unit-satbus-3c2/.

(15) Moog. Radiation Tolerant, 75GLOP 3U SPaceVPX GPU Sinlge Board Computer - Datasheet. *Moog: Space Defense: Space Literature.* [Online] 2020. https://www.moog.com/content/dam/moog/literature/Space_Defense/spaceliterature/avi

onics/Moog-Rad-Tolerant-75GFLOP-3U-SpaceVPX-GPU-Single-Board-Computer-Datasheet.pdf.

(16) SEAKR. Commercial Products. *SEAKR: Catalog.* [Online] 2020. https://www.seakr.com/catalog/.

(17) Moog. Integrated Avionics Unit - Datasheet. *Moog: Space: Avionics.* [Online] 2020. https://www.moog.com/content/dam/moog/literature/Space_Defense/spaceliterature/avionics/moog-integrated-avionics-unit-datasheet.pdf.

(18) Wooster, P, et al.: *"Open Source Software for Small Satellites."* AIAA/USU Conference on Small Satellites. *No. #SSC07-XII-3.* 2007.

(19) Cudmore, Alan: "*Pi-Sat: a Low Cost Small Satellite and Distributed Spacecraft Mission System Test Platform."* s.l.: NASA GSFC, 2015. GSFC-E-DAA-TN27347.

(20) Nguyen, M.: *"FPGA Advances Improve Radiation Mitigation for Remote-Sensing Satellites."* 2015, pp. vol. 17, no. 8.

(21) Ball Aerospace & Technologies Corp. "The User Interface for Command and Control of Embedded Systems." 2015.

(22) Henkel, H.: "Total Dose Radiation Tests at FRAM Non-Volatile Memories." 1996.

(23) NASA Goddard Space Flight Center. "GSFC Open Source Software." 2015.

(24) Bardoux, A., et al.: *"Radiation Effects on Image Sensors."* International Conference on Space Optics. 2012.

(25) Chapman, T.: "Radiation Tolerances." 2015.

(26) Holbert, K. E.: "Single Effect Events." 2015.

(27) Mauere, R., et al.: *"Harsh Environments: Space Radiation Environment, Effects, and Migitation."* pp. Vol. 28, no. 1. 2008.

(28) LaBel, K. A. et. al.: *"Commercial Microelectronics Technologies for Applications in the Satellite radiation Environment."* Aerospace Applications Conference. 1996.

(29) Fitzsimmons, S.: *"Open-source Software for CubeSat Satellites."* AIAA/USU Conference on Small Satellites. 2012.

(30) NASA Goddard Space Flight Center. "Core Flight Software System." 2015.

(31) Kosmidis, L., et al.: "*GPU4S: Embedded GPUs in Space – Latest Project Updates.* s.l.: Microprocessors and Microsystems. Vol. 77. 2020

9.0 Flight Software

9.1 Introduction

The Flight Software (FSW) is, at a fundamental level, the instructions for the spacecraft to perform all operations necessary for the mission. These include all the science objectives as regular tasks (commands) to keep the spacecraft functioning and ensure the storage and communication of data (telemetry). The FSW is usually thought of as the programs that run on the Command & Data Handling (C&DH) avionics, but should also include all software running on the various subsystems and payload(s).

Flight Software complexity (the amount of operations to be performed) is not based on the size of the spacecraft, but the overall requirements and mission objectives. The more software has to do, the bigger the task and cost. This complexity is what primarily drives the cost and schedule for the program or mission. Required reliability and fault management can also increase complexity and cost, regardless of the size of the spacecraft.

With the increase in processing capability with C&DH and other processors, more capabilities have been enabled with FSW. Previously, larger processors have only been in larger spacecraft and would not be possible in CubeSats and MicroSats. There have been several advances that make more processing capability now available for CubeSats. Low-power ARM-based processors, as well as advances in radiation hardened processors, have brought similar processing capabilities down to the small size of CubeSats. All of this has brought increased demands and requirements on FSW.

FSW must operate in a real-time environment. This definition can have numerous interpretations. Generally, C&DH and other subsystems need to be able to supervise several inputs and outputs as well as process and store data within a fixed time period. These all need to be performed in a reliable and predictable fashion throughout the lifetime of the mission. The needs of each mission can vary greatly, but this basic deterministic and reliable processing is a fundamental requirement.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

9.2 Processor Types

The processor and memory available on the C&DH can put significant limitations on the FSW. For some of the smaller jobs, or to reduce electronic complexity, smaller processors are used. These have typically been thought of as embedded processors, with many of them containing dedicated memory. Programs are very integrated with the hardware, requiring careful implementation and integration. Software development environments for these kinds of processors usually come from the microprocessor themselves, or from third party vendors. Some of the past tools (and processors used) have been MPLAB (Microchip PIC family), and TI CCStudio (TI MSP430). On these types of processors a “Bare Bones” approach to the software design is usually implemented with limited to no operating system. This is primarily because of memory and processor limitations. These programs tend to be highly optimized. Part of the challenge with these systems is development and testing. Most interactions with the software must be done remotely through a secondary processor, usually a PC. This type of development usually requires unique skills and can involve a significant learning curve for developers. Efficient programmers need to have a good understanding of both the software and hardware and how they function together. Timing and performance matter greatly, so that they need to be able to write code in an efficient manner. Typically, these projects have up to 20,000 lines of code.

Larger processors have been increasing in popularity with current missions, especially CubeSats. With increases in power production as well as lower power processors, radiation tolerant processors have been available in both SmallSats and CubeSats. Several vendors have larger processors that can run Real-Time Operating Systems (RTOS) such as VxWorks, RTEMS and FreeRTOS that are described below. These give software developers a significant advantage with a software development environment and usually a base implementation on the processing target. RTOS have been designed to operate in minimal processor/memory environments with real-time needs. These projects typically have for small projects 50K to 70K lines of code, to larger projects that can exceed a million.

There are many factors in the selection of a development environment and/or operating system used for a space mission. A major factor is the amount of memory and computational resources. There are always financial and schedule concerns. Another factor is what past software an organization may have used and their experiences with that software. Also, the maturity of the software as well as its availability on the target are additional factors to be considered in the final selection.

9.2.1 VxWorks

Windriver calls VxWorks the Industry-Leading RTOS. VxWorks is fully featured and has been used by the industry for many years. It has been used by NASA for over 20 years since the Clementine mission. It is used in satellites as well as robotics such as Robonaut and MER. It has many features of a user operating system with tasks and processes, memory protection and separation. VxWorks has a commercial license, with several of the advanced development and diagnostic tools licensed separately. Due to the cost, VxWorks needs to be budgeted for the life of the mission.

VxWorks currently supports 32- and 64-bit processors as well as multi-core including Intel, Arm, Power Architecture and RISC-V. Multi-core processors support both asymmetric and symmetric multiprocessing. There are numerous board support packages for enabling early prototyping and aiding development of software (1).

9.2.2 RTEMS

From the RTEMS.org website: “the Real-Time Executive for Multiprocessor Systems or RTEMS is an open source Real Time Operating System (RTOS) that supports open standard application programming interfaces (API) such as POSIX. It is used in space flight, medical, networking and many more embedded devices. RTEMS currently supports 18 processor architectures and approximately 200 BSPs. These include ARM, PowerPC, Intel, SPARC, RISC-V, MIPS, and more. RTEMS includes multiple file systems, symmetric multiprocessing (SMP), embedded shell, and dynamic loading, as well as a high-performance, full-featured IPV4/IPV6 TCP/IP stack from FreeBSD which also provides RTEMS with USB.”

RTEMS is considered open source, released under a modified GNU General Public License. Support is available through the primary manager OAR. It has been sponsored, deployed, and used widely on several NASA and ESA missions. RTEMS has been in development since the 1980s. RTEMS could be considered a simpler operating system with no provided memory or process management. Although build environments are provided, development tools are not as featured as commercial products (2).

9.2.3 FreeRTOS

FreeRTOS is a small, real-time operating system kernel designed for embedded devices. It is open source and released under the MIT license. FreeRTOS is designed to be small and simple; however, it lacks some of the more advanced features found on larger operating systems. FreeRTOS has been used on several CubeSat projects where memory is limited.

9.2.4 Linux

Linux is another operating system that is being implemented on several spacecraft. Linux is deployed on PowerPC-, LEON-, and ARM-based processors. It is readily available and widely used in both government and commercial sectors. There are several distributions and guides that have been developed for embedded use that would be suitable for spacecraft use. Some of the distributions have been Yocto (Xilinx ZYNQ) and Debian (BeagleBone Black and PowerPC). There are real-time extensions, as well as additional extensions such as Xenomai, to improve critical real-time performance. Numerous development and diagnostic tools are available. Linux is a full featured operating system that has been used for desktop use. Linux tends to be larger, requiring more memory and processing capability. It is popular on the ARM processors because those issues tend not to be a factor.

9.3 Open Source Frameworks

Several open source frameworks are now available to anyone under a variety of licensing agreements. Most of these are available on the community and industry accepted standard, github website repository at https://github.com. NASA embraces the open source movement and has made numerous contributions see https://github.com/nasa. Below are a few examples of Open Source Frameworks.

9.3.1 cFS/cFE

The core Flight System (cFS) is a generic flight software architecture framework. cFS has been used in dozens of space missions ranging from flagship spacecraft to small satellite and CubeSats. cFS is actively being used in a number of missions both in flight and in development.

The core Executive (cFE) and core Flight services (cFS) are a set of applications, application framework, and runtime environment developed by Goddard Space Flight Center. cFE includes core services like messaging, timekeeping, events, and table-driven commanding and configuration (3). cFS is built on an Operating System Abstraction Layer (OSAL) that leads to the same code base running on different operating systems. cFS provides most of the basic functionality to operate a spacecraft. The core Flight System, as well as supporting infrastructure, has been used by NASA on numerous missions and is being used by other organizations. cFS, as well as the supporting OSAL, are open source and currently released under the Apache 2.0 license (4).

9.3.2 F’ (F Prime)

From the F’ description: “F’ is a software framework for rapid development and deployment of embedded systems and spaceflight applications. Originally developed at JPL, F´ is open source software that has been successfully deployed for several space applications. It has been used for, but is not limited to, CubeSats, SmallSats, instruments, and deployables.” F’ is currently released under the Apache 2.0 license (5) (6).

9.3.3 Trick

From the trick description: “The Trick Simulation Environment, developed at the NASA Johnson Space Center (JSC), is a powerful simulation development framework that enables users to build applications for all phases of space vehicle development. Trick expedites the creation of simulations for early vehicle design, performance evaluation, flight software development, flight vehicle dynamic load analysis, and virtual/hardware in-the-loop training. Trick's purpose is to provide a common set of simulation capabilities that allow users to concentrate on their domain specific models, rather than simulation-specific functions like job ordering, input file processing, or data recording." Trick is released under the NASA Open Source Agreement Version 1.3 (7) (8).

9.3.4 42

From the 42 description: "42 is a comprehensive general-purpose simulation of spacecraft attitude and orbit dynamics. Its primary purpose is to support design and validation of attitude control systems, from concept studies through integration and test. 42 accurately models multi-body spacecraft attitude dynamics (with rigid and/or flexible bodies), and both two-body and three-body orbital flight regimes, modelling environments from low-Earth orbit to throughout the solar system. 42 simulates multiple spacecraft concurrently, facilitating studies of rendezvous, proximity operations, and precision formation flying. It also features visualization of spacecraft attitude" (9).

9.4 Development Environments and Tools

Most software development tools that are used for FSW are also used in the overall software development industry. Common version control tools are Git and Subversion. More large projects are switching to Git repository due to its distributed nature and merging features. The NASA cFS project uses Git and is sourced on https://github.com/.

Additional tools have been used with these version control tools to provide more process control and configuration management. The Atlassian tools are an example of these. They interface directly to Git or Subversion and provide issue/bug tracking (Jira), documentation (Confluence), continuous integration (Bamboo) and others. The Atlassian tools are a licensed product that is free for trial and suitable for a small number of users.

There are several other tools for each of these functions that are used. For instance, Trac is an open-source web-based project management and bug tracking system.

9.5 Auto-Generation of Software

Automatic generation of source code from higher symbolic languages is being adopted by a wide number of missions. This technique is commonly being used by several NASA centers including ARC, GSFC and JSC. Key advantages of using this approach are rapid development and testing, and significant time and cost savings. There are a variety of tools that have been used in the past, but the most popular is MATLAB/Simulink. This allows an engineer to completely develop the algorithms in a graphical or higher-level language and have flight code automatically generated. Simulations and tests are also developed within MATLAB/Simulink. A common way that these kinds of tools are used are within the GNC development, but other missions such as LADEE have used it for almost the entire FSW with over 85% of the new code generated in this manner (10) (11).

Using these tools has advantages. They are designed for analysis and have built-in simulation tools. They are usually seen as being easier to understand due to their graphical nature. These tools are familiar to many engineers since they have been used by several colleges and universities. One thing to be aware when developing software with this method is that good modeling practices need to be adopted so that the resultant models produce good code. These include all the best practices performed with traditional software development. An example is to establish and use modeling guidelines so that the resultant code is consistent.

9.6 Simulations and Simulators

Simulations are needed to fully test software before release to verify and help validate the software. In a sense, unit tests are very simple simulations. Overall simulations need to be large enough to run all of the released flight software. The preferred method is to test all the FSW in an integrated fashion. If that cannot be performed, then partial tests may have to be performed. The testing should be designed to cover all executed code. The issues of not testing all the code is that total execution performance and possible interactions between modules may not be tested. Scenarios or a “Day in the Life” tests should be covered as well as off-nominal fault recovery.

Simulators usually refer to the hardware and infrastructure needed to run the FSW and simulations. The main part of the simulation is the actual FSW. This should be run on a processing environment as close to the flight processor as possible. For some situations, that can be an actual spare flight unit. For some processors that are costly, such as the RAD750, either an engineering unit or a similar PowerPC processor that is binary compatible may be used. These processors are either connected to actual hardware interfaces that are connected to spacecraft subsystems, or subsystem simulators. These types of simulators are referred to as Hardware-in-the-Loop (HIL) simulators because they use actual hardware for testing. The other type of simulator is a processor-in-the-loop (PIL) simulator where a flight-like processor is tested against simulations of the hardware and subsystems. Depending on the environment and processing load, this is usually done in a separate processor, but can be done on a single flight-like processor. The simulation portion (non-flight software) is almost always preferred to be executed on a separate processor so that interference with the flight software is minimized or eliminated.

NASA Ames has created a development environment where the same flight executable can be executed on a flight-like processor in simulation. This is done by simulating each of the interfaces through a standard POSIX interface and having the flight executable talk to that interface. Lower level interface communication can then occur either through a hardware interface (flight-like), or UDP Ethernet (simulation) based on the simulator configuration. In this way the same FSW can be executed in several ways without changes to the FSW.

9.7 Ground Support Software

Although not directly used on the spacecraft, operators need a way to talk to the spacecraft. Ground operations and testing needs that same capability. For smaller spacecraft and missions, it is usually best to use the same ground support software for these three tasks: mission operations, integration and testing, and development and testing. There are numerous proprietary tools and programs. A small set of tools that have been used at NASA are described below.

Integrated Test and Operations System (ITOS) is a space ground system developed for GSFC by the Hammers Company (12). ITOS is a comprehensive command and telemetry solution for spacecraft, component, and instrument development, integration, testing, and mission operations. It is highly user configurable, and provides a scalable, cost-effective platform for small-budget projects to billion-dollar observatories. It includes multi-spacecraft control and closed-loop simulation capabilities.

Advanced Spacecraft Integration and System Test (ASIST) is also a space ground system developed for GSFC by designAmerica. ASIST provides satellite telemetry and command processing for integration and testing (I&T) and operations environments (13). ASIST is described as “an object-oriented, real-time command and control system for spacecraft development, integration, and operations. Mature and reliable, ASIST has logged hundreds of thousands of hours in component development, spacecraft integration, and validation labs.”

COSMOS is a tool developed by Ball Aerospace that provides a framework for operating and testing an embedded system (14). COSMOS is open source, licensed under the MIT license. The tool includes modules for telemetry display, plotting, scripting, logging, and configuration table management. For more information, please refer to the Ground Data System and Mission Operations chapter.

INCONTROL is a proprietary tool developed by L3HARRIS. Some of the features include providing support for single-mission, multi-mission, and constellation support. It also provides capabilities for automation, event logging, data distribution, procedure development, archiving, data displays, equipment monitor and control, data retrieval, report generation, and simulation (15).

9.7.1 Software Best Practices and NPR7150

Software can be complex and overwhelming because of the large scope and unique nature of software development. Additionally, flight software can be costly and have reliability issues because it can be large in scope, complex, and there are significant difficulties with testing in a flight like environment. To help address developmental challenges, software development has created best practices. These can be implemented several ways but encompass some basic parts. Some software best practices include:

- Create a plan*, schedule, and budget for software: a plan is needed to fully understand the scope of the software effort. Ideally, plans would be developed based on previous experiences, but there may not be a similar experience that can be used for a particular project, and the software manager has to rely on instinct and best judgement. Usually software will require multiple releases because incrementally developed features of the software are needed by the customer at various stages of the project (e.g. I&T, pre-launch, operations). Include a cost discussion and customer sign-off.
- Configuration management/revision control: this should be used for all software development not just FSW. There are many readily available tools, but two of the most popular are Git and Subversion. These tools provide an automatic history of the software development. CM allows coordination between multiple team members, assists in the overall software release, and tracks what changes are in that release. CM also allows back tracing to see when a software bug may have been introduced.
- Code reviews: all code should be inspected prior to being accepted by the project. These reviews can be performed in a variety of methods, from off-line informal peer reviews, to more formal meetings such as perspective-based code inspections. Some developers believe that this is a poor use of time and are hesitant to have others look at their work. Code reviews lead to a higher quality product and better understanding of the software.
- Documentation: documentation can be both within the code or developed separately. Some documentation tools process the software code to produce formal documentation. The documentation should be consistent with the overall software effort.
- Testing: testing can come as three different parts.
    - Unit- and component-level tests: each software module should have a unit test (function level) and/or component test (module level) that is required to pass before that code is accepted for release. A record of these tests should be kept as part of the overall software release procedure. When fixing a discrepancy or bug the unit test should be modified to test those fixes.
    - Manual or interface testing: software is tested against the actual devices or a copy to ensure that both the hardware and software can successfully communicate and control each subsystem. Tests should be repeated, and edge cases should be tested whenever possible.
    - Integrated testing: integrated testing is the main time that all the FSW can be tested together. This ensures that the overall system operates in an expected

and reliable manner. Ideally subsystems have actual hardware, but simulations can be used.

- Continuous integration: continuous integration (CI) works with the CM tools to know when changes have been committed. The CI tools automatically build executables and run configured tests (unit and integrated tests). This removes the burden of building and testing from the developers, and finds any issues with new code much faster. CI does require setup time and understanding the tools.

*Software planning is a whole topic unto itself. There are several software development approaches. Currently agile software development is one of the most popular. The overall cost of the software development effort needs to be understood, and a detailed cost estimate should be performed. As the complexity of the FSW increases, so does the cost and the effort of estimating that cost. There are a number of different methods for estimating those costs, including analogy, parametric models such as Cocomo, and bottoms-up cost estimates (16) (17) (18). Typically, there is a lot of uncertainty in software cost estimates, so it is important to try to understand the bounds of that uncertainty and, if possible, to give confidence in the estimate.

In order to ensure that all NASA projects follow best software practices NASA Software Engineering Requirements standard NPR 7150.2 (currently NPR7150.2C – for updated NPR standards please see https://nodis3.gsfc.nasa.gov/) is mandated for all NASA Flight Software (and NASA developed software in general). It covers requirements for software management and planning, software engineering life cycle requirements, and supporting software life cycle requirements. Overall NPR 7150.2 addresses:

- Roles and responsibilities for tailoring requirements
- Software management
    - Software lifecycle planning
    - Cost estimates
    - Training
    - Classification assessments
    - Software assurance and software verification and validation
- Software engineering life cycle requirements
    - Requirements
    - Architecture
    - Design
    - Implementation
    - Testing
    - Operations, maintenance and retirement
- Supporting software life cycle requirements
    - Configuration management
    - Risk management
    - Peer reviews/inspections
    - Measurements
    - Non-conformance or defect management
- Recommended software documentation

9.8 Summary

FSW is key to mission success. The field of software is a very dynamic environment and continuously evolving. The challenges with flight software usually remain the same regardless of the size of the spacecraft (CubeSat to SmallSat), and are related to the size and complexity of the endeavor. Overall, flight software can be known for scheduling issues and implementation issues especially during integration and test. Temptation of adding additional features is usually present. All of these factors can drive up overall complexity and threaten success of FSW and the mission as a whole.

It is essential that FSW be as simple as possible. It is critical to survey the options and plan early any FSW effort. Wherever possible early development and testing should be exercised. Efforts to add additional features should be looked at very critically with strong efforts to stick to the existing plan. With good planning and careful execution, a favorable outcome can be achieved.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

References

(1) Windriver. VXWORKS. [Online] https://www.windriver.com/products/vxworks/.

(2) RTEMS. RTEMS Real Time Operating System (RTOS). [Online] 2020. https://www.rtems.org.

(3) *Open-source Software for CubeSat Satellites.* Fitzsimmons, S. s.l. : AIAA/USU Conference on Small Satellites, 2012.

(4) NASA. core Flight System (cFS). *core Flight System: A paradign shift in flight software development.* [Online] 2020. https://cfs.gsfc.nasa.gov.

(5) NASA. A Flight Software and Embedded Systems Framework. [Online] 2020. https://nasa.github.io/fprime/.

(6) Bocchino, Robert, et al.: "*F Prime: An Open-Source Framework for Small-Scale Flight Software Systems."* Logan: 32nd Annual Small Satellite Conference, 2018.

(7) Trick. Trick. [Online] https://nasa.github.io/trick/.

(8) J.Penn, S.Lin: "The Trick Simulation Toolkit: A NASA/Open source Framework for Running Time Based Physics Models." *NTRS - NASA Technical Reports Server.* [Online] 2015. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150021786.pdf.

(9) NASA. 42: A Comprehensive General-Purpose Simulation of Attitude and Trajectory Dynamics and Control of Multiple Spacecraft Composed of Multiple Rigid or Flexible Bodies. [Online] 2020. https://software.nasa.gov/software/GSC-16720-1.

(10) *Multi-Purpose Spacecraft Simulator for the LADEE Mission.* Benz, Nathaniel, Viazzo, Danilo and Gundy-Burlet, Karen. s.l.: IEEE, 2015.

(11) Gundy-Burlet, Karen: "*Validation and Verification of LADEE Models and Software.".* s.l. : American Institute of Aeronautics and Astronautics.

(12) NASA. ITOS Capabilities. *Integrated Test and Operations Systems (ITOS) .* [Online] 2020. https://itos.gsfc.nasa.gov/itos-capabilities.php.

(13) NASA. ASIST Public Web Site - NASA. [Online] 2012. https://nasa-asist.gsfc.nasa.gov.

(14) Ball Aerospace. The User Interface for Command and Control of Embedded Systems. [Online] 2020. https://cosmosrb.com/.

(15) L3Harris Technologies. Space Software. *Telemetry and RF products.* [Online] 2020. https://www2.l3t.com/trf/incontrol/index.htm.

(16) Lum, Karen, Powell, John and Hihn, Jairus: "*Validation of Spacecraft Software Cost Estimation Models for Flight and Ground System."* s.l. : NASA, 2002.

(17) T. Hihn, M. Jairus, G. Menzies: "*NASA Software Cost Estimation Model:An Analogy Based Estimation Method."* Moffett Field: 2015 NASA Cost Analysis Symposium, 2015.

(18) Cannon, Howard and Gundy-Burlet, Karen: "*Software Cost Estimation for the LADEE Mission."* 2015.

(19) Ball Aerospace & Technologies Corp. “The User Interface for Command and Control of Embedded Systems.” 2015.

10.0 Communications

10.1 Introduction

The communication system is an essential part of a spacecraft, enabling spacecraft to transmit data and telemetry to Earth, receive commands from Earth, and relay information to one another. A transceiver is a device that both receives and transmits. In contrast, a transponder essentially uses the same technology as a transceiver, but is also capable of providing ranging information, either between spacecraft or with respect to Earth. The small satellite community sometimes refers spacecraft-to-spacecraft communications as an Intersatellite Link (ISL). Traditionally, communication between Earth and spacecraft is in the radio spectrum (from about 30 MHz to 40 GHz). Spacecraft typically use different communication bands as shown in figure 10.1.

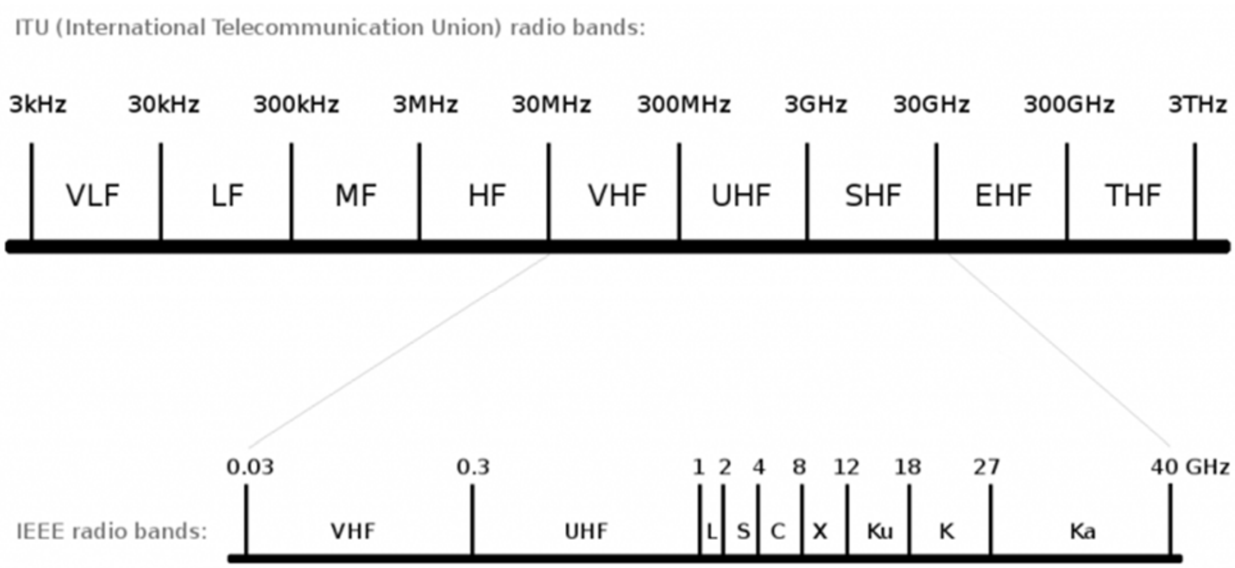


Figure 10.1: Radio spectrum used for spacecraft communication. Credit: NASA.

While the use of radio frequency (RF) for communications is still the state-of-the-art at the time of this publication, advances have been made in recent years towards using higher carrier frequencies (which generally result in higher data rates), up into the X- through Ka-bands. Higher data rates are more readily achievable with higher frequencies because data rate is proportional to the bandwidth used for communication, and bandwidth is more readily available in the higher frequencies. There is currently significant crowding of the lower RF frequencies, especially in S-band from cell phones (1).

This report recommends efficient modulation and coding schemes for spacecraft power and bandwidth in order to increase the data rate and meet bandwidth constraints with the limited power and mass for CubeSat spacecraft. Advanced coding, such as the CCSDS Low-density parity-check code (LDPC) family, with various code rates is a powerful technique to provide bandwidth and power tradeoffs with high-order modulation to achieve high data rate requirements for CubeSat missions. Digital Video Broadcast Satellite Second Generation (DVB-S2), a significant satellite communications standard, is a family of modulations and codes for maximizing data rates and minimizing bandwidth use, along with size, weight, and power (SWaP). DVB-S2 uses power and bandwidth efficient modulation and coding techniques to deliver performance approaching theoretical limits of radio frequency (RF) channels. NASA's Near Earth Network (NEN) has conducted testing at NASA WFF to successfully demonstrate DVB-S2 over a S-band 5 MHz channel achieving 15 Mbps with 16 APSK LDPC 9/10 code (2)

Received signal power will decrease, as the transmission distance gets larger, thus larger spacecraft on deep space missions usually use dish antennas because of their ability to focus radio transmissions into a precise directional beam. Thus, spacecraft must be able to point accurately. The large physical size and high pointing requirements of a parabolic dish antenna make such an antenna difficult to integrate with a CubeSat. Developers have sought alternatives, especially as the attitude determination and control of CubeSats gets better (refer to GNC Chapter).

As of this 2020 edition, only the two MarCO SmallSats have operated beyond low-Earth orbit. This restricted mission distance has allowed SmallSat designers to take advantage of (lower gain) whip or patch antennas in their communication systems. Due to their low directionality, these antennas can generally maintain a communication link even when the spacecraft is tumbling, which is advantageous for CubeSats lacking accurate pointing control. Monopole antennas are easily deployable from a CubeSat and multiple spacecraft teams have used VHF and UHF communications (figure 10.2). Patch antennas, such as the one shown in figure 10.3, are small and robust and do not require deployment. They are generally used from UHF through S-band on CubeSats, and are being explored for use in X-band arrays on CubeSats (3) and beyond.

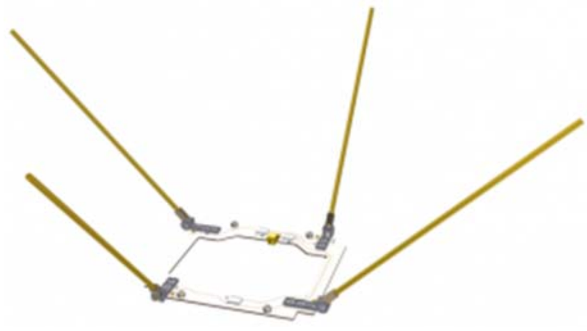


Figure 10.2 UHF deployable (4) monopole antennas for use on CubeSats. Credit: GomSpace.

Figure 10.3: CubeSat-compatible S-band patch antenna. Credit: IQ Wireless.

When deployable solar panels are not an option, as the already limited surface is prime real estate for solar cells, optically transparent antennas can maximize CubeSat surface area. Groups at the University of Houston (4) and Utah State University (5) have developed prototypes of these small, optically transparent antennas. Owing to progress from MMA Design, deployable antennas have become common in the CubeSat world. They are developing a revolutionary deployable antenna that is extremely compact and combines positive attributes of currently available CubeSat antennas. They predict that the deployable antenna will enable performance for SmallSats consistent with today's large spacecraft (6). NASA MSFC has a similar design. The Lightweight Integrated Solar Array and Transceiver (LISA-T) is a deployable array on which thin-film photovoltaic and antenna elements are embedded (7).

A key advantage of higher frequency bands (especially for CubeSats) is that antenna aperture decreases but gain remains similar. This is advantageous for ground systems too. One major disadvantage is that the atmosphere readily absorbs higher frequencies. In the Ka-band, water droplets heavily attenuate the signal, resulting in "rain fade," so greater transmitting power is required to close the link. However, this does not present a problem for intersatellite links, which do not pass through the atmosphere.

Another trend that aids in the improvement of RF based communication systems is the development of software-defined radios (SDR). By using Field Programmable Gate Arrays (FPGAs), SDRs (figure 10.4) have great flexibility that allows them to be used with multiple bands, filtering, adaptive modulation and coding schemes, without much (if any) change to hardware (1). Furthermore, spacecraft teams can change such characteristics in-flight by uploading new settings from the ground. SDRs are especially attractive for use on CubeSats, as they are becoming increasingly small and efficient as electronics become smaller and require less power. Since 2012, NASA has been operating the Space Communications and Navigation (SCaN) Testbed on the International Space Station for the purpose of SDR Technology Readiness Level (TRL) advancement, among other things (8).

Figure 10.4: Example of software defined radio, tunable in the range 70 MHz to 6 GHz. Credit: GomSpace.

CubeSat missions communicate with fixed channel codes, modulations, and symbol rates, resulting in a constant data rate that does not adapt to the dynamic link margin. Variable Coded Modulation (VCM) and Adaptive coding and modulation (ACM) adapt to the dynamics of the link by transmitting at higher data rates when the signal-to-noise ratio (SNR) is high. A flexible SDR that is capable of adaptively adjusting its modulation and coding protocol inflight with VCM/ACM will maximize the information throughput for a given communication link. NASA GRC has conducted DVB-S2 VCM/ACM experiments over S-band using a direct-to-Earth link between the SCaN Testbed and the GRC ground station (9). GRC also has demonstrated a DVB-S2 experiment using a space-based SDR transceiver on-board the SCaN Testbed to evaluate the performance of DVB-S2 VCM/ACM over the NASA Space Network (SN) (10).

In collaboration with NASA NEN, University of Alaska Fairbanks (UAF) will fly a DVB-S2 SDR in the CubeSat Communication Platform (CCP), which is the first mission to demonstrate VCM with a NEN ground station. UAF will launch CCP in the 2023 timeframe (2).

NASA has demonstrated laser-based communication (“lasercom”) with larger spacecraft such as LADEE (11). Small spacecraft have also demonstrated lasercom, such as the Optical Communications and Sensor Demonstration (OCSD) mission that launched in 2017 and successfully transmitted data, but the era for lasercom on CubeSats is just beginning.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that TRL designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

10.2 State-of-the-Art in Communication Subsystems

10.2.1 VHF and UHF

VHF and UHF frequencies are mature bands used for CubeSat communication, with several radio developers. Table 10-1 details mature technologies. Note that AAC Clyde Space’s VUTRX transceiver was developed by the French South African Institute of Technology (F’SATI) at Cape

Peninsula University of Technology (CPUT) (12). More information on L3 Communications' Cadet Radio is in (13).

Table 10-1: Developers and Products for Use in VHF/UHF		
Product	**Manufacturer**	**TRL**
Lithium-1	Astronautical Development LLC	9
CSK Phasing Board	Astronautical Development LLC	9
VUTRX	AAC Clyde Space	9
UHF Antenna	EnduroSat	9
UHF Transceiver Type II	EnduroSat	9
ETT-01EBA102-00	Emhiser Research, Inc.	9
NanoCom AX100	GomSpace	8
NanoCom ANT430	GomSpace	9
NanoCom SDR	GomSpace	7
P/N 17100	Haigh-Farr, Inc.	9
Helios Deployable Antenna	Helical Communications Technologies	6
TRXUV	ISIS	9
TRXVU	ISIS	8
Deployable Antenna System for CubeSats	ISIS	9
Cadet	L3 Communications, Inc./SDL	9
SatCOM TP0	LY3H	9
SatCOM UHF	NanoAvionics	9
UHF Antenna	NanoAvionics	9

Typically, spacecraft will use a small patch antenna or whip antenna to transmit VHF and UHF. Aside from the TRL 9 antennas listed in Table 10-1, other deployable, higher gain antennas (figure 10.5) are being developed, including a TRL 6 deployable quadrifilar helical UHF through S-band antenna by Helical Communication Technologies (figure 10.6), and a deployable helical UHF antenna by Northrop Grumman Aerospace System (14). The Dynamic Ionosphere CubeSat Experiment (DICE) mission used the L-3 Cadet NanoSat radio to downlink data at three Mbps to the NASA WFF ground station. EnduroSat has developed a UHF antenna at 435 – 438 MHz that is compatible with EnduroSat Z solar panels (figure 10.7) that was launched on the Edurosat-1 spacecraft in May 2018.

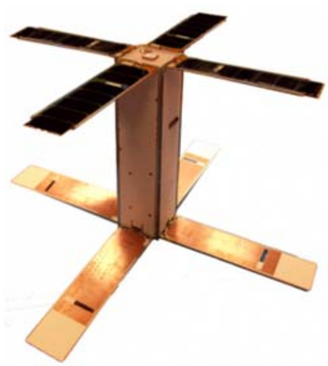


Figure 10.5: SNaP spacecraft with Haigh-Farr's deployable UHF Crossed Dipole antenna. Credit: Space Missile and Defense Command.

Figure 10.6: Example of deployable quadrifilar helical antenna. Credit: Helical Communication Technologies.

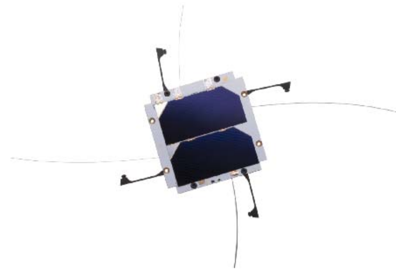


Figure 10.7: EnduroSat UHF antenna with EnduroSat solar panels. Credit: EnduroSat.

10.2.2 L-Band

In L-band, CubeSats can take advantage of legacy communications networks such as Globalstar and Iridium by using network specific transponders to relay information to and from Earth. These networks remove dependence on dedicated ground station equipment, as discussed further in the ground support equipment (GSE) section.

Table 10-2 shows examples of network-specific transponders. NearSpace Launch's (NSL) EyeStar-D2 Satellite Duplex radio has flight heritage from 2015, but no large file transfer was possible during the flight due to an unplanned two revolution per minute (rpm) spin rate (15). Since then, NSL has successfully operated EyeStar-D2 Duplex on Air Force Research Laboratory's (AFRL) SHARC, GEARRS#1, 2 and Challenger, with an on-orbit success rate of 100% (16). NSL has also developed a simplex radio, EyeStar-S2, which was successfully operated on TSAT and GEARRS #1, 2 (17). Its next generation version, EyeStar-S3 is TRL 8.

In addition, sci_Zone, Inc. is developing its next generation of simplex radio, STX3, as well as a duplex radio, and both will use the Globalstar constellation (18). The multiband HCT quadrifilar helical antenna mentioned earlier can also operate in L-band. The Hiber SmallSat flew the antenna in late 2018. (19). The HaloSat 6U CubeSat mission, launched on May 21, 2018, used the Globalstar GSP-1720, developed by Qualcomm, to receive spacecraft health status.

Table 10-2: Developers and Products for Use in L-band

Product	Type	Manufacturer	TRL	Flight Heritage
Helios Deployable Antenna	Antenna (Quadrifilar Helical)	Helical Communications Technologies	9	Hiber Smallsat
NAL Iridium 9602-LP,	Iridium Transceiver (Duplex)	NAL Research Corporation	9	
NAL Iridium 9603-3G	Iridium Transceiver (Duplex)	NAL Research Corporation	9	

EyeStar-S2	Globalstar Transmitter (Simplex)	NearSpace Launch	9	TSAT, GEARRS #1,2
EyeStar-S3	Globalstar Transmitter (Simplex)	NearSpace Launch	8	None
EyeStar-D2	Globalstar Duplex Radio	NearSpace Launch	9	GEARRS #1,2, SHARC, Challenger
Antenna SYN7391-A/B/C (Iridium)	Iridium Antenna	NAL Research Corporation	9	
STX2/STX3 Simplex	Globalstar Simplex Radio	sci_Zone, Inc.	9	
GSP-1720	Globalstar Duplex Radio	Qualcomm	9	HaloSat

10.2.3 S-Band

Table 10-3 shows examples of TRL 7+ S-band communication technology. Figure 10.8 shows a CubeSat-compatible S-band transmitter. Note that F'SATI at CPUT developed the AAC Clyde Space's products SANT and STX. The CPOD 3U CubeSat mission, which launched in mid-2018, planned to fly Haigh-Farr's S-band antennas.

Figure 10.8: CubeSat-compatible S-band transmitter for either amateur or commercial bands. Credit: AAC Clyde Space.

LJT & Associates have developed the LCT2-b, an S-band transponder to work with the Tracking and Data Relay Satellite System (TDRSS). The LCT2-b S-band BPSK TDRSS transmitter has already flown on the SOAREX-VI flight experiment (20). Similarly, Surrey Satellite Technology US LLC developed an S-band quadrifilar antenna, S-band downlink transmitter, and S-band receiver with flight heritage on spacecraft that are less than 180 kg in mass, though they have not flown on a CubeSat mission to the best knowledge of the author. Haigh-Farr also offers high-TRL technology for S-band communications.

The TechEdSat CubeSat series is a collaborative project between San Jose State University (SJSU) and the University of Idaho with oversight from the NASA ARC. The radio on the latest TechEdSat-10 (TES 10) spacecraft is an S-band transceiver using an Ettus B205mini SDR radio and a 5W RF power amplifier. This transceiver was tested at NASA WFF using BPSK modulation at 120 kbps and at ARC using QPSK at 5 Mbps. The TES 10 spacecraft deployed in July 2020 will demonstrate the radio in flight.

Table 10-3: Manufacturers and Products for Use in S-band		
Product	**Manufacturer**	**TRL**
Beryllium 2	Astronautical Development LLC	9
NanoTX	Quasonix	9
S-band Patch Antenna	Haigh-Farr, Inc.	9
B205mini	NI Ettus Research	8
SANT	AAC Clyde Space	9
STX	AAC Clyde Space	9
S-band Patch Antenna	EnduroSat	9
S-band Transmitter	EnduroSat	9
Helios Deployable Antenna	Helical Communications Technologies	6
SCR-104	Innoflight, Inc.	9
HISPICO	IQ Wireless GmbH	9
SLINK-PHY	IQ Wireless GmbH	8
TXS	ISIS	8
S-Band Patch Antenna	Surrey Satellite Technology, Ltd.	9
EWC31	Syrlinks	9
SPAN-S-T3	Syrlinks	9
SWIFT-SLX	Tethers Unlimited	9
SWIFT-XTS	Tethers Unlimited	9
CSR-SDR-S/S	Vulcan Wireless, Inc.	9
CXS-1000	L3Harris	9
Nano N2420	Microhard	9

Many antennas are available in S-band, including a NewSpace Systems stacked patch S-band antenna and the HCT quadrifilar helical antenna mentioned in the VHF and UHF section. AntDevCo, IQ Wireless, Surrey Satellite Technology and many others make S-band patch antennas that could be compatible with CubeSats. Innovation Solutions in Space (ISIS) resells the S-band patch antenna, and transmitter and receiver for IQ Wireless' HISPICO communication system. Syrlinks is a strong competitor in the European market and offers patch antennas in the S- and X-bands, among many other high-TRL products. NASA spacecraft, which use the government bands of S-band, X-band and Ka-band, may use the NASA NEN at no charge. The primary frequency bands of S, X, and Ka are more advantageous than using the UHF band, which is allocated as a secondary frequency and has an increased probability of local interference.

CubeSats have used the unlicensed ISM (Industrial, Scientific, and Medical) bands for communications. Notably, a group at Singapore's Nanyang Technological University used a 2.4 GHz ZigBee radio on its VELOX-I mission to demonstrate COTS land-based wireless systems for inter-CubeSat communication (21). Similarly, current investigations are looking at using wireless COTS products, such as Bluetooth-compatible hardware, for intra-satellite communications (22).

Furthermore, companies that traditionally design communications for larger spacecraft are now modifying some of their products for use on smaller spacecraft. One example is the COM DEV S-band transceiver (23). Honeywell acquired COM DEV in 2016, but many legacy COM DEV products are still available in their Honeywell incarnation.

10.2.4 X-band

X-band transmitters have recently become a reality for CubeSats because of the advent of commercially available Monolithic Microwave Integrated Circuits (MMICs). Industry, universities and government centers alike are trying to develop communications systems at this wavelength (24).

Table 10-4 displays TRL 9 CubeSat-compatible X-band communication hardware. Note that AntDevCo's designed "evolved" wire antennas using X5 Systems' AntSyn (Antenna Synthesis) software. The corresponding flight heritage (ST5 mission) is not of the CubeSat form factor, but each of the five spacecraft still fit into the small satellite category with a mass of 25 kg. AntDevCo also develops X-band patch antennas. Planet Labs uses a proprietary X-band radio (25).

Table 10-4: Manufacturers and Products for Use in X-band

Product	Manufacturer	TRL
Evolved X-band wire antennas	Antenna Development Corporation, Inc. (AntDevCo)	9
Quadrifilar Helix Antenna	Antenna Development Corporation, Inc. (AntDevCo)	9
EWC-30 X-band Transmitter	Syrlinks	9
EWC27 + OPT27-SRX S/X Transceiver	Syrlinks	9
XTX	AAC Clyde Space	9
XANT	AAC Clyde Space	9
X-band Patch Antenna	EnduroSat	9
X-band Transmitter	EnduroSat	9
XLINK	IQ Wireless GmbH	9
IRIS V2	JPL/SDL	9
SPAN-X-T2	Syrlinks	9

SPAN-X-T3	Syrlinks	9
HDR-TM	Syrlinks	9
EWC27	Syrlinks	9
X-band Radio	Laboratory for Atmospheric and Space Physics (LASP)/Blue Canyon Technologies (BCT)	8
SWIFT-XTX	Tethers Unlimited	9
X-band	Innoflight	5

Surrey Satellite Technology developed a high-gain X-band antenna and corresponding pointing mechanism (see figure 10.9), and an X-band transmitter that have flight heritage on spacecraft less than 180 kg in mass, but have not flown on a CubeSat mission to the best knowledge of the author.

Figure 10.9: X-band high-gain antenna and pointing mechanism. Credit: Surrey Satellite Technology, Ltd.

As of March 2019, the NEN provided service to its first CubeSat mission, the SeaHawk-1 CubeSat with a Syrlinks X-band radio. The NASA NEN WFF 11-m antenna (WG1) tracked the spacecraft with a small X-band antenna at a data rate of three Mbps. The WG1 detected good signal strength, autotracked, locked on to collect data, and successfully completed file delivery. In June 2019, the spacecraft transmitted at 50 Mbps, which is a very high data rate for a CubeSat.

JPL has also developed a CubeSat compatible transponder, IRIS V2 (figure 10.10), suitable for deep space communications in X-, Ka-, S-bands, and UHF (26). Space Dynamics Laboratory (SDL) licensed the IRIS radios. SDL will deliver future iterations of the radio. Colorado University (CU) Boulder and NASA GSFC jointly developed an X-band SDR. BCT is now selling the radio. Lower TRL technologies include an X-band transmitter from NewSpace Systems (3). A team from Utah State University has been working on an X-band antenna array that is integrated with solar panels, a novel idea that could greatly save space. This project successfully completed antenna design, inkjet printing of the antenna on glass, assembling 6U solar panel, and performing all performance tests on antennas and solar panel in the lab environment (27).

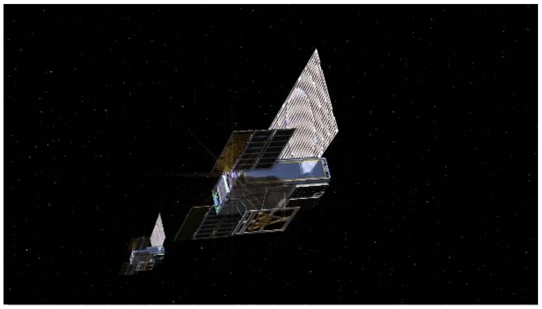


Figure 10.10: Artist's rendition of JPL's MarCO CubeSats, which use the IRIS V2 deep space transponder. Credit: JPL.

10.2.5 Lasercom

CubeSats have successfully demonstrated laser communication in space, and the technology is quickly maturing. The Aerospace Corporation, in cooperation with NASA ARC, launched three CubeSats in its AeroCube Optical Communication and Sensor Demonstration (figure 10.11). In March 2018, a systems checkout was completed and the mission entered the operational phase.

AeroCube's optical system successfully transmitted in mid-2018. The technology has matured to TRL 7.

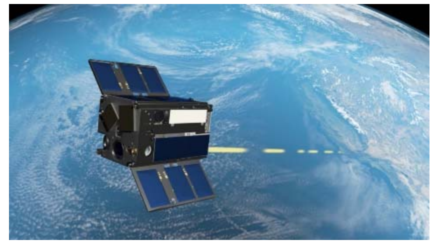


Figure 10.11: An artist rendering of laser communications for the OCSD. Credit: NASA.

Fibertek developed a 2U CubeSat lasercom system in 2018 based on a work performed under a NASA ARC Small Business Innovation Research program (SBIR), and continued to make substantial progress in lasercom and LiDAR technologies. Sinclair Interplanetary is developing the DCL-17 (TRL 5), a self-contained optical communications terminal that incorporates a built-in star tracker and a 1 Gbps laser downlink. Future lasercom endeavors include the NASA-sponsored Miniature Optical Communication Transmitter (28) and the CLICK mission (29) CLICK is a two part mission, sponsored and overseen by NASA's SST Program and involving MIT, and University of Florida for the payload and BCT for the bus. CLICK-A will demonstrate a laser downlink, CLICKB/C a laser cross-link. All CLICK spacecraft at 3U spacecraft and the payload occupies approximately 1.5U. The CubeSat lasercom module, by Hyperion Technologies, enables a bidirectional space-to-ground communication link between a CubeSat and an optical ground station, with downlink speeds of up to one Gbps and an uplink data rate of 200 Kbps.

Many other international entities are advancing in the area of CubeSat laser communications as well. The first attempt to demonstrate laser communication on a CubeSat was on-board FITSAT-1, a 1U system developed at the Fukuoka Institute of Technology in Japan. The satellite carried two arrays of high-power LEDs along with an experimental RF transceiver. The robotic arm of the International Space Station (ISS) deployed FITSAT-1 in October 2012. The German Aerospace Center is currently flying two lasercom terminals as part of its OSIRIS program. The Small Optical Transponder (SOTA) developed by the National Institute of Information and Communications Technology in Japan (NICT) has successfully demonstrated a laser space-ground link from a 50 kg microsatellite (30). Tesat-Spacecom offers the CubeLCT laser communication terminal (0.3U, 0.4 kg, 8 W, also known as OSIRIS4CubeSat (31) and offers high bandwidth space to ground data transmissions of up to 100 Mbit/s. CubeLCT is scheduled to launch aboard CubeL in 2020 (32). In addition to CubeSat terminals, larger terminals for SmallSats are under development by Tesat, Mynaric (33) and SpaceMirco (34).

All of these ventures use lasers onboard, but another lower TRL lasercom concept involves an asymmetric optical link, whereby the laser hardware is on Earth and a modulating retroreflector is on the spacecraft (refer to the Asymmetric Lasercom section).

10.2.6 Ku- to Ka-band

Ku-, K-, and Ka-band communication systems are the state-of-the-art for large spacecraft, especially in spacecraft-to-spacecraft communications, but they are still young technologies in the CubeSat world. Developers working on CubeSat compatible Ka-band communication systems include Astro Digital, Micro Aerospace Solutions, NewSpace Systems and Tethers Unlimited.

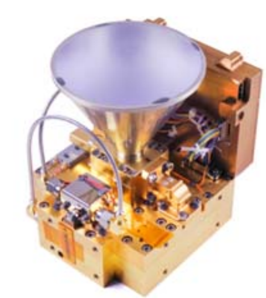


Figure 10.12: Ka-band transmitter with a horn antenna. Credit: Astro Digital.

Astro Digital, formerly known as Aquila Space, has already launched Landmapper-HD 1, a 20 kg 16U microsatellite that is the first in a constellation of 20 imaging satellites. It has a 300 Mbps Ka-band downlink DVB-S2 transmitter shown in figure 10.12. The Landmapper-BC is the predecessor to the Landmapper-HD constellation, but it unfortunately lost four satellites to launch damage. Landmapper-BC 3 v2, launched in January 2018, weighs 1 kg, and boasts a 320 Mbps

Ka-band data rate. The next generation of Ka-band DVB-S2X transmitters from Astro Digital will increase the data rate to 800 Mbps (Generation 4) and 2.0 Gbps (Generation 5).

Micro Aerospace Solutions has a TRL 5 Ku/Ka-band transceiver with a deployable 60 cm CubeSat dish antenna (35) and Tethers Unlimited has a TRL 7 Ka-band SDR transmitter called SWIFT-KTX and a TRL 5 Ka-band transceiver called SWIFT-KTRX. Table 10-5 lists some current state-of-the-art communications equipment in this category.

Table 10-5: Manufacturers and Products for Use in Ka- to Ku-band

Product	Manufacturer	TRL
AS-10075	Astro Digital	9
Ku-band Transceiver	NewSpace Systems	6
1 Gbit Transponder	NewSpace Systems	6
SDR Transceiver	NewSpace Systems	6
SWIFT-KTX	Tethers Unlimited	7
SWIFT-KTRX	Tethers Unlimited	5

At the higher frequencies, rain fade becomes a significant problem for communications between a spacecraft and Earth (36). Nonetheless, the benefits of operating at higher frequencies have justified further research by both industry and government alike. At JPL, the Integrated Solar Array and Reflectarray Antenna (ISARA) mission demonstrated high bandwidth Ka-band CubeSat communications with over 100 Mbps downlink rate (37). Essentially, the back of the 3U CubeSat is fitted with a high gain reflectarray antenna integrated into an existing solar array. The ISARA technology is currently in orbit and has recently completed a systems checkout. It will be TRL 7 following successful demonstration.

10.3 On the Horizon — Asymmetric Laser Communications

Spacecraft parameters like power, mass, and volume are constrained by cost and current capability. Ground operations, on the other hand, are not subject to the same limitations. Asymmetric laser communications leverage this imbalance. Asymmetric laser communication uses a remotely generated laser (e.g., does not require an on-board signal carrier) and modulating retroreflector (MRR) to reflect and modulate a laser beam (encoding it with spacecraft data) back to Earth (figure 10.13). The laser is located on Earth, where power and volume constraints are not as tight, while the communications payload on the spacecraft is limited to only a few watts for operation. The Naval Information Warfare Center Pacific (NIWC Pacific, formerly SPAWAR) is developing this technology using a MEMS-based MRR (38). The Navy has funded Boston Micromachines via their SBIR program to develop a Large Aperture MEMS MRR. The goal of the project is to develop MRRs with a clear aperture of 25.4 mm with packaging to survive the launch environment and operate in the vacuum of space. NASA ARC was developing a similar capability using a modulating quantum well (MQW) device as the MRR (39). NASA ARC development is currently on hold.

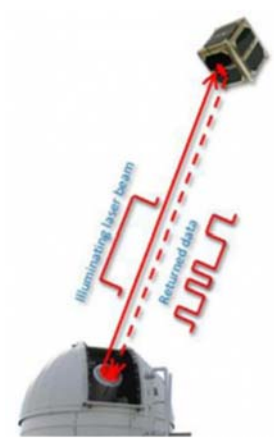


Figure 10.13: Scheme for using land-based laser to transmit data from CubeSat using on-board MRR. Credit: Salas et al. (2012)

10.3.1 Inter-CubeSat Communications and Operations

There are multiple advantages to communicating between spacecraft. As CubeSat missions employ more automation, constellations could exchange information to maintain precise positions without input from the ground. Spacecraft may relay data to increase the coverage from limited ground stations. Finally, inter-CubeSat transponders may very well become a vital element of eventual deep space missions, since CubeSats are typically limited in broadcasting power due to their small size and may be better suited to relay information to Earth via a larger, more powerful mothership.

CubeSat constellations optimize coverage over specific areas or improve global revisit times to fulfill mission objectives. There is growing interest among the NASA science community in using constellations of CubeSats to enhance observations for Earth and space science. NASA GSFC has conducted research on future CubeSat constellations. This includes CubeSat swarms, daughter ship/mother ship constellations, and NEN S- and X-band direct-to-ground links, TDRSS Multiple Access (MA) array and Single Access modes. The mothership may be a store-forward relay which is capable of transmit/receive between the subordinate CubeSats, and may downlink the science data to the ground either through a NEN direct-to-ground link at X-band or through a TDRSS Ka-band Single Access (KaSA) service. The mothership may use patch antennas to communicate with subordinate CubeSats for the inter-satellite communication link to provide the required omni-coverage using an accurate attitude pointing system for each daughtership. The mothership may use Earth coverage antennas in X-band with uniform gain for communication. In case of emergency or other reasons, the CubeSat communication may take place directly through TDRSS MA array mode, or through the NEN direct-to-ground station mode (40).

A CubeSat constellation may involve numerous CubeSats in the constellation, (e.g., tens or hundreds). Each CubeSat is typically identical from a communication perspective. One CubeSat may be mother ship-capable while the others may be subordinate (e.g., daughterships), however, multiple CubeSats may have the ability to fulfill the role of a mothership.

The study developed a Coded Division Multiple Access (CDMA) signal simulation model as a tool to support the analysis and trade study of CubeSat constellation inter-satellite link signal/orbit design optimization. The study was intended to solve for the most appropriate CDMA signal characteristics/design and CubeSat orbit for mother/daughter constellation inter-satellite link communications that would be able to downlink an adequate daily data volume to the ground. Results of the study indicate that the constellation mother/daughter ship architecture is able to produce an adequate daily data volume if the daughter and mothership CubeSats are in a coordinated orbit (for instance, formation flying). Spacecraft teams may trade the CDMA signal parameters to produce an optimum daily data volume.

If the mother/daughtership CubeSats are in an unsynchronized orbit, in order to downlink a meaningful/adequate daily volume of science data, the use of a mothership CubeSat as a store-forward relay requires intelligent protocols capable of performing efficient management and operation control of signal flow for the inter-satellite links. Cognitive radio/ad-hoc networking is a potential candidate technique for providing the functions necessary for an autonomous CubeSat inter-satellite communication network management system.

Spacecraft routinely use transponders, however, networked swarms of CubeSats that pass information to each other and then eventually to ground, have not flown. Developing networked swarms is less of a hardware engineering problem than a systems and software engineering problem, as demonstrated by NASA ARC's Edison Demonstration of Smallsat Networks (EDSN) mission (40), figure 10.14. Unfortunately, the eight small satellites that comprise the EDSN mission were lost due to launch failure. The ARC follow-on mission, the two 1.5 U Network & Operations Demonstration Satellites (Nodes), deployed from the ISS in 2016. The Nodes mission will be an opportunity to complete some of the tasks set forth in the EDSN mission. Similarly, the CubeSat Proximity Operations Demonstration (CPOD) mission, led by Tyvak Nano-Satellite Systems, "will demonstrate rendezvous, proximity operations and docking using two 3U CubeSats" (41).

Engineers from NASA MSFC are also developing inter-CubeSat communication using a peer-to-peer topology. The mesh network architecture allows for the exchange of telemetry and other data between spacecraft with no central router (42).

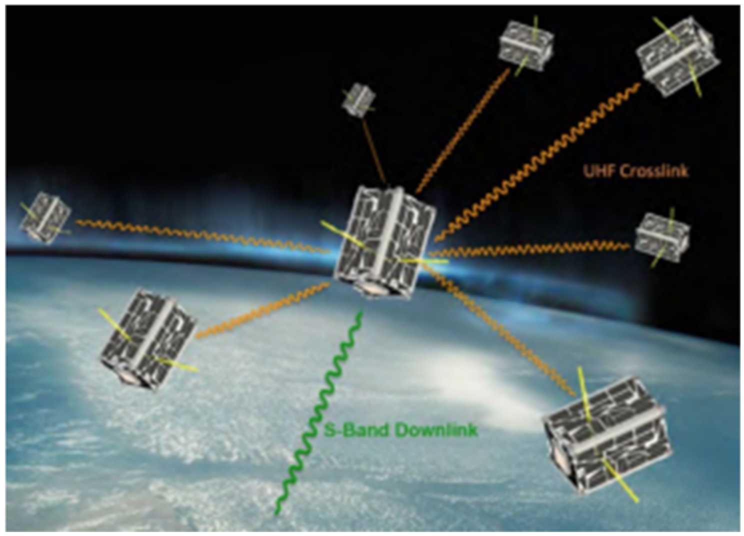


Figure 10.14: Scheme for inter-CubeSat communication for EDSN mission. Credit: NASA.

AAC Clyde Space is in the early stages of its ambitious project called the Outernet, a low-cost, mass-producible constellation of 1U CubeSats that will provide a near continuous broadcast of humanitarian data to those in need (43).

10.4 Summary

There is already strong flight heritage for many UHF/VHF and S-band communication systems for CubeSats. Less common, but with growing flight heritage, are X-band systems. Higher RF frequencies and laser communication already have CubeSat flight heritage, but with limited (or yet to be demonstrated) performance. Although there are limited Ka-band systems for CubeSats today, high rate transmitters such as the Astro Digital AS-10075 demonstrated 320 Mbps in the Landmapper-BC 3 v2 mission. On the other hand, laser communication is a spaceflight ready technology that should see future onboard laser systems with increased performance. Alternatively, a few groups are working on asymmetric laser communication, but this is still a relatively low TRL technology. There is growing interest among the NASA science community in using constellations of CubeSats to enhance observations for earth and space science.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

References

(1) Wertz, James R., Everett, David F. and Puschell, Jeffery J.: "*Space Mission Engineering: The New SMAD."* Hawthorne, CA : Microcosm Press, 2015.

(2) Wong, Yen, et al.: "*NASA Near Earth Network (NEN) DVB-S2 Demonstration Testing for Enhancing Data Rates for CubeSats."* Logan: 31th Annual AIAA/USU Conference on Small Satellites, 2019.

(3) Altunc, Serhat, et al.: "*X-band CubeSat Communication System Demonstration."* Logan, UT: s.n. 29th Annual AIAA/USU Conference on Small Satellites.

(4) Montano, R., et al.: "*Development of Low-profile Antennas for CubeSats."* 2014. 28th Annual AIAA/USU Conference on Small Satellites.

(5) Genc, A., et al.: "*Active Integrated Meshed Patch Antennas For Small Satellites."* 2012, Microwave and Optical Technology Letters, Vol. 54, pp. 1593-1595.

(6) Kelly, P.K.: "*A Scalable Deployable High Gain Antenna - DaHGR."* Logan, UT: s.n., 2016. 30th Annual AIAA/USU Conference on Small Satellites.

(7) Carr, J.A., et al.: "*The Lightweight Integrated Solar Array and Transceiver (LISA-T): second generation advancements and the future of SmallSat power generation."* Logan, UT : s.n., 2016. 30th Annual AIAA/USU Conference on Small Satellites.

(8) Johnson, S.K., Reinhart, R.C. and Kacpura, T.J.: "*CoNNeCT's approach for the development of three Software Defined Radios for space application."* Big Sky, MT: s.n., 2012 IEEE Aerospace Conference. pp. 1-13. 2012.

(9) Downey, Joseph A., et al.: "*Adaptive Coding and Modulation Experiment with NASA's Space Communication and Navigation."* s.l.: 34th AIAA International Communications Satellite Systems Conference, 2016.

(10) Downey, Joseph A. and Evans, Michael A: *DVB-S2 Experiment over NASA's Space Network.* s.l.: NASA/TM-2017-219524, 2017.

(11) Buck, Joshua and Washington, Dewayne: "NASA Laser Communication System Sets Record with Data Transmissions to and from Moon." *nasa.gov.* [Online] October 22, 2013. https://www.nasa.gov/press/2013/october/nasa-laser-communication-system-sets-record-with-data-transmissions-to-and-from/#.WzusFvlKiUk.

(12) Products. *French South African Institute of Technology.* [Online] 2015.

(13) Kneller, E.W. and Hyer, K.L.: "*Cadet: a High Data Rate Software Defined Radio for SmallSat Applications."* Logan, UT : s.n., 26th Annual AIAA/USU Conference on Small Satellites. 2012.

(14) Ochoa, D., Hummer, K. and Ciffone, M.: *"Deployable Helical Antenna for Nano-Satellites.*" 28th Annual AIAA/USU Conference on Small Satellites. Logan, UT: s.n., 2014.

(15) Voss, H.D., et al.: "*TSAT Globalstar ELaNa-5 Extremely Low-Earth (ELEO) Satellite."* 28th Annual AIAA/USU Conference on Small Satellites. 2014.

(16) Pumpkin. NSL EyeStar-D2 Duplex Globalstar Communication System . [Online] 2019. https://www.pumpkinspace.com/store/p200/NSL_EyeStar-D2_Duplex_Globalstar_Communication_System.html.

(17) Near Space Launch. EyeStar-S2 SatelliteSimplexRadio datasheet. 2020.

(18) Santangelo, A. and Skentzos, P.: "*Linkstar, a Globalstar Based Duplex Radio for Satellites In LEO - Architecture and Test Results."* Logan, UT : s.n., 30th Annual AIAA/USU Conference on Small Satellites. 2016.

(19) Satnews. Helical Communications Technology Launches Their First Antenna for Hiber Satellite. [Online] 04 16, 2019. http://www.satnews.com/story.php?number=551401380.

(20) White, B., Morgan, H. and Murbach, M.: "*SOAREX-VI Re-entry Flight Test Experiment - Electronic Systems of the Slotted Compression Ramp (SCRAMP) Probe."* 2007. International Planetary Probe Workshop - IPPW-5.

(21) Xie, Shuanglong, et al.: "*Wireless Sensor Network for Satellite Applications: a Survey and Case Study."* Unmanned Systems, Vol. 2, pp. 261-277. 2014.

(22) Schoemaker, R. and Bouwmeester, J.: "*Evaluation of Bluetooth Low Energy Wireless Internal Data Communication for Nanosatellites."* Small Satellites Systems and Services Symposium. pp. 1-15. 2014.

(23) Hatziathanasiou, I. and McLaren, C.: "*Flexible S-Band TTC (Telemetry, Tracking, and Command) for Small Spacecraft in LEO."* Logan, UT: s.n., 28th Annual AIAA/USU Conference on Small Satellites. 2014.

(24) Palo, S., et al.: "*Expanding CubeSat Capabilities with a Low Cost Transceiver."* Logan, UT: s.n., 281th Annual AIAA/USU Conference on Small Satellites. 2014.

(25) Bshuizen, C.R., et al.: "*Results from the Planet Labs Flock Constellation."* Logan, UT : s.n., 28th Annual AIAA/USU Conference on Small Satellites. 2014.

(26) Duncan, C.B., Smith, A.E. and Aguirre, F.H.: "*Iris Transponder-Communications and Navigation for Deep Space."* Logan, UT: s.n., 28th Annual AIAA/USU Conference on Small Satellites. 2014.

(27) Yekan, T., et al.: "*Integrated Solar-Panel Antenna Array for CubeSats (ISAAC)."* Logan, UT: s.n., 30th Annual AIAA/USU Conference on Small Satellites. 2016.

(28) Serra, P., et al.: "*Deep Space Laser Communication Transmitter and High Precision Timing System for Small Satellites."* Logan, UT : s.n., 2016. 30th Annual AIAA/USU Conference on Small Satellites.

(29) NASA. CubeSat Laser Infrared CrosslinK. [Online] 07 31, 2020. https://www.nasa.gov/directorates/spacetech/small_spacecraft/cubesat_laser_infrared_crosslink/.

(30) National Institute of Information and Communications Technology. World's First Demonstration of Space Quantum Communication Using a Microsatellite. *NICT.* [Online] 2017.

(31) Tesat. CubelC: SmalleSt laSer CommuniCation tranSmitter WorldWide datasheet. *Products.* [Online] 2020. https://www.tesat.de/images/tesat/products/CubeLCT_Data-Sheet.pdf.

(32) Grillmayer, Lukas and Arnold, Saskia: "*Integrating the Cubesat Space Protocol into GSOC's Multi-Mission Environment."* 34th Annual Small Satellite Conference. 2020.

(33) Mynaric. Mynaric on track to become industry-first supplier of satellite constellation-grade laser communication. [Online] 04 03, 2020. https://mynaric.com/news/mynaric-on-track-to-become-industry-first-supplier-of-satellite-constellation-grade-laser-communication/) .

(34) SpaceMicro. Laser Communication Terminals. [Online] 2020. https://www.spacemicro.com/products/lasercom.html.

(35) Lyons, R., et al.: "*Enhanced Small Satellite Communication System for Remote Planetary Exploration."* 66th International Astronautical Congress. 2015.

(36) Pelton, J.N.: "*The Basics of Satellite Communications."* s.l.: Professional Education International, Inc., 2006.

(37) National Aeronautics and Space Administration. Integrated Solar Array and Reflectarray Antenna (ISARA) for High Bandwidth Cubesats. *NASA.* [Online] 2016.

(38) Wayne, D., et al.: "*Design and Testing of a CubeSat-Sized Retroreflector Payload."* 29th Annual AIAA/USU Conference of Small Satellites. 2015.

(39) Salas, A.G., Stupl, J. and Mason, J.: "*Modulating Retro-Reflectors: Technology, Link Budgets And Applications."* 63rd International Astronautical Congress. 2012.

(40) Wong, Yen, et al.: "*An Optimum Space-to-Ground Communication Concept for CubeSat Platform Utilizing NASA Space Network and Near Earth Network."* Logan UT: 29th Annual AIAA/USU Conference on Small Satellites. 2016.

(41) Hanson, J., et al.: "*The EDSN Intersatellite Communications Architecture."* Logan, UT : s.n., 28th Annual AIAA/USU Conference on Small Satellites. 2014.

(42) National Aeronautics and Space Administration. Cubesat Proximity Operations Demonstration. *NASA.* [Online] 2013.

(43) Becker, C.: "*Mesh Network Architecture for Enabling Inter-Spacecraft Communication."* Logan, UT: s.n., 31st Annual AIAA/USU Conference on Small Satellites. 2017.

(44) Anderson, P. and Karim, S.: "*Outernet: The Development of 1U CubeSat Platforms to Enable Low-Cost Global Data Provision."* Logan, UT : s.n., 30th Annual AIAA/USU Conference on Small Satellites. 2016.

11.0 Integration, Launch, and Deployment

11.1 Introduction

Of the 492 total spacecraft launched in 2019, 245 (~50%) had mass under 200 kg and 144 (~30%) had mass between 201 kg and 600 kg (1). With an estimated 125 SmallSat constellations currently being planned, the demand for launch of SmallSats will continue to rise (2).

Since launch vehicle capability usually exceeds primary customer requirements, there is typically mass, volume, and other performance margins to consider for the inclusion of a secondary small spacecraft. Small spacecraft can exploit this surplus capacity for a relatively inexpensive ride to space. A large market of adapters and dispensers has been created to compactly house multiple small spacecraft on existing launchers. These technologies provide a structural attachment to the launcher as well as deployment mechanisms. This method, known as "rideshare," is still the main way of putting small spacecraft into orbit. As these adapters and dispensers have become more developed, dedicated ridesharing, where an integrator books a complete launch and sells the available capacity to multiple spacecraft operators without the presence of a primary customer, has taken on more popularity. Additionally, nanosatellite form factors are increasing in dimension, which require larger dispensers to accommodate these larger CubeSat sizes.

Although not a new idea, using orbital maneuvering systems to deliver small spacecraft to intended orbits is another emerging technology. Several commercial companies are developing orbital tugs to be launched with launch vehicles to an approximate orbit, which then propel themselves with their on-board propulsion system to another orbit where they will deploy their hosted small spacecraft.

In the future, the expanding capabilities of small satellites will also demand dedicated launchers. For missions that need a very specific orbit, interplanetary trajectories, precisely timed rendezvous, or special environmental considerations, flying the spacecraft as a primary spacecraft may be the best method of ascent. Technology developers and hard sciences can take advantage of the quick iteration time and low capital cost of small spacecraft, to yield new and exciting advances in space capabilities and scientific understanding.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

11.2 State-of-the-Art – Launch Integration Role

Launch options for a SmallSat include dedicated launch, traditional rideshare launch, or multi-mission launch, as described in the launch section below. Regardless of the approach, however, integration with the launch vehicle is a complex and critical portion of the mission. The launch integration effort for a primary spacecraft typically includes the launch service provider, the spacecraft manufacturer, the spacecraft customer, the launch range operator, and sometimes a launch service integration contractor (3). When launching on either a multi-mission or rideshare launch, the launch integration becomes even more complex.

When flying as a secondary spacecraft on a rideshare launch, it is generally the primary spacecraft customer who decides whether secondary spacecraft will share a ride with the primary spacecraft and, if so, how and when secondary spacecraft are dispensed. This is not always the case, however, as there are occasions where the launch vehicle contractor or a third-party integration company can determine rideshare possibilities. More flexibility may be available to secondary spacecraft that are funded through such a program, although the mission schedule is normally still determined by the primary spacecraft.

There are several options for identifying and booking a ride for a SmallSat. For rideshare and multi-mission launches, the spacecraft customer may choose to use a launch broker or aggregator to facilitate the manifesting, or work directly with the launch service provider. A launch broker matches a spacecraft with a launch opportunity whereas an aggregator provides additional services related to manifesting. In the event of a dedicated launch, the spacecraft customer generally does not use a launch broker or aggregator. In both cases, however, key aspects for integration must be managed and a launch integrator can assist or coordinate those activities for the spacecraft customer.

Whether a spacecraft customer chooses to use a launch integrator or not, certification of flight is a key spacecraft responsibility. Requirements for radio frequency licensing, NOAA remote sensing licensing, and laser communication approval are all the responsibility of the spacecraft operator to obtain (4) (5). The launch integrator or the launch service provider will require proof of licensure before launching the satellite. They will also require additional analyses and supporting data prior to launch. This may include safety documentation, orbital debris information, materials and venting data, and spacecraft specific models (6).

For rideshare and multi-mission launches, many satellites are subject to a "do no harm" requirement to protect the primary satellite or other satellites on a multi-mission launch. A list of do no harm requirements are imposed on the rideshare satellite by the launch provider, launch integrator, or primary mission owner. These requirements vary by launch provider and launch integrator, but usually include restrictions on transmitters, post separation mechanical deployments, and hazardous materials. A more comprehensive list of do no harm categories is provided in TOR-2016-02946 Rev A (7).

11.2.1 Launch Broker

A launch broker for small satellites is an individual or organization which matches a spacecraft with a launch opportunity, usually as a rideshare satellite or a multi-mission manifest spacecraft. Typically, a launch broker does not provide any additional launch integration services beyond coordinating the relationship between the spacecraft manufacturer or customer and the launch service provider.

11.2.2 Launch Aggregator

A launch aggregator performs the same services as a launch broker, but generally also provides services related to manifesting. These services can include working with the satellite customer and the launch vehicle provider to ensure that the customer's spacecraft is compatible with the launch vehicle's mission, and by performing analyses and physical integration.

11.2.3 Launch Integrator

A launch integrator may perform the services of a launch broker or aggregator, but the services associated with a launch integrator are typically much more involved. The US General Services Administration's (GSA) Professional Services Schedule (PSS) includes Commercial Space Launch Integrated Services (SLIS) for concept design and requirements analysis; system design, engineering, and integration; test and evaluation, and integrated logistics support (8). The launch integrator "works with the launch vehicle provider and coordinates all aspects, on behalf of the customer, necessary to integrate, launch, and deploy the satellite from the launch vehicle" (9).

Launch integrators can provide the integration hardware, such as CubeSat dispenser, separation system, or other hardware as described below, or this hardware may be provided by either the spacecraft customer or the launch services provider.

11.3 Launch Paradigms

The SmallSat market has grown considerably over the past decade experiencing a 23% compound annual growth rate from 2009 to 2018 (10). From 2013 to 2017 there was an average of about 140 SmallSats (less than 200 kg) launched per year. From 2017 to 2019 this number jumped to around 300 SmallSats per year and in the 1st quarter of 2020 there were over 300 SmallSats launched (1). This increase in small satellite demand has caused a shift in the launch vehicle market, as well as with many companies creating or advertising launch platforms centered around small satellites. This section will detail three types of launch methods for SmallSats and the current state of these markets. While other chapters in this report cite specific companies providing “state-of-the-art” technologies, this section will provide an overview of the different types of launches available for SmallSats rather than highlighting specific companies.

11.3.1 Dedicated Launches

In the context of this report, dedicated launches for SmallSats are those that use launch vehicles which are generally meant to be used to launch satellites with a mass less than 180 kg. This does not mean that the maximum mass to orbit is 180 kg or less, however. For the purposes of this paper, dedicated launchers will have a maximum payload of 1000 kg, as many launch vehicles being marketed for SmallSats have masses to orbit that are higher than 180 kg. The primary orbit for this type of launch are low-Earth orbit with very few companies currently targeting highly elliptical orbit (HEO), medium Earth orbit (MEO), or geostationary orbit (GEO). As reported in October, 2019, there were 148 small launch vehicles with a maximum capability of less than 1000 kg to low-Earth orbit being tracked as current and future launch vehicles, however only eight from that list were successfully flown (11).

Dedicated launches for SmallSats have many advantages. A SmallSat on a dedicated launch controls the mission requirements in whole, what they need, when they want to launch, and where they want to go. They generally have a “go / no-go” call on launch day, in case something goes wrong with their satellite pre-launch. They can also request special launch accommodations, such as a nitrogen purge or late battery charge, that are generally not available to a rideshare launch. The downside to a dedicated launch is that they are generally much more expensive than a rideshare launch.

11.3.2 Traditional Rideshare Launches

Until recently, there were only a few launchers that allowed small spacecraft to ride as primary spacecraft. The majority of small spacecraft are carried to orbit as secondary spacecraft, using the excess launch capability of larger rockets. Standard ridesharing consists of a primary mission with surplus mass, volume, and performance margins which are used by another spacecraft. Secondary spacecraft are also called auxiliary spacecraft or piggyback spacecraft. For educational small spacecraft, several initiatives have helped provide these opportunities. NASA’s CubeSat launch initiative (CSLI) for example, has provided rides to several schools, non-profit organizations, and NASA centers. As of February 2020, 109 CubeSats have been launched, and the program continues to select CubeSats for launch (12). ESA Fly Your Satellite program is a similar program which provides launch opportunities to university CubeSat teams from ESA Member States, Canada, and Slovenia (13).

From the secondary spacecraft designers’ perspective, rideshare arrangements provide far more options for immediate launch with demonstrated launch vehicles. Since almost any large launcher can fit a small payload within its mass and volume margins, there is no shortage of options for craft that want to fly as a secondary spacecraft. On the other hand, there are downsides of hitching a ride. The launch date and trajectory are determined by the primary spacecraft, and the smaller craft must take what is available. In some cases, they need to be delivered to the launch provider and be integrated on the adapter weeks before the actual launch date. Generally, the secondary spacecraft are given permission to be deployed once the primary spacecraft successfully separates from the launch vehicle, but there are instances where the rideshare spacecraft separate prior to the primary satellite (14).

11.3.3 Dedicated Rideshare Launches

Dedicated rideshare launches, also known as multi-mission launches, are those that use launch vehicles to exclusively launch multiple SmallSats. These launches have shown the ability to hold and deploy dozens of satellites to multiple altitudes, though these orbits tend not to be vastly different. While this type of mission would seem to offer more opportunities to launch small satellites, dedicated rideshare missions are not as common as traditional rideshare missions. This is likely due to difficulties in the logistics of managing so many entities with unique visions and needs, which requires a dedicated systems integrator (15).

This type of launch is particularly important to megaconstellations, however. Megaconstellations place hundreds of satellites in orbit and using small launchers will not allow for these constellations to be operational within a reasonable amount of time. Dedicated rideshares provide the opportunity to place large numbers of satellites into orbit on a single launch. In fact, dedicated rideshares for megaconstellations accounted for over 300 SmallSats launched in Q1 2020 (16), (17) (18).

11.4 Deployment Methods

The method by which SmallSats are deployed into orbit is a critical part of the launch process. The choice of deployment method depends on the form factor of the satellite. This section will discuss the deployment of CubeSats, which generally use CubeSat dispensers, and the deployment of freeflying SmallSats.

11.4.1 CubeSat Dispensers

The CubeSat form factor is a very common standard for spacecraft up to approximately 24 kg (12U CubeSat) but can also be extended to approximately 54 kg in a 27U configuration. The CubeSat form lends itself to container-based integration systems, or dispensers, which serve as an interface between the CubeSat and the launch vehicle. It’s a rectangular box with a hinged door and spring mechanism. Once the door is commanded to open, the spring deploys the CubeSat.

Many companies currently manufacture dispensers for the CubeSat form factor which follow one of two constraint systems, the rail-type dispenser and the tab-type dispenser. Due to the large number of dispenser manufacturers, the different companies are not listed here. Instead, a brief overview of the two types of dispensers is provided.

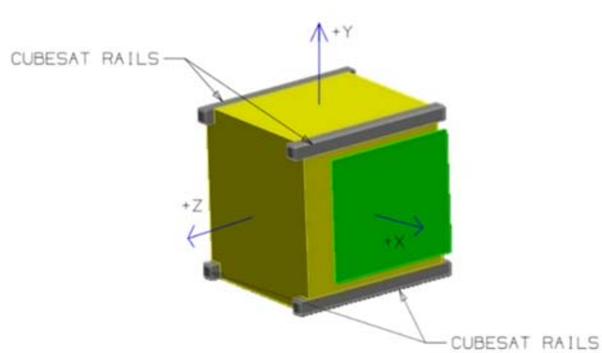


Figure 11.1: The Rail-type CubeSat. Credit: CalPoly’s CubeSat Program.

A rail-type dispenser (figure 11.1) supports CubeSats that have rails which extend the length of the CubeSat on four parallel edges. The rails on the CubeSat prevent it from rotating while inside the dispenser. After the dispenser door has been commanded to open, the rails slide along guides inside the dispenser and the CubeSat is deployed. This type of dispenser is the most widely manufactured configuration, with more than fifteen manufacturers worldwide.

A tab-type dispenser (figure 11.2) supports CubeSats with tabs which run the length of the CubeSat on two parallel edges. The dispenser grips the tabs to hold the CubeSat in place, only releasing after the door has been commanded to open. This type of dispenser is not widely manufactured as Planetary Systems Corporation holds the patent for the design (19).

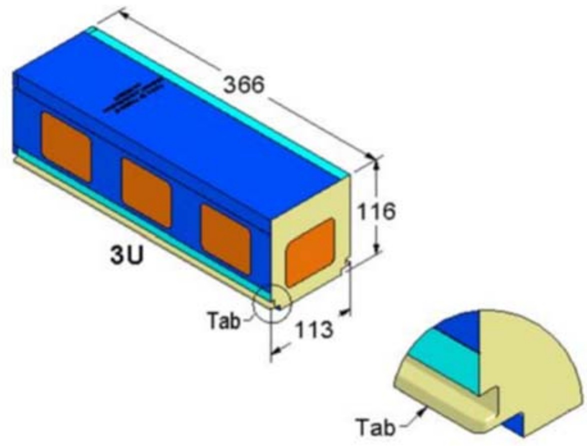


Figure 11.2: The Tab-type CubeSat. Credit: Planetary Systems Corporation.

The choice of dispenser is not always a decision made by the CubeSat. In many cases, the launch vehicle provider or launch aggregator/integrator has already determined which dispensers will be installed on the launch vehicle. As each dispenser manufacturer has slightly different volumes and requirements, it is beneficial for the CubeSat to design for as wide a range of dispensers as possible to maximize launch opportunities. Additionally, some dispenser manufacturers offer accommodations which may violate the Do No Harm requirements set forth by the launch vehicle or launch integrator, such has inhibits on deployables and transmitters. Therefore, it is beneficial for the CubeSat to evaluate Do No Harm recommendations for different launch vehicles (7).

SmallSat Separation Systems

Small satellites which do not meet the form factor of a CubeSat, or will not be using a CubeSat dispenser for integration to the launch vehicle, require a different separation mechanism. Separation systems for SmallSats generally follow either a circular pattern or a multi-point (3 or 4 point) pattern. Depending on the launch vehicle, separation systems may already be in place and available to secondary spacecraft.

Circular separation systems use two rings, held together by a clamping mechanism. One ring is attached to the launch vehicle and the other ring is attached to the spacecraft. Once the clamping mechanism is released, the two rings separate and are pushed apart by springs. Each ring then remains with the spacecraft or the launch vehicle. There are two primary types of clamping configurations, the motorized light bands (MLB) and Marman clamps.

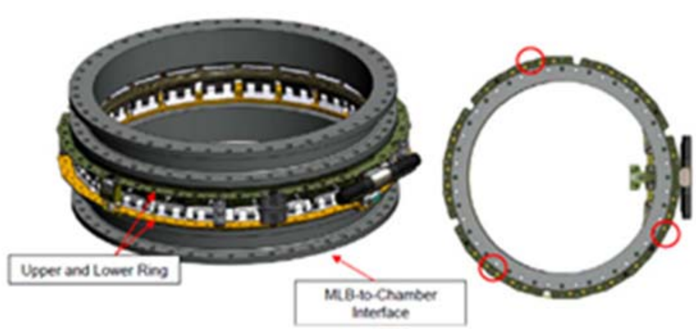


Figure 11.3: MkII Motorized Lightband. Credit: Planetary Systems Corporation.

The MLB (figure 11.3) is a motorized separation system that ranges from 8 inches to 38 inches in diameter. Smaller MLB systems are used to deploy spacecraft less than 180 kg, while larger variations may be used to separate larger spacecraft or other integration hardware such as orbital maneuvering systems, which are discussed below. The MLB's separation system eliminates the need for pyrotechnic separation, and thus deployment results in lower shock with no post-separation debris.

Marman band separation systems use energy stored in a clamp band, often along with springs, to achieve separation. The Marman band is tensioned to hold the spacecraft in place. Some Marman bands use pyrotechnic devices to cut the clamping bolt, however many companies offer a low shock release mechanism which is potentially better for the spacecraft. Sierra Nevada produces a Marman band separation system known as Qwksep, which uses a series of separation springs to help deploy the spacecraft after clamp band release. RUAG Space provides several circular separation systems which use their Clamp Band Opening Device (CBOD) release mechanism to reduce shock impact on the spacecraft (20).

Several companies are now providing multi-point separation systems instead of the circular band. Using a multi-point separation system may result in mass savings over a circular separation system. However, some systems require additional simultaneous signals from the launch vehicle provider to ensure proper release. The RUAG PSM 3/8B is a low-shock separation nut developed to fit the OneWeb satellites (21). It requires additional firing commands from the launch vehicle or a dedicated sequencing system. ISIS has also developed the M3S Micro Satellite Separation System, see figure 11.4, which is designed for satellites up to 100 kg but can be configured for higher masses (22).

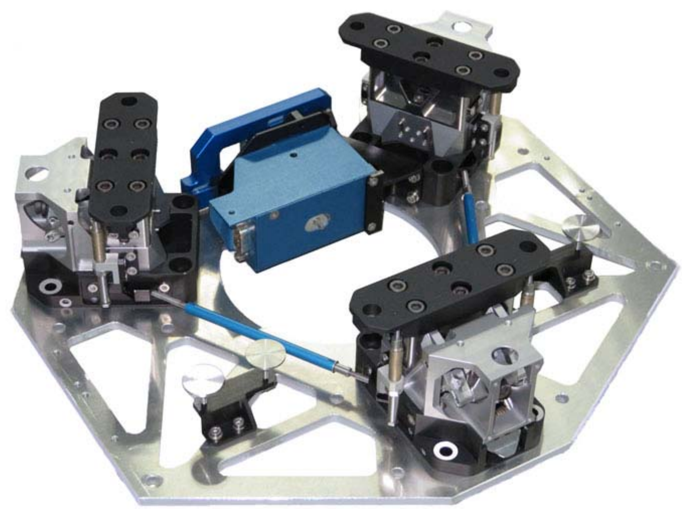


Figure 11.4: ISIS M3S Micro Satellite System. Credit: ISIS.

11.4.3 Integration Hardware

Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)

The ESPA ring (figure 11.5) is a multi-payload adapter for large primary spacecraft originally developed by Moog Space and Defense Group. Six 38 cm (15") circular ports can support six auxiliary payloads up to 257 kg (567 lb) each. It was used for the first time on the Atlas V STP-1 mission in 2007. The ESPA Grande (figure 11.6) uses four 61 cm (24") circular ports which can carry spacecraft up to 450 kg (991 lb) (23). Although developed by Moog, a number of other companies now offer similar designs in different configurations.

Figure 11.6: ESPA Grande Ring. Credit: Moog, Inc.

Small Spacecraft Mission Service (SSMS) Dispenser

ESA has developed the Small Spacecraft Mission Service dispenser for the Vega launch vehicle (figure 11.7). This dispenser comes in a variety of different modular parts which can be configured based on the satellite launch manifest. The modularity of the dispenser provides greater flexibility for accommodating different customers (24).

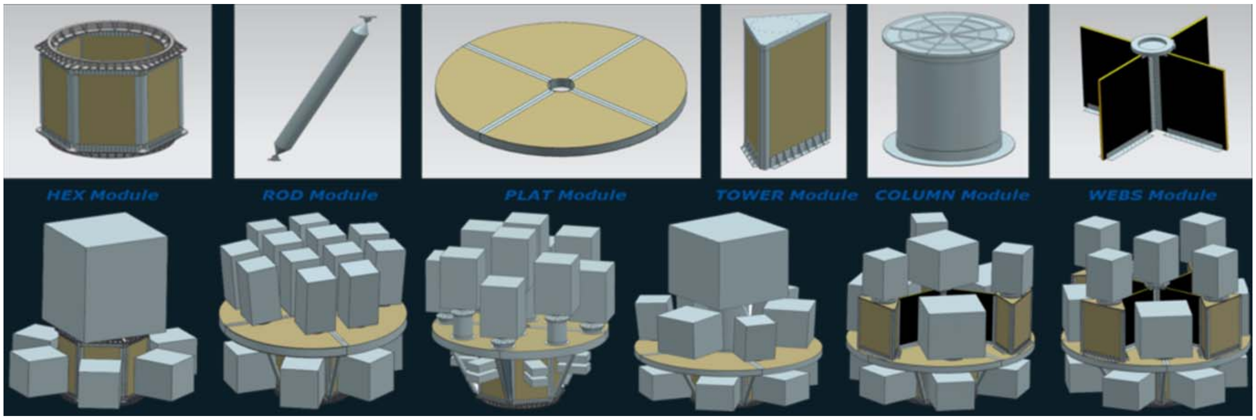


Figure 11.7: The European Space Agency Small Spacecraft Mission Service Dispenser for the Vega Launch Vehicle (24). Credit: European Space Agency.

Dual / Multi Payload Attach Fittings (DPAF / MPAF)

Many launch vehicle providers have existing accommodations for two or more payloads which are sometimes referred to as Dual Payload Attach Fittings (DPAF) or Multi Payload Attach Fittings (MPAF). As these are generally launch vehicle specific, and occasionally mission specific, they are not discussed here.

Orbital Maneuvering / Transfer Vehicles

One of the main disadvantages of riding as a secondary spacecraft (even on a dedicated ride-share mission) is the inability to launch into the desired orbit. The primary spacecraft determines the orbital destination, so the secondary spacecraft orbit usually does not perfectly match the customer's needs. However, by using a space tug, secondary spacecraft are able to maneuver much closer to their desired orbits.

Propulsive ESPA

The ESPA Ring, discussed above, provides the structure to which SmallSats or CubeSat dispensers are mounted. However, there are several options to add propulsion to the ESPA ring to use it as a space tug.

Moog OMV

Moog Space and Defense has developed the Moog Orbital Maneuvering Vehicle (OMV), see figure 11.8, line of tugs which support different mission types. COMET is the baseline OMV

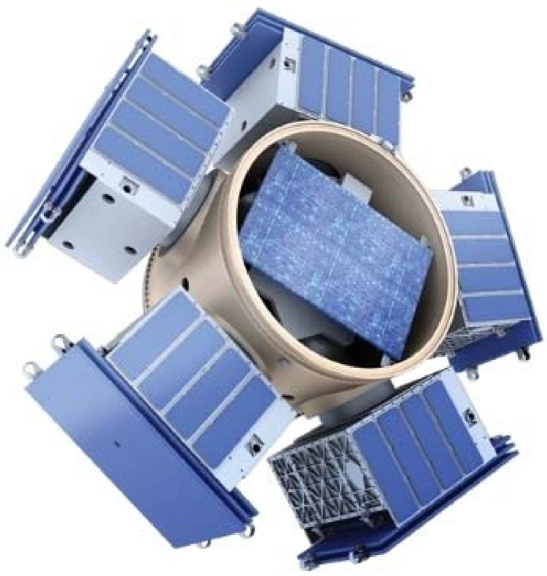


Figure 11.8: Moog OMV. Credit: Moog, Inc.

and it can fly with several satellites mounted to it on a multi-manifest mission. Once COMET has separated from the launch vehicle, it can maneuver to reach an orbit that is more desirable for the spacecraft mounted to it. Moog has several variations on the COMET OMV for longer duration or higher-power missions (25). Moog has also developed OMVs for launch vehicles that have spacecraft interfaces smaller than 60 inches, specifically the Minotaur Orbital Maneuvering Vehicle (M-OMV), which is packaged specifically for the Northrop Grumman Minotaur launch vehicles, and the Small Launch Orbital Maneuvering Vehicle (SL-OMV).

Northrop Grumman ESPAStar

Northrop Grumman's ESPAStar platform (figure 11.9) is similar to the Moog COMET in that it uses an ESPA ring as part of the structure. Additionally, it provides power, pointing, telemetry, command and control for the attached satellites or payloads (26). ESPAStar was developed from the ESPA Augmented Geostationary Laboratory Experiment (EAGLE), which was developed for the Air Force Research Laboratory and was launched in April 2018.

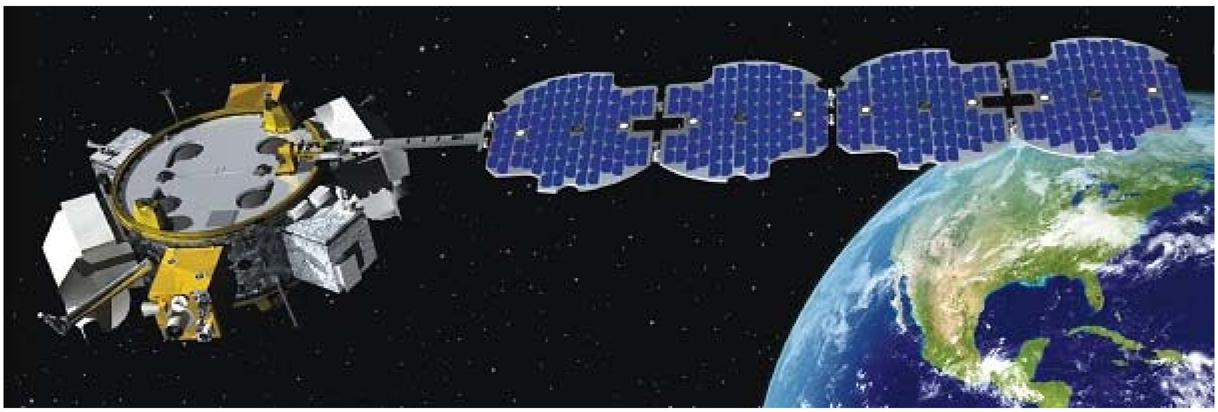


Figure 11.9: Northrop Grumman's ESPAStar Platform. Credit: Northrop Grumman.

Spaceflight Sherpa

In addition to Moog and Northrop Grumman, Spaceflight will also offer a series of orbital transfer vehicles beginning no earlier than the end of 2020 (27). Spaceflight's platform, the Sherpa, is a SmallSat deployer and space tug that can host payloads. At the time of the 2020 report, details on the Sherpa NG (next generation) were not available.

ION CubeSat Carrier

D-Orbit is an Italian space company which has developed a free-flying propulsive dispenser, the ION CubeSat Carrier. This carrier can host CubeSats from 3U to 12U in size and up to a total volume of 48U. Once the dispenser has separated from the launch vehicle, it can ferry satellites around in low-Earth orbit or carry them up to medium earth orbit and release them into distinct orbital slots (28). The first launch of the ION CubeSat Carrier is scheduled for August 2020.

Vigoride

Momentus Space is developing an in-space orbit transfer service for SmallSats, named Vigoride (figure 11.10). The maximum payload mass on Vigoride is 700 kg, and it can be launched from an ESPA or ESPA Grande ring, from ISS airlocks, or a launch vehicle. It uses water plasma engines to change the orbit prior to releasing payloads at their final orbit (29). The first flight for Vigoride is planned for fourth quarter 2020.

The orbital maneuvering and transfer vehicles listed here are not an exhaustive list of all those being developed, but they provide an overview of current state-of-the-art technologies and their development status. There was no intention of mentioning certain companies and omitting others based on their technologies.

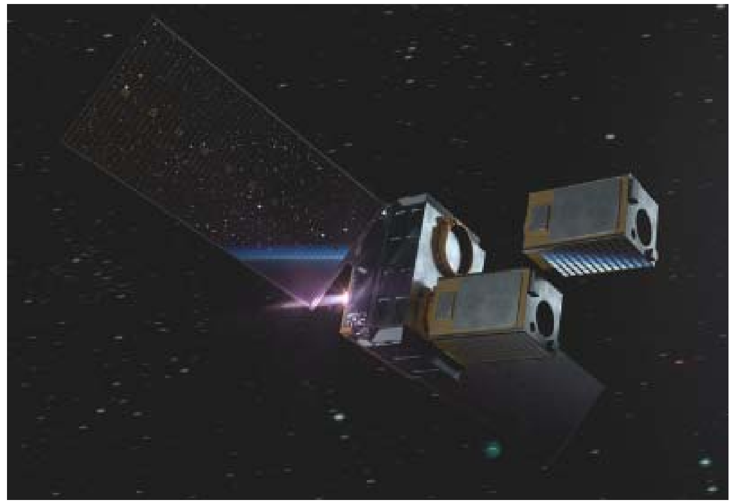


Figure 11.10: Vigoride Credit: Momentus.

11.5 International Space Station Options

The International Space Station (ISS) provides several methods for deploying CubeSats and SmallSats. The sections below discuss SmallSat deployment from the ISS as well as deployment above the ISS. The ISS also accommodates hosted payloads for experiments, but those accommodations are outside the scope of this chapter as they are for individual payloads themselves and not satellites.

11.5.1 Deployment from ISS

The ISS also provides several options for deploying satellites. Generally, the satellites are launched below the ISS to avoid potential contact with the ISS. Below are several options available for launching from the ISS.

Nanoracks ISS CubeSat Deployer (NRCSD)

Nanoracks CubeSat Deployer (NRCSD) (figure 11.11) is a self-contained CubeSat dispenser system that mechanically and electrically isolates CubeSats from the ISS, cargo resupply vehicles, and ISS crew. The NRCSD is a rectangular tube that consists of anodized aluminum plates, base plate assembly, access panels, and deployer doors. The inside walls of the NRCSD are a smooth bore design to minimize and/or preclude hang-up or jamming of CubeSat appendages during deployment, should they become released prematurely.

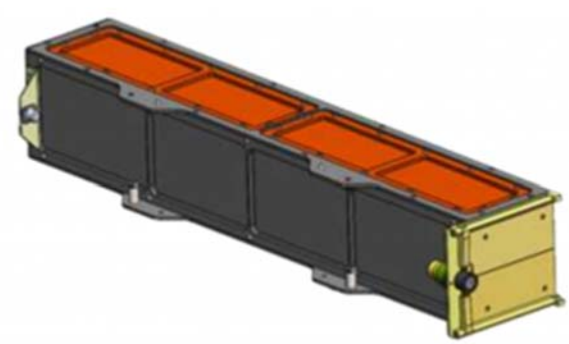


Figure 11.11: Nanoracks CubeSat Deployer. Credit: Nanoracks.

For deployment, the platform is moved outside via the Kibo Module's Airlock and slide table that allows the Japanese Experimental Module Remote Manipulator System (JEMRMS) to move the dispensers to the correct orientation and provides command and control to the dispensers. Each NRCSD is capable of holding six CubeSat units as large as a 6U (1 x 6U). The NRCSD DoubleWide can accommodate CubeSats up to 12U (2 x 6U) with Nanoracks being able to launch up to 48U per cycle. The CubeSats deploy at a 51.6° inclination, 400 – 415 km orbit 1 to 3 months after berthing at station. As of February 2020, Nanoracks has completed its 17th mission (30).

Nanoracks ISS MicroSatellite Deployment – Kaber Deployer Program

Nanoracks Kaber Microsat Deployer is a reusable system that provides command and control for satellite deployments into orbit from the Japanese Experimental Module Airlock Slide Table of the ISS. The Kaber supports satellites with a form factor of up to 24U and mass of 82 kg, and uses a Nanoracks separation system with circular interface similar to the separation systems discussed above. Satellites are launched to the ISS on a pressurized launch vehicle, mounted to the Kaber deployer, and deployed outside the ISS (31).

JEM Small Satellite Orbital Deployer (J-SSOD)

The Japanese Experimental Module (JEM) Small Satellite Orbital Deployer (J-SSOD) is a Japanese Aerospace Exploration Agency (JAXA) developed CubeSat deployer used to launch CubeSats from the ISS. The J-SSOD can launch CubeSats up to the 6U form factor (2x3 configuration). The satellites, with their dispensers, are installed on the Multi-Purpose Experiment Platform prior to Kibo's robotic arm Japanese Experiment Module Remote Manipulator System (JEMRMS) transferring the MPEP to the release location. At that point, the CubeSats are deployed (32).

11.5.5 Deployment Above ISS

Regular access to the ISS is very attractive for many satellite providers. However, the lower altitude of the ISS means the in-orbit lifetime for the satellite is generally shorter. This section discusses the options that have been developed to deploy CubeSats above the ISS using a cargo resupply module.

Nanoracks External CubeSat Deployer (ENRCSD)

Nanoracks External CubeSat Deployer (ENRCSD) is a system to deploy CubeSats into orbit above the ISS by using the Northrop Grumman Cygnus ISS Cargo Resupply vehicle. The first mission to use the ENRCSD was on the OA-6 mission in March 2016. Up to 36U of CubeSats in the 1U to 6U linear form factor may be deployed above the ISS with each Cygnus mission. CubeSats are installed in the Nanoracks deployer and mounted externally to the Cygnus vehicle before launch. They remain external to the ISS for the duration of time that Cygnus is attached to the station. Once Cygnus departs the ISS, it raises to an altitude of approximately 500 km and deploys the CubeSats (33).

SEOPS SlingShot

SEOPS SlingShot is a system to deploy CubeSats into orbit above the ISS using the Northrop Grumman Cygnus ISS Cargo Resupply vehicle. The first mission to use the SlingShot was in 2019. SlingShot can fly up to 72U of CubeSats per Cygnus mission; the largest CubeSat form factor it can fly is 12U. This deployment method differs from the ENRCSD in that the satellites and their dispensers are flown to the ISS as pressurized cargo on a resupply mission. Astronauts remove the satellites and install the dispensers onto the Cygnus Passive Common Berthing Mechanism (PCBM) just prior to Cygnus' departure from the station. Once Cygnus departs the ISS, it raises to an altitude of approximately 500 km and deploys the CubeSats (34). As these CubeSats are hosted in a different location and manner than the ENRCSD CubeSats, it is possible for Cygnus to carry CubeSats in both locations on a single mission.

11.7 On the Horizon

11.7.1 Integration

From a launch broker perspective, there are some companies hoping to develop an online booking system for launches, similar to web-based airline ticket platforms. One of these companies is Precious Payloads (35). The premise is that you click on your preferred destination and timeline and the website provides you with launch options. As the supply of launches increases, there may be a larger increase in demand for this type of service.

11.7.2 Launch

As discussed in the launch section above, there are always several new launch vehicles in development. The number continues to grow every year and how many become realized remains to be seen.

11.7.3 Deployment

There are a number of emerging capabilities in the area of SmallSat deployment. They consist of CubeSat dispensers, SmallSat separation systems, and orbital maneuvering and transfer vehicles. The technologies listed below are not a comprehensive list, but simply highlight two of the more unique forthcoming capabilities.

FANTM-RiDE

The FANTM-RiDE small spacecraft dispenser (figure 11.12) was initially developed by TriSept Corporation and Moog, Inc. before TriSept spun-off the effort to the Xtenti company. It deploys CubeSats or SmallSats from an ESPA compatible volume (24 x 28 x 38 in). It is compatible with multiple vehicles and adapters and is designed to be mass- and center-of-gravity-tuned, meaning it maintains the same mass properties regardless of its contents. This property allows for late spacecraft swap-outs or removals from the launch vehicle without affecting launch vehicle specific analyses, like the coupled loads analysis (36).

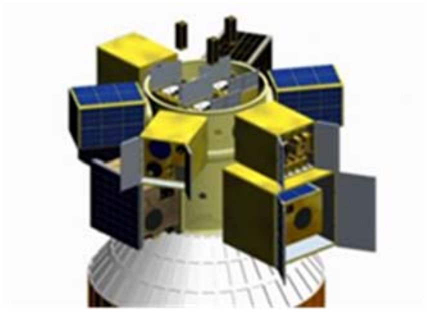


Figure 11.12: FANTM-RIDE. Credit: Xtenti.

11.8 International Space Station

11.8.1 Bishop Nanoracks Airlock Module

A new airlock module is being developed for the ISS by Nanoracks. This module, Bishop, would be the first commercialized, private module for the space station (37). Bishop provides more than five times the volume of the current Japanese Experimental Module (JEM) airlock, allowing for larger satellites and payload experiments. Bishop can host satellites and payloads, as well as deploy them, based on the needs of the mission **Error! Reference source not found.**.

11.9 Summary

A wide variety of integration and deployment systems exist to provide access to space for small spacecraft. While leveraging excess LV performance will continue to be profitable into the future, dedicated launch vehicles and new integration systems for small spacecraft are becoming popular. Dedicated launch vehicles take advantage of rapid integration and mission design flexibility, enabling small spacecraft to dictate mission parameters. New integration systems will greatly increase the mission envelope of small spacecraft riding as secondary spacecraft. Advanced systems may be used to host secondary spacecraft in-orbit, to increase mission lifetime, expand mission capabilities, and enable orbit maneuvering. In the future, these technologies may yield exciting advances in space capabilities.

The previous few years have shown an increase in the number of available launch vehicles dedicated to small spacecraft. Additionally, the CubeSat Design Specification has been revised to include the nanosatellite classification to 12U (38), which has led to the design of dispensers that can be accommodated on a variety of launch vehicles.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email.

References

(1) Bryce Space and Technology. Smallsats by the Numbers 2020. [Online] https://brycetech.com/reports/report-documents/Bryce_Smallsats_2020.pdf.

(2) ISS National Laboratory. Investment Perspectives: Charts and Thoughts from SmallSat Symposium 2020. [Online] https://www.issnationallab.org/blog/investment-perspectives-charts-thoughts-2020smallsat-symposium/.

(3) AIAA. AIAA R-099-2001. *Recommended Practice Space Launch Integration.* Reston, VA, USA : American Institute of Aeronautics and Astronautics, 2001.

(4) Sims, Eleni M and Braun, Barbara M. Navigating the Policy Compliance Roadmap for Small Satellites. s.l. : The Aerospace Corporation, November 2017.

(5) Department of Defense. *DoD Instruction 3100.11: Management of Laser Illumination of Objects in Space.* 2016.

(6) California Polytechnic State University, San Luis Obispo (Cal Poly) CubeSat Systems Engineer Lab. CubeSat 101 Basic Concepts and Processes for First-Time CubeSat Developers. s.l. : NASA CubeSat Launch Initiative, October 2017.

(7) Read, Andrew, et al. Rideshare Mission Assurance and the Do No Harm Process. s.l. : The Aerospace Corporation, February 28, 2019.

(8) Kenitzer, Stephanie. *Three, Two, One …. Liftoff - GSA Adds Commercial Space Launch Integration Services to Schedules.* [Online] March 30, 2016. https://interact.gsa.gov/blog/three-two-one-%E2%80%A6-liftoff-gsa-adds-commercial-space-launch-integration-services-schedules.

(9) US General Services Administration. GSA Professional Services Schedule Space Launch Integrated Services (SLIS) Implementation Guide. March 16, 2016.

(10) Puteaux, Maxime and Najjar, Alexandre. Analysis | Are smallsats entering the maturity stage? *SpaceNews.* [Online] August 6, 2019. https://spacenews.com/analysis-are-smallsats-entering-the-maturity-stage/.

(11) Werner, Debra. How many small launch vehicles are being developed? Too many to track! *SpaceNews.* [Online] October 24, 2019. https://spacenews.com/carlos-launch-vehicle-update-iac/.

(12) Hill, Denise. The CubeSat Launch Initiative Celebrates its 100th CubeSat Mission Deployment. [Online] February 19, 2020. https://www.nasa.gov/feature/the-cubesat-launch-initiative-celebrates-its-100th-cubesat-mission-deployment.

(13) New CubeSat Missions Selected for the Third Cycle of Fly Your Satellite. [Online] 02 03, 2020. https://www.esa.int/Education/CubeSats_-_Fly_Your_Satellite/New_CubeSat_missions_selected_for_the_third_cycle_of_Fly_Your_Satellite.

(14) Erwin, Sandra. Air Force cubesat successful deployed from Atlas 5 upper stage. *Spacenews.* [Online] 08 08, 2019. https://spacenews.com/air-force-cubesat-successfully-deployed-from-atlas-5-upper-stage/.

(15) *Behind the US's largest Rideshare Launch: Spaceflight's SSO-A.* Roberts, Jeffrey and Hadaller, Adam. Logan, UT : s.n., 2019. SmallSat. p. 10.

(16) Atkinson, Ian.: "Spacex Successfully Launches Sixth Starlink Launch Despite Engine Issue." *NASA Spaceflight.* [Online] March 18, 2020. https://www.nasaspaceflight.com/2020/03/spacex-sixth-starlink-fifth-booster-reflight/.

(17) Wattles, Jackie: "The race for space-based broadband: OneWeb launches 34 more internet satellites." *CNN Business.* [Online] February 6, 2020. https://www.cnn.com/2020/02/06/tech/oneweb-satellite-internet-launch-scn/index.html.

(18) Henry, Caleb: "Soyuz Launches 34 Oneweb Satellites." *SpaceNews.* [Online] March 21, 2020. https://spacenews.com/soyuz-launches-34-oneweb-satellites/.

(19) Holemans, Walter and Hevner, Ryan: "*Canisterized Satellite Dispenser." 9,415,883 B2* United States of America, 2016.

(20) RUAG. Payload Adapter Systems for EELV. [Online] https://www.ruag.com/sites/default/files/2016-11/payload_adapter_system_for_EELV.pdf.

(21) RUAG. Separation Nut PSM 3/8B. [Online] https://www.ruag.com/sites/default/files/media_document/2019-03/Separation%20Nut%20PSM%2038B.pdf.

(22) ISIS. M3S Micro Satellite Separation System. [Online] https://www.isispace.nl/wp-content/uploads/2018/09/M3S_Flyer.pdf.

(23) Moog. ESPA Overview. [Online] https://www.csaengineering.com/products-services/espa.html.

(24) European Space Agency. SSMS modular parts. [Online] https://www.esa.int/ESA_Multimedia/Images/2019/06/SSMS_modular_parts#.XuOX3YQCe7o.link.

(25) Moog. The Orbital Maneuvering Vehicle. [Online] https://www.moog.com/markets/space/omv.html.

(26) Messier, Doug. Orbital ATK Awarded USAF Contract for Long-Duration Propulsion ESPA Spacecraft. *Parabolic Arc.* [Online] December 12, 2017. http://www.parabolicarc.com/2017/12/12/orbital-atk-awarded/.

(27) Henry, Caleb: "Spaceflight Planning Three Sherpa Launches in 2021." *Spacenews.com.* [Online] Aug. 20, 2020. https://spacenews.com/spaceflight-planning-three-sherpa-launches-in-2021/.

(28) D-Orbit. D-Orbit About Us. [Online] https://www.dorbit.space/about-us.

(29) Momentus. Vigoride User's Guide V1.0. [Online] February 23, 2020. https://momentus.space/site/wp-content/uploads/2020/02/Momentus-Vigoride-Users-Guide.pdf.

(30) Nanoracks. ISS CubeSat Deployment. [Online] https://nanoracks.com/products/iss-cubesat-deployment/.

(31) Nanoracks. Kaber Nanoracks ISS Microsatellite Deployment System. [Online] https://nanoracks.com/wp-content/uploads/NRMSD-overview.pdf.

(32) JAXA. JEM Small Satellite Orbital Deployer (J-SSOD). [Online] https://iss.jaxa.jp/en/kiboexp/jssod/.

(33) Nanoracks. External Cygnus Deployment. [Online] https://nanoracks.com/products/external-cygnus-deployment/.

(34) NASA. SlingShot. [Online] https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Facility.html?#id=7847.

(35) Foust, Jeff: "Options Grow For Smallsats Seeking Secondary Payload Opportunities." *SpaceNews.* [Online] August 17, 2017. https://spacenews.com/options-grow-for-smallsats-seeking-secondary-payload-opportunities/.

(36) Xtenti. FANTM-RiDE Features. [Online] http://www.fantm-ride.com/news_features/news_features.html.

(37) Natario, Nick: "Commercial Space Companies In Houston Looking Forward To Spacex Launch." *ABC13 Eyewitness News.* [Online] May 26, 2020. https://abc13.com/society/commercial-space-companies-looking-forward-to-spacex-launch-/6213469/.

(38) The CubeSat Program, Cal Poly SLO. CubeSat Design Specification (CDS) Rev 14. San Luis Obispo, California : s.n., July 14, 2020.

12.0 Ground Data Systems & Mission Operations

12.1 Introduction

A typical mission is comprised of three operational components: space, ground, and user segments, as illustrated in figure 12.1.

The space segment consists of the payload and spacecraft bus system and relies on its ability maintain operational stability in order to receive and transmit information. The ground segment includes all the ground-based elements that are used to collect and disseminate information from the satellite to the user. The primary elements of a ground system are summarized in table 12-1.

All small satellites use some form of a ground segment to communicate with the spacecraft, whether it be hand-held radios using an amateur frequency, or a large dish pulling down data on a non-federal or federal frequency.

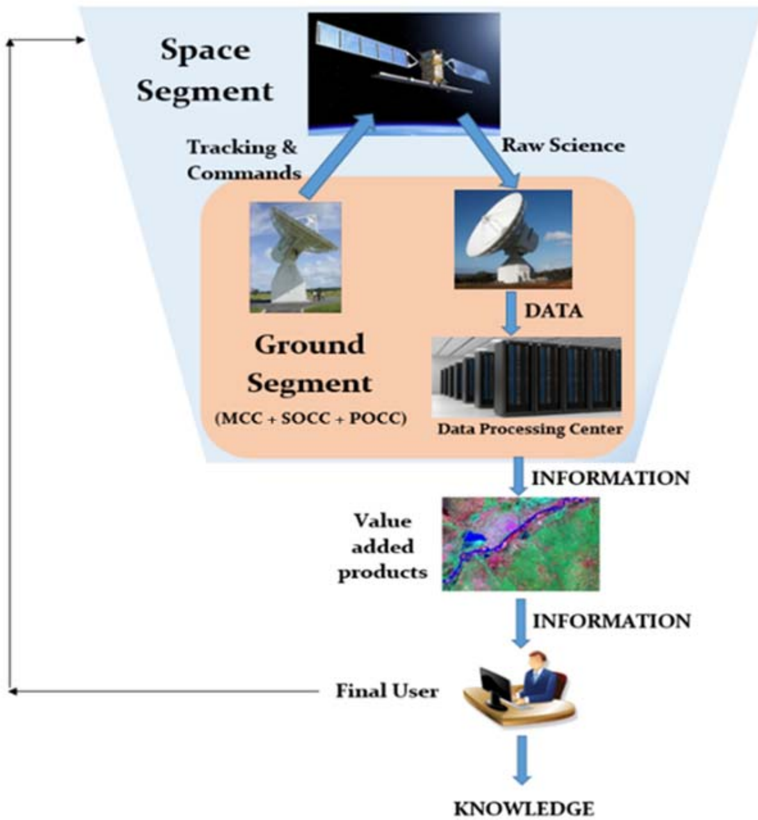


Figure 12.1: Functional relationship between the space segment, ground segment and final user for a small satellite mission. Credit: NASA.

Table 12-1: Primary Elements of a Ground System	
Element	**Function**
Ground Stations	Telemetry, tracking, and command interface with the spacecraft
Ground Networks	Connection between multiple ground elements
Control Centers	Management of the spacecraft operations
Remote Terminals	User interface to retrieve transmitted information for additional processing

The ground segment design can depend on a number of factors which may include, but are not limited, to the following:

- Data volume to satisfy mission requirements
- Location of the ground assets relative to mission orbit parameters
- Budget limitations
- Distribution of the team

- Affiliation of who controls the spacecraft (federal vs. non-federal users)
- Regulatory requirements

The ground system is responsible for collecting and distributing the most valuable asset of the mission: the data. Using the proper ground system is key to mission success. The sections to follow will discuss elements of the ground system in more detail, provide a snapshot of current ground system technologies, and touch on new technologies that can provide future advancement. The author would like to highlight that the presented tables are not intended to be exhaustive but to provide an overview of current state-of-the-art technologies and their development status. There was no intention of mentioning certain companies and omitting others based on their technologies.

12.2 Ground Systems Architecture

A typical small satellite mission has the following elements within the ground system architecture:

- Spacecraft Terminal: Transceiver (optical, RF or other) on the spacecraft to transmit and receive information, including related hardware such as antennas
- Ground Station Terminal: Transmitter and receiver or transceiver (optical, RF or other) at the ground station to transmit and receive information, including related hardware such as antennas
- Mission Operations Center (MOC):
  - Commands the spacecraft
  - Monitors spacecraft performance
  - Requests and retrieves data as necessary
- Science Operations Center (SOC):
  - Generates and disseminates science data products
  - Determines science operations to be relayed to the MOC
- Ground Station Data Storage and Network:
  - Provides live connectivity to a MOC for commands and telemetry
  - Temporarily stores data to be retrieved by the MOC and/or SOC

Figure 12.2 shows a generic small satellite ground architecture that uses NASA's Near Earth Network (NEN) for nominal ground passes and the NASA Space Network (SN) for low-latency messaging. In this architecture, the MOC is responsible for all communication to and from the spacecraft, while the SOC and engineering teams can work both directly through the MOC to process commands. This is especially helpful during commissioning and troubleshooting instances where the engineering team needs direct access to the flight system. This architecture also provides a separate database generated from the MOC of telemetry and housekeeping data that is accessible to stakeholders.

12.3 Frequency Considerations

In order for the spacecraft transceiver to talk with the ground station, they need to be on a coordinated frequency. Selecting transmit and receive frequencies are a critical part of the spacecraft communications system design process. Key drivers in selecting a frequency include data volume needs and ground station availability (number of passes). Frequencies are divided into different bands as shown in table 12-2.

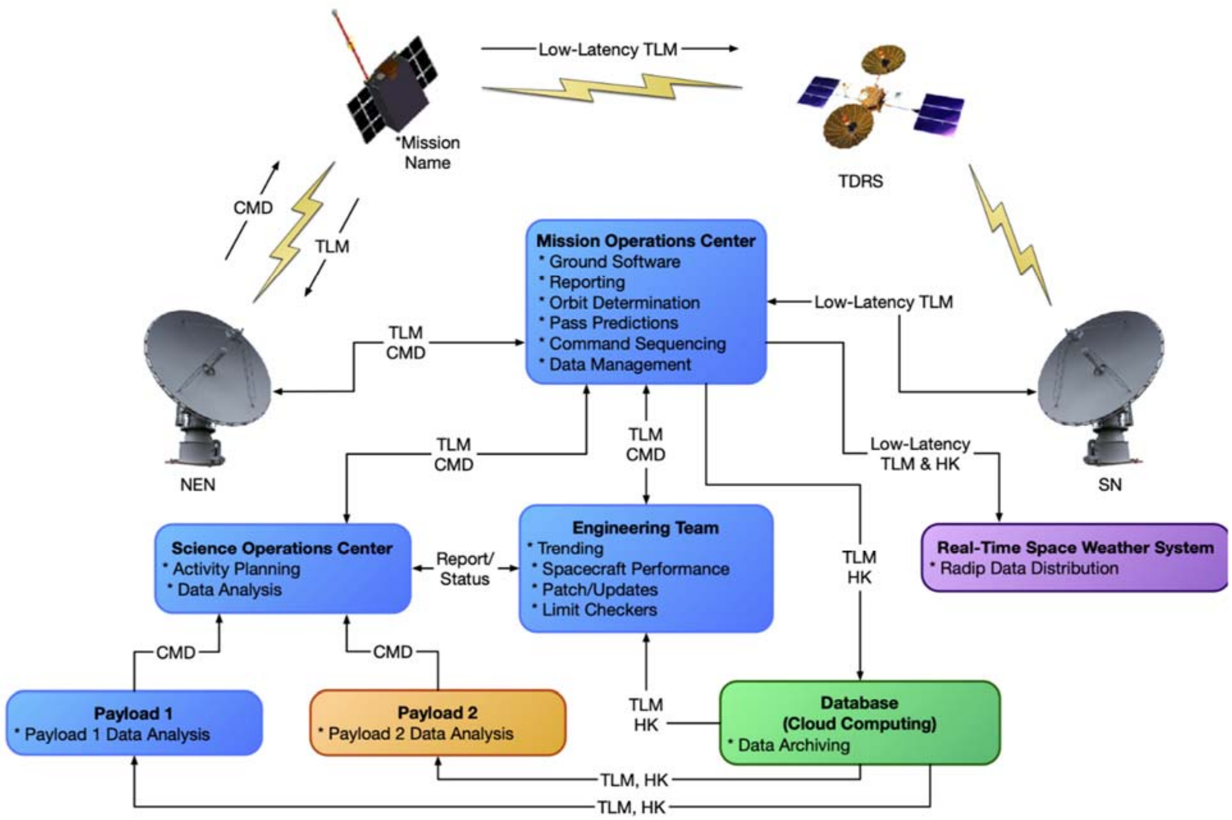


Figure 12.2: Example of a ground system architecture for a small satellite using NASA's Near Earth Network and Space Network. Credit: NASA.

Typical bands considered for small satellites are UHF, S, X, and Ka. UHF was the band of choice for early small satellites, but in recent years, there has been more of a shift to S and X. Ka remains on the horizon as there are current hardware limitations for small spacecraft, however, this is NASA's desired band for future small satellite missions. This shift has been driven by higher data demands and frequency control. The higher frequencies permit more data to be transmitted over a given period of time, but do require the spacecraft and ground antennas to be more focused. UHF yields lower data rates and has a higher probability for interference as it is commonly used by local municipalities. It was appealing to early users, particularly universities, due to the lower cost of hardware for both the spacecraft and ground station, good link margins, and more omni-directional pattern capability with the spacecraft.

Table 12-1: Frequency Bands

Band	Frequency
HF	3 to 30 MHz
VHF	30 to 300 MHz
UHF	300 to 1000 MHz
L	1 to 2 GHz
S	2 to 4 GHz
C	4 to 8 GHz
X	8 to 12 GHz
Ku	12 to 18 GHz
Ka	27 to 40 GHz
V	40 to 75 GHz
W	75 to 110 GHz
mm	110 to 300 GHz

12.3.1 Frequency Licensing

Satellite communication frequencies are intentionally protected. The signals from satellites in space are very weak, and if there is too much interference they cannot be heard. Within each frequency band there are government and non-government designations amongst the frequencies. Some frequencies are government use only, others are non-government only, and some are shared. Government bodies that regulate the frequency usage in the United States are the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA). Other countries may have their own national governing bodies, and all national bodies around the world must coordinate with the International Telecommunications Union (ITU), which is the governing body at the international level. The FCC is responsible for issuing communications licenses to non-government users and the NTIA handles government users. Licenses are required for both the satellite and ground station to transmit on a designated frequency or frequencies. It is becoming more common for small satellites to use multiple bands. For example, some missions have used UHF for uplink and S-band for downlink, while others have used S-band for uplink and X-band for downlink. Some of the non-government frequencies are dedicated for amateur usage. Early university small satellites relied heavily on the use of amateur frequency bands. In recent years, there has been movement by the International Amateur Radio Union (IARU) and the FCC to significantly limit the use of amateur frequencies for small satellites. Those interested in using these frequencies are expected to first communicate their intention with the IARU and obtain a coordination letter prior to submitting an application with the FCC. It is recommended that missions with a new communication system design submit an application with the FCC or NTIA once an operations concept and a spacecraft design are defined, in order to verify a proper communications approach and associated hardware has been selected. Missions using a legacy communications approach can typically wait until they have been given a launch manifest. The licensing process can take several months and needs to be completed prior to launch. Some of the processing time is associated with the FCC and NTIA having to also coordinate with the ITU. Both the FCC and ITU are working to implement more streamlined small satellite licensing options. Such improvements will be necessary as constellations of small satellites become more prevalent.

12.4 Cybersecurity

With the ongoing proliferation of small satellites in low-Earth orbit, cybersecurity is something the community is being forced to look at very closely. With the low-cost nature of small satellites driving the use of commercial off-the-shelf (COTS) hardware, open source software, and web-based ground station services, the opportunity for vulnerabilities increase. The addition of propulsion systems further raises concern, as there is the potential for a malevolent actor to take control of the spacecraft and use it to target and collide with other spacecraft. In response to this threat, NASA requires any of its propulsive spacecraft within 2 million kilometers of Earth to protect their command uplink with encryption that is compliant with Level 1 of the Federal Information Processing Standard (FIPS) 140-2. The FCC has also considered requiring encryption on the telemetry, tracking, and command communications for propulsive spacecraft, but recently opted not to incorporate a specific requirement at this time. Measures to protect against cyberattacks should be considered for both the spacecraft and ground systems. While additional federal regulations remain on the horizon, spacecraft operators are expected to follow best practices. The MITRE Corporation has offered the following ten elements to be considered for small satellite cybersecurity best practices:

1. Authenticated Communication
2. Encryption of Data in Transmit
3. Access Control
4. White Listing and Input Verification/Constraints
5. Logging and Auditing
6. Secure Updates

7. Secure Engineering Processes
8. Antivirus Capabilities
9. BIOS Security
10. Fail Safe Capability

12.5 Ground Stations and Networks

12.5.1 Types of Ground Services

Ground services may be either Direct-to-Earth (DTE) or space relay as illustrated in figure 12.3. DTE ground stations are located on the Earth's surface. They provide direct point-to-point access with antennas at ground stations which are strategically located and equipped with telemetry, command, and tracking services. DTE antennas can range from simple UHF Yagi antennas to more complex high gain parabolic dish antennas used to support S, X, and Ka bands. DTE ground stations could also incorporate phased array antenna systems or equipment for optical communications. The DTE services are especially effective for missions needing frequent, short-duration contacts with high data throughput. They are also capable of handling longer latency durations due to orbital dynamics and station visibility.

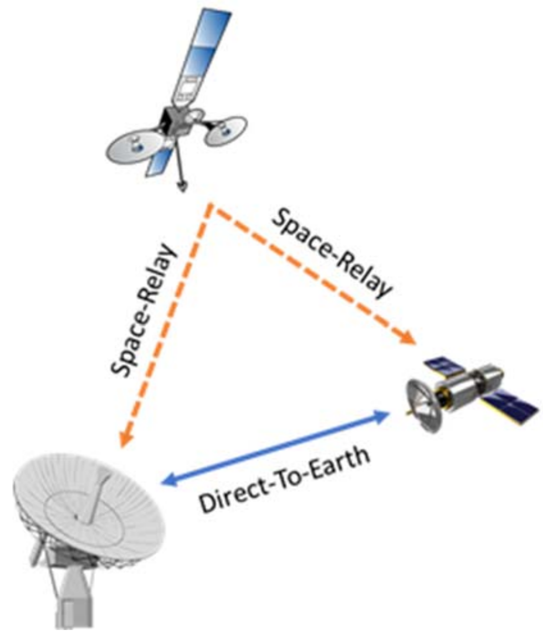


Figure 12.3: Illustration of Direct-to-Earth and Relay Concepts. Credit: NASA.

Space relay services involve an intermediate satellite that communicates with a ground station on the Earth's surface. Relay communication satellites for low-Earth orbit spacecraft can be located in Geosynchronous Orbit (GEO), about 36,000 km from Earth, or also in low-Earth orbit. Relays are essential for providing communication and tracking when direct-to-ground communications are not feasible due to physical asset visibility constraints. It is common for a low-Earth orbit spacecraft to only be in a DTE ground station's line of sight for a portion of the orbit. The addition of space-based relay assets can provide missions with full-time coverage and continuous access to communication and tracking services. They are most useful for missions that need continuous coverage, low latencies, and coverage of launch, critical events, or emergencies.

Communication with DTE ground stations can achieve much higher data rates than what is possible for space-based relays. When considering a GEO relay satellite, it can be ten times the distance from the low-Earth orbit spacecraft than the DTE ground station. With communication propagation losses being a function of the reciprocal of the distance squared, the same communications system can achieve orders of magnitude higher data rates with the DTE ground station. Achieving comparative data rates for a relay system would require a significant increase in power. The current low-Earth orbit relays have hardware limitations that permit data rates of 9.6 kbps or less, which is low relative to SmallSats being able to achieve 3 Mbps or more with DTE ground stations.

12.5.2 Ground Station Hardware, Software and Operation

A DTE ground station is comprised of a system of hardware and software working together to convert the RF signal from a satellite signal into digital data. The first key element of the system is the antenna. It is chosen based on the frequency and gain required to talk with a satellite. The two most common types of directional antenna are the Yagi-Uda (Yagi for short) and the parabolic reflector antenna. Dish antennas are capable of higher gain than the Yagi antennas and therefore can have a farther reach in space and achieve higher data rates.

The Yagi antennas consist of a single feed or driven element that is accompanied by parasitic elements that help reflect or transmit energy in a particular direction. The length of the feed antenna is sized relative to its resonance in the presence of the parasitic elements, which is approximately a half-wavelength long at the frequency of operation. The Yagi antenna shown in figure 12.4 (left) consists of multiple parallel metal rod dipoles and is a common solution for wavelengths less than 1.5 GHz. The typical Yagi gain ranges from 6 – 20 dBi.

Figure 12.1: (left) The California State University Northridge Yagi ground station at 437 MHz and (right) The Aerospace Corporation parabolic dish ground station in Florida at 915 MHz. Credit: California State University of California, Northridge.

The dish antenna uses a parabolic reflector to collect signals from the spacecraft and focus them onto a feed antenna. The feed antenna is typically a horn antenna with a circular aperture. The size of a dish is at least several wavelengths in diameter at the frequency of operation and can be on the order of several 100 wavelengths for higher gains. The distance between the feed antenna and parabolic reflector can also be several wavelengths. For example, a Ka-band 34 m deep space antenna with a feed distance of 15 m would be approximately 3,000 wavelengths for the dish diameter and 1,500 wavelengths for the feed distance relative to a 1 cm Ka-band wavelength. The gain of a dish reflector is directly related to the square of its diameter. The 1.8 meter diameter dish antenna shown in figure 12.4 (right) is used for frequencies above 915 MHz and has 19 dBi gain. Dish antennas are available in sizes from 1 meter to 70 meters in diameter.

The antenna collects RF waves and the antenna feed converts the electromagnetic waves into conducted RF electrical signals. The feed consists of a resonant pickup that is tuned to the transmit or receive frequency, a low gain low-noise amplifier, a sharp filter, and a second low noise amplifier with more gain than the first amplifier. These elements condition the signal. The signal then traverses through a coaxial cable to a nearby location where a radio demodulates the RF signal into digital data. In the uplink direction, the radio modulates the data bits onto an RF carrier which is amplified to 10 or more watts. The amplified RF resonates in the antenna feed, and the antenna amplifies the electromagnetic waves and focuses them towards the satellite.

It is desirable to have significant antenna gain, but as the gain increases, the beamwidth of the antenna decreases. There is a practical compromise where the beamwidth is so small that tracking is difficult and when the antenna gets so large that it is difficult to procure or manage. A typical antenna pattern is shown in figure 12.5. There is a center lobe where most of the transmitted energy is contained. The remaining energy is stored in the sidelobes on either side of the main lobe. The diminished side lobes are intentional so that ground noise from other emitters on Earth are not collected when receiving and so that interference to terrestrial systems is not created when transmitting. The blue arrows in the figure indicate the full-width-half-max gain point at about ±6°, which should result in an antenna pointing error of less than 6° and the full-width-half-max gain of 16 dBi to be used in a link budget. If more gain is needed, then the antenna will increase in size and the beamwidth will correspondingly decrease.

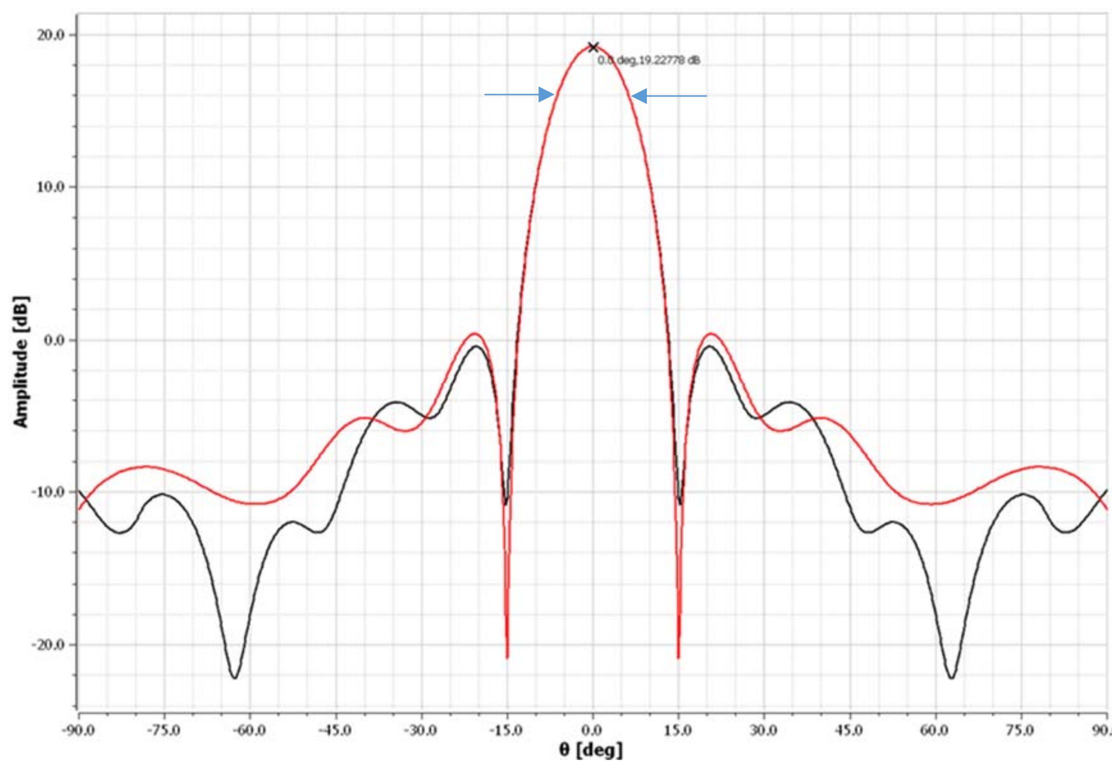


Figure 12.5: Antenna pattern from a 1.8 meter diameter parabolic dish operating at 915 Mhz with a high gain center lobe and diminished side lobes. Credit: NASA.

Directional antennas point towards the satellite as it moves over the ground station. Pointing adjustments are necessary in both the vertical (elevation) and horizontal (azimuth) directions. These movements are accomplished through the use of motors and gears. Tracking software is used to predict the satellites future location. The satellite position and time are processed through additional software that converts this information into commands for the motor controller. Time is an important factor and Global Positioning System (GPS) time is used by the computer generating the satellite position estimate. A dedicated GPS receiver is connected to the computer for that purpose.

The cost of a DTE ground station is directly correlated with the size of the aperture, which drives the ground station foundation, pedestal, motors, and gears. The Yagi is less expensive. It sustains low wind loads and therefore can use a smaller foundation for support. In contrast, the dish antenna reflector sustains comparatively high wind loading and therefore needs a stronger concrete foundation and larger motors and gear box elements than the Yagi antenna.

12.5.3 RF Link Budget

Calculating the RF link budget is the first step when designing a telecommunications system. It is a theoretical calculation of the end-to-end performance of the communications link and it will determine the system margin. Maintaining a 6 dB link margin is desirable, however a 3 dB link margin is adequate for a satellite in low-Earth orbit at a slant range of 1,500 km. When considering deep space communication, a 3 dB link margin is desired, but for distant spacecraft, such as New Horizons at 7 billion kilometers from Earth, 1 dB or less margin may be all that is practically possible. The budget calculation adds and subtracts all of the power gains and losses that a communication signal will experience within the system. Factors such as uplink amplifier gain and noise, transmit antenna gain, slant angles and corresponding loss over distance, satellite transceiver noise levels and power gains, receive antenna and amplifier gains and noise, cable losses, adjacent satellite interference levels, and climate related attenuation are considered. The satellite and ground antenna gains and amplifiers are then sized to provide the necessary link margin at an acceptable data rate.

The test plan for the satellite and ground segments will measure the key radio parameters identified in the link budget. The ground station antenna pattern is often not verified because it is designed such that its ideal pattern is not modified by its surroundings, i.e. high up on a mast above a building or in an open field. Established service providers can provide characteristics for the ground systems and can assist customers with link margin and coverage analysis. Figure 12.6 provides an example of S-band antenna telemetry characteristics for one of NASA's NEN stations. The antenna pattern on the satellite has less flexibility and is often modified by the nearby spacecraft structure. It is best to measure the actual satellite antenna pattern in an anechoic chamber using a satellite model.

Characteristic	Value
Frequency	2200 – 2400 MHz
G/T	22.8 dB/K (clear sky & 41° elevation angle)
Polarization	RHC or LHC
Antenna Beamwidth	0.85 deg
Antenna Gain	45.8 dBi
Carrier Modulation	PM/PCM, FM/PCM, BPSK, or QPSK / OQPSK
Modulation Index	PM: 0.2 – 2.8 Radians (peak)
Carrier Data Rate (High Rate Telemetry Channel)	1 Kbps – 10 Mbps (FM/PCM) 100 bps – 20 Mbps (PM/PCM, BPSK, OQPSK) 1 Kbps – 40 Mbps (QPSK) [< 20 Mbps per channel]
Carrier Data Format	NRZ-L, M or S, Biϕ-L, M or S; DM-M or S; DBP-M or S; RNRZ
Subcarrier Frequency	5 kHz – 2 MHz
Subcarrier Modulation	PSK, BPSK, PCM/PM for high BW telemetry
Subcarrier Data Rate	100 bps – 600 Kbps
Subcarrier Data Format	Passes all NRZ or Biϕ or DM
Decoding	Derandomization, Viterbi and/or Reed-Solomon (Ref Para 1.3 s)

Figure 12.6: S-band Telemetry Characteristics for the WG1 Antenna at NASA Wallops Flight Facility. Credit: NASA.

12.5.4 Ground Networks

The ground station(s), MOC, SOC, and the supporting infrastructure connecting them together, make up a ground network. As more ground stations are added, a ground network becomes larger and additional considerations are required to ensure that the MOC can communicate with each of the ground stations in the network.

Understanding how many ground stations are required to support the mission is the first step in designing a ground architecture and determining if a ground network is necessary. The number of ground stations required for a mission depends upon multiple factors, including the number of satellites, the orbit regimes and inclinations, and the data latency or data volume requirements. For example, if a satellite has an orbit that regularly crosses over the same spot on the Earth (such as the poles in a sun synchronous orbit in low-Earth orbit), that mission could be supported by a single ground station at that frequently revisited spot. However, if a satellite's orbit does not frequently revisit the same spot on the Earth (as is the case with many mid-inclination low-Earth orbit orbits), then multiple ground stations will be required to support that mission. Similarly, if a mission requires the satellite to downlink collected data as soon as possible (i.e. low data latency requirements) or if the mission will generate a large volume of data during each orbit (e.g. many remote sensing missions), then more ground stations will be required to support the mission. The same applies for a mission with multiple satellites as well.

Determining the number of ground stations required for the mission will dictate the size of the ground network. Missions that require only a single ground station with a co-located MOC have a very simple ground network. Missions that require multiple, geographically-dispersed ground stations will have a larger ground network with provisions to ensure that the MOC can communicate with each of those ground stations. Figure 12.7 shows an example of a large ground network, NASA's NEN, which consists of 15 geographically-dispersed ground stations that are operated by NASA and its commercial partners.

Figure 12.7: Map of NASA's Near Earth Network Service Providers & Locations. Credit: NASA.

While NASA's NEN is often reserved for NASA-funded missions, there are other ground network options that exist for non-government-funded satellite operators. One common option, especially amongst amateur operators, is to take advantage of the vast amateur network around the world. This is typically done with UHF and VHF bands at low data rates and must be coordinated with the amateur user community.

Over the last few years, a number of options for ground networks have also become prevalent in commercial industry. Each of these commercial ground service providers offers an array of services, including various frequency bands, serviceable orbits, and ground station locations. Scheduling and data retrieval for these networks are often done through web interfaces, and pricing plans are flexible and scalable depending upon an operator's needs. Many commercial satellite operators are choosing to buy time on these networks, rather than build their own.

12.5.5 Space Relay Networks

Unlike a traditional ground network that goes direct from a "client" satellite to a ground station on the ground, a space relay networks consist of communication satellites that relay data from the "client" satellite down to a ground station. One of the most well-known space relay networks is NASA's Tracking and Data Relay Satellite System (TDRSS), shown in figure 12.8. TDRSS relays data from the International Space Station and the Hubble Space Telescope to NASA ground stations around the world.

Space relay networks can be beneficial for small satellites in low-Earth orbit because those SmallSats are only in view of a ground station for a portion of their orbit. However, depending on the orbit of the relay satellites, a low-Earth orbit SmallSat could be in view of a relay satellite for most of its orbit. This makes a relay network beneficial for a SmallSat, especially right after SmallSat deployment when a ground station is still trying to locate the satellite. The space relay can transmit satellite telemetry, tracking, and control data to the ground, enabling faster satellite identification. This proves to be even more valuable when the satellite is deployed with several others for a given rideshare opportunity. This data can also contain satellite health information to give mission teams either peace of mind while awaiting acquisition by the ground station, or

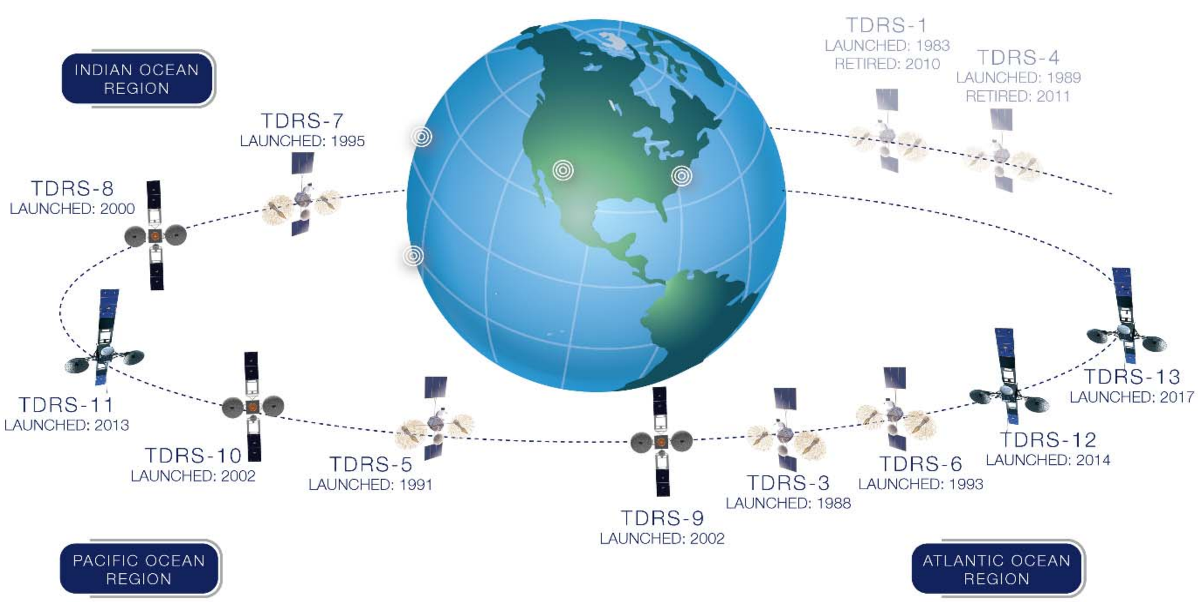


Figure 12.8: NASA's Tracking and Data Relay Satellite System. Credit: NASA.

information for troubleshooting prior to the commissioning phase. Another benefit is the ability to obtain real-time event notifications without the need for prior scheduling. Scientists are interested in using this technology to alert the science community when certain phenomenon are observed.

Space relay networks often require special hardware or software that must be added to a satellite before launch. In general, a satellite operator will purchase a modem compatible with the relay network and fly it on their satellite in order to access the network. It is common for the network providers to license their proprietary chipset to developers who build the modem hardware and serve as a service broker. Because of this added hardware component, the decision to leverage a space relay network must be made before the satellite has been launched.

12.5.6 Considerations for Buying Ground Services vs. Building a Ground System

As SmallSats have become more prevalent and prolific over the last decade, so too have ground services companies, to the point where the discussion of buying ground station services versus building and owning a ground station becomes a very relevant consideration in the ground architecture design. Key considerations would include scheduling flexibility, operational manpower, frequency licensing processes, and pricing scalability. A summary of factors relative to these considerations is shown in figure 12.9. Ultimately, the decision of whether to buy ground services versus build and own a ground station will vary depending on the mission architecture, the program budget, the potential for student learning opportunities, and many other factors.

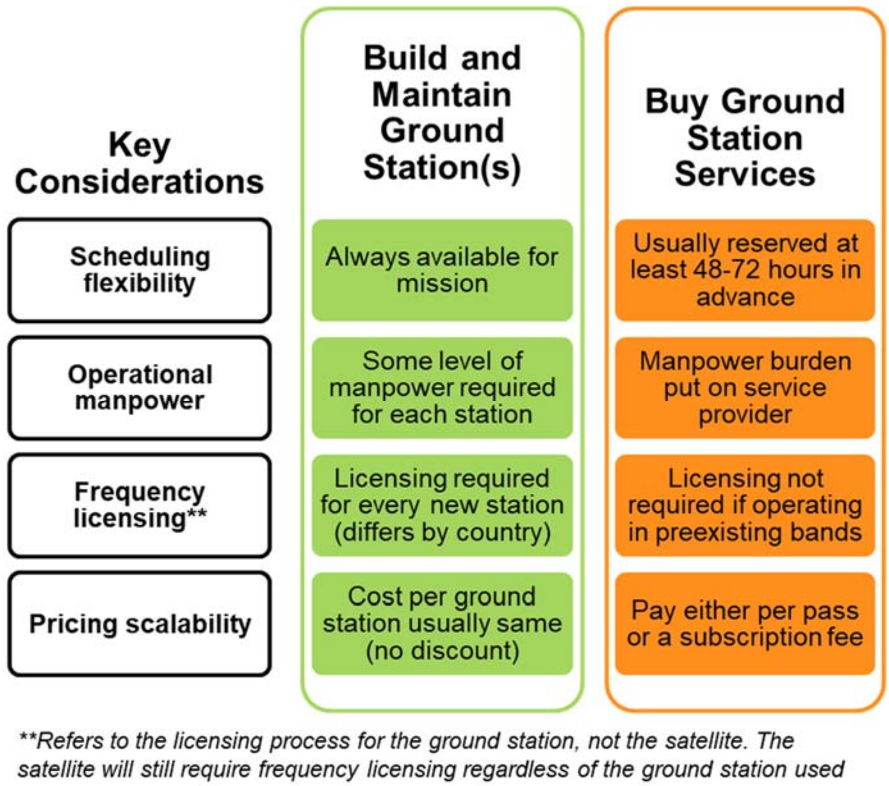


Figure 12.9: A summary of considerations when deciding to buy service or own a ground station. Credit: NASA.

Building and owning a ground station means that the ground station is always available for the mission when the satellite is in view, allowing for maximum scheduling flexibility (it also means that there may be significant time periods where the ground station is inactive). On the other hand, most ground services companies require an operator to reserve their time on a station anywhere from 48 to 72 hours in advance of the pass, and, in the event of a conflict, mission priority-level is usually determined by the operator that has paid the highest premium.

Most ground stations require some level of effort to keep them operational, especially for routine maintenance or when an anomaly arises with the ground station itself. If the ground station is built and owned by the satellite operator, that labor burden falls to the operator. If the operator is buying time on a ground station, the ground service provider has the staffing burden.

Frequency licensing is a critical step in the ground architecture process. In addition to the satellite being licensed to transmit to the ground, any ground station has to be licensed to transmit up to a satellite. When an operator buys their own ground station, they must get it licensed by the FCC (or another regulatory body/bodies if outside of the United States). If an operator buys time from a ground service provider, the licensing is performed by the service provider, and the process is usually much faster since it is an addendum to an existing license, rather than a brand new one (assuming the operator is using the same bands that the station was previously authorized to use).

Pricing scalability is also a point to consider, especially when using more than one ground station. No matter the geographic location, each new ground station must be built, licensed, tested, and maintained, and the cost for that process usually does not drop as more ground stations are built. In other words, the cost per ground station for one station or 20 stations is usually the same, and sometimes even higher due to the complexity of navigating multiple nations' licensing processes. On the other hand, ground service providers have multiple pricing scales depending on the mission need. For missions needing single ground station support, operators can pay on a per-pass basis. For missions requiring multiple ground stations, operators can pay a regular subscription fee. This variable pricing offers more flexibility for operators as their mission scales.

12.6 Mission and Science Operations Centers

The MOC is where all of the satellite commanding is generated, ground station control is managed, and satellite telemetry is archived. It is typically a physical location where everything required to operate the satellite is located. It is often in a secure room with controlled access to protect the satellite operating equipment and prevent unauthorized satellite control. Inside the room are typically several terminals so that multiple subsystem experts can be reviewing telemetry or running their analysis programs concurrently. An example of a MOC with multiple terminals is shown in figure 12.10.

Figure 12.10: MOC at NASA Ames Research Center. Credit: NASA.

The size of the MOC is determined by the complexity of the mission. There are more experts on complex missions, and their inputs are often required during critical events or to resolve an anomaly. For a SmallSat mission, the complexity is usually lower and the MOC is a much smaller room. In addition to the terminals and telemetry analysis software are other resources for managing the satellite. This may include a physical model of the satellite to study when contemplating anomalous telemetry. In the case of CubeSats, due to their small size, a functioning spacecraft engineering model may be useful to test commands and reproduce anomalies.

All tasking requests for future satellite operations are managed by the mission operations team. They will generate command plans, simulate satellite response to verify those plans, and if confidence in the simulations is not sufficient, they will run the commands on engineering model hardware prior to approving them for upload. The MOC team will also manage downloads. They will decide what data should come down next and what ground resources are available when. If the MOC does not own its ground stations, a request for contact will be submitted to the ground station managing company. If the MOC owns its ground stations, then it will task them directly. In either case, the MOC submits data necessary for commanding the satellite for upload which includes commands and parameter settings for the payloads, a schedule of events for the flight computer, and ephemeris and pointing tables for the attitude control system along with its own timeline of events. For that same contact, the MOC will also submit commands to download specific telemetry and science data. When the contact is complete, the data will be sent back to the MOC by the ground station.

At the time of launch, the MOC will be fully populated, as this is a critical event. The satellite when it first comes online in space will likely present some anomalous telemetry that will have to be interpreted and acted upon in short order. Prior to a launch, there will be rehearsals with everyone at their stations and simulated telemetry is used with anomalous readings inserted to test the team. This ensures that they are ready with the proper analysis software or integration test data available to quickly diagnose the problem and propose a plan of action.

The Science Operations Center (SOC) is the focal point for all mission science and data resources. The science team will utilize it to store and analyze the data. From that analysis, the science team generates satellite tasking requests that are sent to the mission operations team who evaluate them for feasibility and generate future satellite task plans. Negotiation is often required between the satellite operators and the scientists due to the practical limitations of the satellite and the ground segment infrastructure. External requests for additional data collection come through the science team first to assess feasibility with the instrumentation before tasking requests are made to the operations team.

The SOC is typically physically separate from the MOC. The payload for most spacecraft is produced by another company, different than the satellite bus and different from the company operating the MOC. The payload developer will have their own operations center located at their facility and easy access to supporting resources. In the past, before cloud data storage, the SOC was a physical place was where data servers resided to archive the mission science data. Also, before secure network solutions, dedicated computers were located inside the SOC that would run programs written specifically to analyze the science data. If the mission was secure and the data classified, then the physical SOC would be protected behind a locked door. Missions that do not produce classified data can take advantage of the latest technologies for considerable convenience. The SOC can be virtual instead of a physical location and the science data and special programs for analyzing can reside in the cloud. The virtual SOC allows scientists to log on from anywhere and perform work without the need to come to a physical location and pass through secure doors. In the future, as cyber techniques improve, it is likely that more and more secure missions will be comfortable with the virtual SOC solution and only the highest classification missions will maintain a secure physical SOC.

12.6.1 Software for Mission Operations

Mission operations relies on software across all the elements of the ground segment. Figure 12.11 outlines software functions for each of these elements. Software supporting the ground segment exists in the satellite, at the physical ground stations and in the MOC (server infrastructure and end-user software).

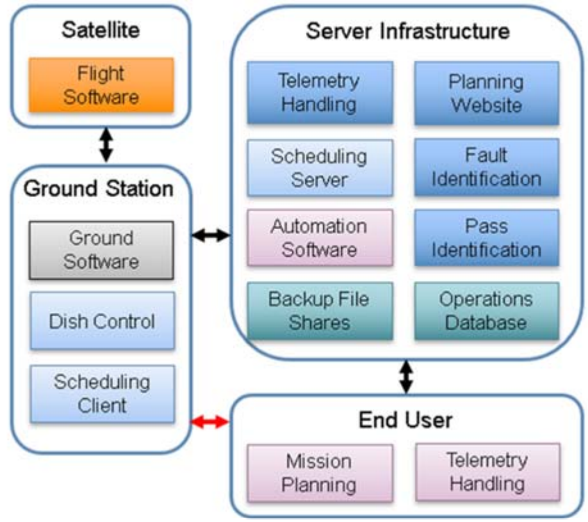


Figure 12.11: Software functions for elements within the ground segment. Credit: NASA.

Satellite flight software not only manages state-of-health telemetry and payload data, but also software specific to the ground segment. Figure 12.12 provides an example of a command and telemetry data flow for a mission using DTE and relay services. Transmission can start autonomously by programming the satellite to know when it is over a ground station or within sight of a relay satellite. It can also be triggered by a command received from the ground station or relay satellite. When a communications link is established, the radio enters a higher power transmit mode and sends the data. The flight software manages the flow control of information into and out of the radio, making sure that no buffers are overflowed. It also formats the housekeeping and science data to be transmitted into a packetized file format that can be accepted by the ground station. Ground networks have specific data protocol standards

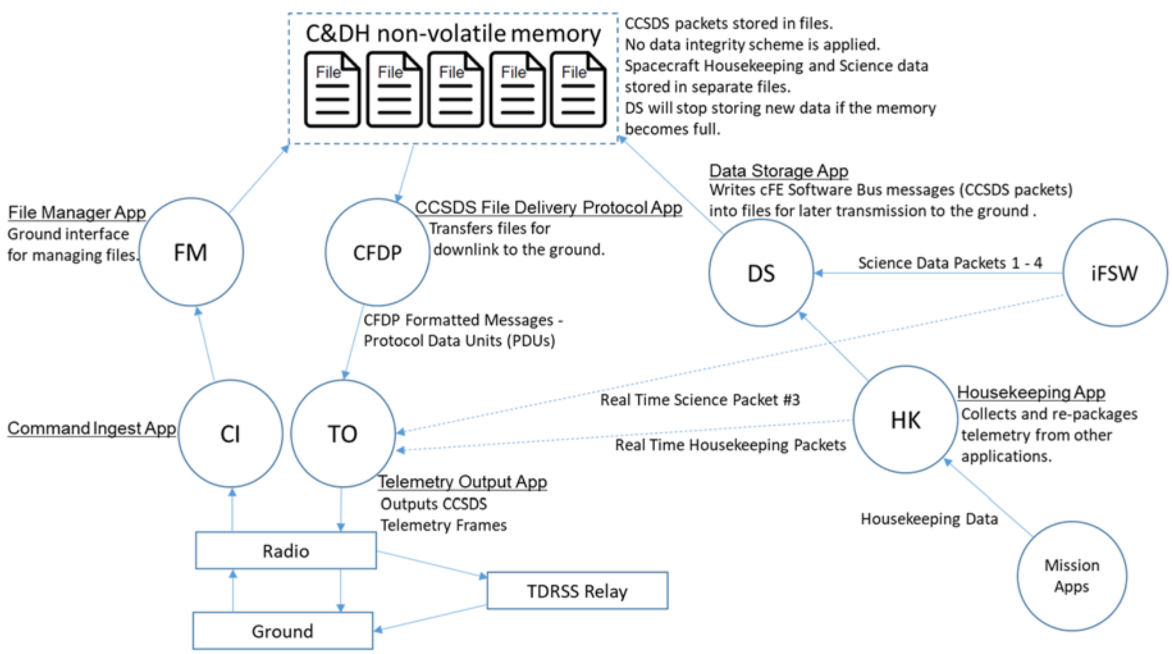


Figure 12.12: Command and telemetry data flow for a SmallSat mission using DTE and relay services. Credit: NASA.

developed from experience. For example, the NASA's NEN incorporates standards proposed by the Consultative Committee for Space Data Systems (CCSDS). The flight software unpacks received packets, retrieving the uploaded commands and data

The ground station uses various software for controlling the antenna, commanding, signal formatting and encoding, scheduling passes, and interfacing with the MOC. One software computes the pointing direction by using a Two-Line Element set (TLE) to define the satellite motion, an accurate model of the pointing system mount, and GPS time. It generates motor commands as a function of time. The motor controller uses these commands to actively track the satellite during a pass. During the pass, another software suite is used to monitor the link, process and encode commands for transmission, handle any signal formatting or encryption, and demodulate and decode the received transmissions. This software also manages the network connection with the MOC over which the TLE is passed, as well as data for uploading and requests for data to be downloaded. When the contact is complete, the data received from the satellite is transferred back the MOC. The ground station may also have its own telemetry for that contact. That data is used to trend its performance. Trending the performance of each contact provides insight and notice of degradation for both the satellite and the ground station. The ground station may also use scheduling software when handling multiple missions. This software uses orbit simulation and current TLE information to determine when the contacts are expected. It will indicate when there are conflicts between contact opportunities and can assist with schedule optimization. A schedule is generated for a given period of time and then programmed into the ground station control system for execution. This process can be automated, but there is typically an operator on staff to monitor the system.

For the MOC, mission planning software is necessary for missions that require complex satellite behavior such as pointing at a target during science data collection. The software will include a model of the satellite dynamics and the capability of its components. The event is planned by listing a series of actions that have to occur in a certain order and spaced out by times that are guessed. The software will simulate the satellite response and then the times and actions are iteratively adjusted as needed to optimize the plan and not cause a satellite fault condition. The output of the plan is all the commands and databases that are required by the satellite. This output is submitted to the ground station ingest software for upload at a time prior to the planned event.

A more mature MOC will include a "lights out" or fully automated option. This requires software on the ground station side to run the antenna automatically. Automation software will receive a list of times that the antenna should track the satellite and it will manage that list. It will send TLEs and data to the antenna with no one present, receive downlinked telemetry, and archive it. As the number of satellites that a MOC serves increases, the software managing the antenna becomes more capable. It can identify when two requests conflict and choose one over the other. With no one at the ground site, a feedback mechanism is required to alert the team of a satellite fault condition. For that, software is needed to automatically parse the telemetry, compare key watch items to defined limits, and alert the team via email or phone text message.

The SOC uses software to handle the receipt, unpacking, reconstruction and post processing of the mission science data. Using an International Space Station (ISS) payload as an example, the science data is downlinked via TDRSS to NASA Marshall Space Flight Center (MSFC) where it is separated into different science streams and piped to the correct payload SOCs. At the SOC, but outside the company firewall, a computer is constantly running and ready to receive the data from MSFC. On that computer, the TReK software provided by NASA is running and it properly handshakes with the MSFC software assuring the data transfer. The science team periodically retrieves the data and safely brings it through the corporate firewall into the SOC. The science team writes parsing software to unpack the data which is stored in CCSDS format. They write another software to arrange the data back into the original image seen by the payload. Still more custom software will process the image to produce post-processed data products that are stored in the SOC archive and distributed to interested customers. The computer languages vary but Interactive Data Language (IDL) and Python are common choices for this type of software.

12.7 End-to-End Communications and Compatibility Testing

A SmallSat undergoes various tests through its development cycle to verify proper functionality. For the communication subsystem, end-to-end communication and compatibility testing with the selected ground network is its most critical test. Compatibility testing verifies that the ground station can properly communicate with the satellite on the uplink and downlink RF channels. Ideally, compatibility would be validated by testing the flight spacecraft with the actual ground station that will be supporting the mission. This may not be practical for larger or high-cost satellites, due to logistics associated with shipping and risk of damage. Two alternatives to shipping the satellites are typically used. One includes sending a replicate set of ground station hardware to the satellite facility for testing. A second option is to test with only the flight or an ETU radio (also common to include the flight computer) at the ground station or at a test lab configured with the ground station hardware. Drawbacks to the alternative options would include not testing the exact command path or determining whether ground sensitivity is sufficient.

For CubeSats, it is commonly feasible to bring the CubeSat to the ground station for testing. If that is not feasible, then at a minimum, the radio and flight processor (or EDUs) should be used. Testing at the ground station allows for the entire equipment chain to be part of the test, including the low-noise amplifier (LNA) and transmit/receive switch, if used. It is desirable to first test in a closed-loop configuration, where the satellite is connected to the ground system at the antenna port via a cable (with appropriate attenuators in line). If the satellite is fully integrated, disconnecting the flight antenna may not be feasible. In this case, a small monopole antenna located indoors near the CubeSat can be connected to the ground system. The monopole antenna connection to the ground system may vary depending on the ground antenna configuration, but should include as much of the ground system electronics as practical.

Some missions elect to include an outdoor open-loop test with the CubeSat and ground antenna. This method allows for the entire ground system, including the ground antenna, to be included in the test. However, the ground antenna typically cannot point directly at the CubeSat due to mechanical limitations or to limit the received signal so the ground system RF components will not be overdriven. Off-pointing and reflections from the ground and local structures can also make it difficult to achieve a valid test.

End-to-end network testing primarily validates the ground station to MOC interface. This test verifies that the MOC can properly receive downlink data from the ground station and verifies that the ground station can receive and process uplink command data from it. Initial end-to-end testing will validate network connectivity, showing that network connections can be established, and firewall rules at the ground station and MOC are in place. Once network connectivity is established, the MOC can transmit commands to the ground station for capture. The ground station can then transmit simulated or recorded data to the MOC for validation.

It is preferable to conduct initial end-to-end network testing prior to compatibility testing. In cases where the satellite can be brought to the ground station, a full end-to-end test can be conducted. Command transmissions from the MOC, through the network and ground system to the satellite can be validated. A complete end-to-end telemetry data flow from the satellite to the control center can also be validated.

12.8 Spacecraft Commissioning

Spacecraft commissioning is a critical stage for a mission. During this period the MOC is fully staffed and there is heightened interaction with the ground network. It is not uncommon for spacecraft anomalies to arise and require troubleshooting. Communication challenges have been prevalent for SmallSats during the commissioning period. The following discusses the commissioning process and identifies how these challenges can be addressed.

The spacecraft commissioning phase consists of early operations to establish the proper or baseline functionality and performance of a spacecraft and ground system. In general, this is a 2-step process: establish reliable communication link between the ground station and the spacecraft, and establish proper or baseline performance of the spacecraft (bus and payloads).

The first step involves trying to point the ground station antenna towards the satellite. This step simplifies when using low data-rate communication with omnidirectional capability at the ground and satellite terminals. Challenges associated with initial satellite-to-ground station link closure are generally related to ground antenna pointing predictions. Typically, TLEs or state vectors are established and shared by the launch provider after deployment. This information can be used to create an initial orbit solution for the ground station antenna pointing. Sometimes this method is not successful because the TLEs are either mislabeled or have become outdated within days of deployment and the satellite has moved out of the predicted location, usually a few seconds ahead or behind. Operators can adjust the time offset in their tracking software to search for the satellite. Missions will then rely on NORAD TLE data (see https://www.space-track.org) for the satellite location. However, it could take up to a week or more for NORAD to add the new object to their tracking list. This process could be delayed further if multiple spacecraft are ejected in close proximity and it is not clear which NORAD element set corresponds to which spacecraft. It is not uncommon to spend weeks attempting different NORAD-tracked objects until the correct one is found. The position prediction accuracy based on the NORAD TLE also diverge over time and a new TLE will be needed to maintain data link. This is typically not an issue since the TLE is updated regularly, but on-board GPS data (if equipped) can help determine the orbital parameters for the ground station to define latest orbital parameters.

Another method to locate the satellite includes using the slant range as they rise from the horizon. The uncertainty of the satellite position in an orbit is greatest in the in-track position. This is equivalent to a time error and often satellites being tracked are considered “early” or “late” with respect to their expected position at a specific time. Ground station operators usually point their directional antenna to just above the horizon to “hang” in one place for a time that is sufficient to detect the satellite and synchronize with the radio, provided that the link budget closes at that range. Some antenna tracking software will allow the operator to begin the track after this initial acquisition is successful. The pointing is most critical at the shortest range and if a link is lost, one can gain insight into the magnitude of the time error (number of seconds behind or ahead of the predicted position). This technique of waiting on the horizon will work regardless of the quality or proper tagging of the TLE.

A half-duplex or full-duplex system could make a difference as well. Program track instead of auto-track is used for half-duplex. With a full-duplex system, the ground antenna attempts to acquire the downlink first. Predicts (NORAD or state vectors) are still used to initially acquire the spacecraft. If the predicts are off, the antenna can initiate a mechanical scan to increase the search area. Once the downlink is acquired, the ground antenna can auto-track and automatically point at the satellite for the duration of the pass.

No responses from a satellite could be due to reasons other than bad antenna pointing, such as spacecraft anomalies, ground system anomalies, or spacecraft trajectory. Periodic automated downlink bursts (beacons) or secondary commercial vendor space relay networks could help understand the health of the satellite in these cases. Reduced GPS data, if equipped, may be included in addition to basic housekeeping data to help diagnose possible communication issues.

Spacecraft commissioning will commence once a good link has been established. Typically, the satellite is in a safe mode or sun pointing mode until ground commands a different operating mode. The first step is to verify the basic health of the satellite such as correct pointing, voltages, temperatures, power consumption, and proper battery charge. At this time the payloads are likely off until spacecraft bus checks are performed. A set of housekeeping data is collected over multiple passes to observe trends in behavior over time. Subsystem leads will perform an assessment to verify nominal performance. In addition, the trended data is used to establish a baseline performance for the system. Many assumptions, mostly conservative assumptions, were used during the development of the mission and now is the time to compare predictions with reality. Power, thermal, and pointing performance are some examples of technical baselines to be established. If issues do arise, engineers may desire an increased housekeeping data polling cadence or a higher level of data within a specific mission mode for troubleshooting. It is important to consider how housekeeping data will be handled in the development phase in order to prepare for commissioning activities. The spacecraft may transition to other operating modes once the safe or sun pointing mode has been shown stable.

Payload commissioning will start once the spacecraft bus is shown to be operating nominally or the baseline performance has been determined. The mission may elect to test the instruments while sun pointing if power could be a problem. Otherwise, instrument commissioning can commence using the science pointing mode. The payload will perform a series of tests determined by the science team. Instrument commissioning will include verifying proper functionality of the software and hardware. It may also include the validation of science data and calibration activities.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

12.9 State-of-the-Art

Ground data systems are complex systems and how they are used is highly dependent on the needs of the mission. There are number of established service solutions that can be used to meet mission needs. There is also an array of hardware and software options that can be considered for those that intend to be a bit more hands-on. This section presents a preview of available services, hardware, and software solutions.

12.9.1 Direct-to-Earth (DTE) Ground Service Providers

The following section provides an overview of Direct-to-Earth (DTE) Ground System Network Service Providers. These are ground services, meaning that the satellite operator does not own the ground station(s), but instead buys time with a ground service provider for their ground architecture needs (see 12.5.6 for a discussion on the considerations of buying ground services versus building and owning a ground station).

While the specific and unique qualities of each service provider are discussed below, there are some common features across their services (see table 12-3). In general, they have ground networks that span the globe and can service multiple frequency bands in almost any orbit in low-Earth orbit, and some may be able to service medium Earth orbits (MEO) or GEO orbits as well.

The use of these services will generally require some degree of pre-coordination (or “onboarding”) between the operator and provider, which is usually done before launch. This will vary between providers but may include: contracting mechanisms; frequency licensing and coordination between the operator and the provider; compatibility testing; and the sharing of mission and vehicle specific information to ensure the ground stations are properly configured for the operator to use.

Once the onboarding process is complete, satellite operators can schedule passes between their satellite(s) and desired ground station(s) in advance (the time window varies for each provider), usually through a web-based platform of some kind. The schedules for each ground station are deconflicted based on scheduling priority, and all frequency and modulation adjustments for the satellite is completed in advance of the pass by the service provider.

Most of the ground service providers in this section are TRL 9, since most of them are either currently flying or have previously flown multiple missions. Because so many of these networks are highly advanced, the distinguishing features between them is not their TRL level, but rather the frequency bands, ground station locations, and other unique services and attributes that they offer to operators. TRL 7 – 8 indicates that they have capable systems but have served a limited number of customers.

Table 12-2: Service Providers for DTE Ground System Networks

Product	Manufacturer	TRL	Services
ATLAS Global Network	Atlas Space Operations	9 for ground infrastructure TRL 8 for software integration	S-band, X-band, UHF (Ka-band in 2017) Built on AWS cloud infrastructure
KSATlite	Kongsberg Satellite Services	9	X-band and S-band D/L and S-band U/L. VHF, UHF, Ka-band D/L Designed specifically for SmallSats
Tyvak Ground Network	Tyvak Nano-Satellite Systems, Inc.	9	Global UHF network with S, X, Ka-bands being added, partner with other providers for an expanded network
SSC Infinity	Swedish Space Corporation	9	Designed specifically for SmallSats Uses standardized HW and configurations to help keep costs low
RBC Signals Global Ground Station Network	RBC Signals	9	VHF, UHF, S, C, X, Ku, and Ka-bands

AWS Ground Station	Amazon	7 for ground infrastructure 9 for software integration	Built on AWS cloud infrastructure Using third-party ground stations
UHF Ground Station	NASA	9	18 m dish, operating in UHF (400 – 470 MHz)
Near Earth Network	NASA	9	Global network operating in S, X, and Ka-bands that can reach LEO, GEO, HEO, and Lunar orbits
Deep Space Network	NASA/JPL	9	34 m and 70 m antennas, operating at S, X, K, Ka bands, 8 m optical receive aperture starting in second half of 2020s
DSS-17	Morehead State University	9	21 m operating in X band, serves as a Class D Station for NASA Interplanetary Class D CubeSat missions

Atlas Global Network

ATLAS Space Operations, Inc. is a U.S. owned, non-traditional small business that provides satellite RF communications services to the government and commercial sectors. Through geographical dispersion and cloud services, ATLAS Space Operations provides a resilient capability that delivers low latency data. Integral to the ATLAS mission success model is a global network of operational ground sites, which work together as a mission architecture to meet customer requirements.

All ATLAS ground stations are built upon the Freedom™ Software Platform, which facilitates dynamic demand and scalable growth. Once integrated into the ATLAS Network, a single secure VPN enables access and load balancing of network resources. Freedom™ Core Services advance operations beyond legacy constructs and enable users the freedom and flexibility to reliably schedule satellite passes with minimal human interaction. Entire data processing and forwarding workflows can be automated within the cloud to ensure your data is ready for use as soon as it arrives at the Mission Operations Center.

Through its worldwide ground station network, ATLAS Space Operations provides cloud-based services to support satellite launch and mission operations. ATLAS can provide VHF, UHF, S-band, and X-band capabilities. The existing and planned ATLAS antenna systems support RF connectivity for low-Earth orbit, MEO, GEO, and L1 orbits, and ATLAS is actively pursuing technology development for deep space capabilities. Figure 12.13 shows the ATLAS Space Operations network map for current and future sites.

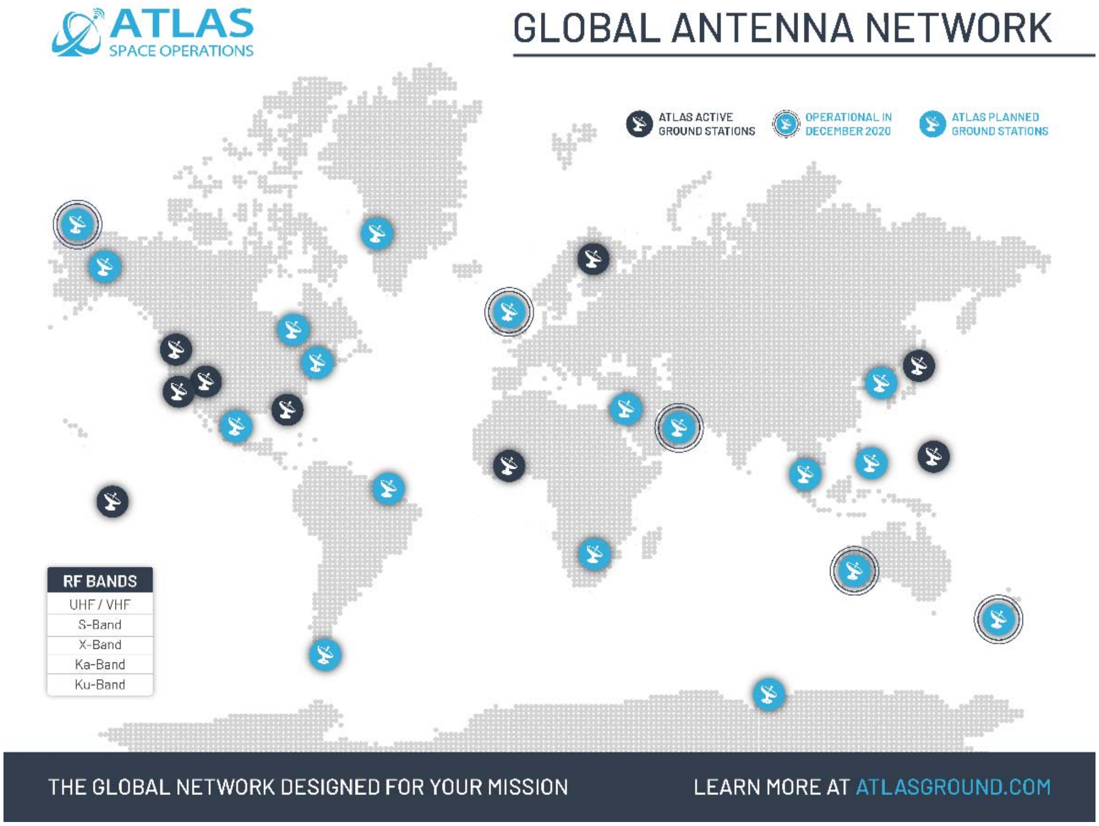


Figure 12.13: ATLAS Space Operations ground network map. Credit: ATLAS Space Operations.

KSATlite

KSATlite is a low-cost ground station antenna network designed to support different phases of small spacecraft missions. The company operates 24 KSATlite antennas at 11 ground station sites across the globe (figure 12.14) and is expanding with additional antennas and sites alongside SmallSat industry growth. KSATlite is an extension of the existing KSAT network but implements lower costs and more flexible options and procedures in terms of priority allocation, availability and pass selection. The KSAT network has uniquely located polar stations in the Arctic and Antarctic regions, providing 100% availability on passes for spacecraft in polar orbit. The network also operates mid-latitude ground stations, providing access for diverse orbits and mission profiles. The baseline KSAT 3.7 m antennas provide X-band and S-band for downlink and S-band for uplink. In addition, KSATlite offers Ka-band downlink and VHF and UHF capacities that support a variety of system configurations (Kongsberg Satellite Services AS, 2020). KSAT is in the process of building out their first two optical ground stations, with testing beginning in late 2020. These stations will support both SmallSats and larger missions that demand a higher throughput or more secure downlink solution.

Figure 12.14: 2020 KSATlite ground network map. Credit: KSAT.

Tyvak Nano-Satellite Systems, Inc. Ground Network

Headquartered in Irvine, California, Tyvak is an industry leader, delivering optimized, end-to-end nano and microsatellite solutions for civil and defense organizations. Tyvak specializes in spacecraft development, launch integration services, and managing in-orbit operations for critical missions across a variety of applications. These include technology demonstration, bringing into use, communications, earth observation, interplanetary science, proximity operations, and space situational awareness. With a dedicated commitment to making space accessible and providing mission assurance for its customers, Tyvak's global ground station network also provides worldwide coverage for in-orbit operations around the clock.

Tyvak currently operates a worldwide network of UHF ground stations, operating in the 400 MHz band. These stations are used to operate spacecraft in-orbit and have accumulated thousands of passes with a variety of spacecraft in several different orbital planes. The network offers at minimum one pass per orbit for a polar orbiting spacecraft, as well as substantial coverage for other inclinations. Tyvak is in the process of upgrading its towers to a new generation, including a number of advanced features, such as unlimited rotation, weatherproofing for harsher environments, and increased system gain. Tyvak is also expanding its network to include several 3.7 m S/X-band ground stations and is planning for additional antennas in the Ka-band. The first of these have already been installed and are supporting in-orbit assets. In addition to the Tyvak network, Tyvak has maintained its partnerships with commercial ground station providers, such as KSAT and Amazon Web Services (AWS), to offer its customers access to a diverse set of antenna assets beyond those owned by Tyvak.

Swedish Space Corporation

Swedish Space Corporation (SSC) is a global provider of ground station services, including support to launch and early operations, in-orbit Telemetry, Tracking and Control (TT&C) and data downlink, and even lunar services. The SSC Infinity Network is specifically designed for constellations of small satellites in low-Earth orbits. The global network provides TT&C and data download and delivery services to SmallSat operators, and customer interfaces consist of web-based portals for pass scheduling on 5 meter and smaller antennas. SSC Infinity also uses standard configurations and standardized ground system hardware, limiting the number of mission configurations to help keep costs lower for satellite operators.

RBC Signals

RBC Signals is a global space communications provider serving government and commercial satellite operators in GEO, low-Earth orbit, & MEO with an improved model for the delivery and processing of data from satellites in orbit. The company's worldwide network includes both company-owned and partner-owned antennas, capitalizing on the sharing economy model, for best-in-class services offering affordability, flexibility and low latency. Their team has deep relationships across the entire space value chain and decades of experience building, operating, and maintaining ground stations for the direct reception and processing of Earth observation satellite data.

For customers needing turnkey access to existing antennas, RBC Signals offers ground station antenna-as-a-service, with the flexibility to secure unlimited satellite passes or 'pay-by-the-pass/minute/GB'. This is made possible through a combination of their own network of highly capable systems and the unique 'sharing economy' model, wherein they leverage the unused excess capacity of dozens of partner-owned antennas worldwide. This amounts to a growing network of over 70 antennas in nearly 50 locations worldwide offering unmatched capabilities. A map of these locations is shown in figure 12.15.

RBC Signals also offers turnkey bring-your-own-antenna hosting solutions that pair customer-owned equipment with reliable, high-end ground infrastructure almost anywhere in the world.

Figure 12.15: RBC Signals ground network map. Credit: RBC Signals.

They also use a distributed compute architecture where some processing will occur on the satellite, most will occur at a data center/cloud, and some processing will occur at the terrestrial edge at the ground station. RBC Signals can host AWS and Microsoft on premise cloud infrastructure, as well as virtual servers at the ground station.

AWS Ground Station

AWS Ground Station enables operators to control and ingest data from orbiting satellites without having to buy or build satellite ground station infrastructure. AWS Ground Station does this by integrating the ground station equipment like antennas, digitizers, and modems into AWS Regions around the world. Operators onboard their satellites and schedule time to communicate with them. There is the option of conducting all satellite operations on the AWS Cloud, including the storing and processing of satellite data with results delivered using AWS services, or the AWS Ground Station can downlink the satellite data and transport it to the user's processing center.

AWS Ground Station antennas are located within fully managed AWS ground station locations, and are interconnected via Amazon's low-latency, highly reliable, scalable and secure global network backbone. Operators can connect with any satellite in low-Earth orbit and MEO operating in X-band and S-band frequencies, including: S-band uplink and downlink, X-band narrowband and wideband downlink. Data downlinked and stored in one AWS Region can be sent to other AWS Regions over the global network for further processing.

AWS Ground Station provides an easy to use graphical console that allows operators to reserve contacts and antenna time for their satellite communications. They can review, cancel, and reschedule contact reservations up to 15 minutes prior to scheduled antenna times. Access can be scheduled to AWS Ground Station antennas on a per-minute basis so operators only pay for the scheduled time. They can access any antenna in the ground station network, and there are no long-term commitments.

AWS Ground Station provides satellite antennas direct access to AWS services for faster, simpler and more cost-effective storage and processing of downloaded data. This allows operators to reduce data processing and analysis times for use cases like weather prediction or natural disaster imagery from hours to minutes or seconds. This also enables operators to quickly create business rules and workflows to organize, structure, and route the satellite data before it can be analyzed and incorporated into key applications such as imaging analysis and weather forecasting. Key AWS services include Amazon EC2, Amazon S3, Amazon VPC, Amazon Rekognition, Amazon SageMaker, and Amazon Kinesis Data Streams (1).

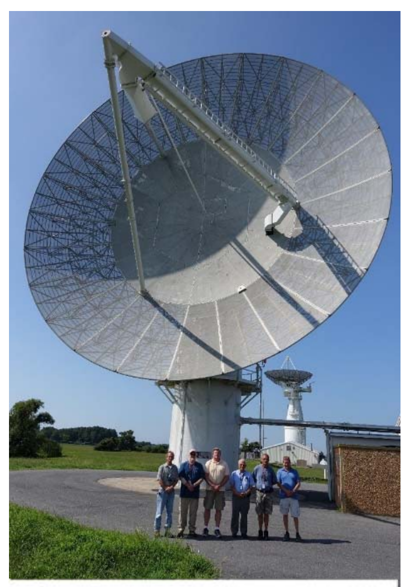


Figure 12.16: 18-meter UHF ground station antenna at NASA Wallops Flight Facility. Credit: NASA.

NASA UHF Ground Station

The Atmospheric Sciences Research Facility (ASRF) SmallSat Ground Station (ASGS) supports a range of small satellite operators with a UHF ground station operating 24/7 at NASA Wallops Flight Facility (WFF). ASGS uses the 18 m UHF antenna shown in figure 12.16 that was originally brought online in 1959 and used as a radar. With this large high-gain antenna (36 dbi gain, 2.9° beamwidth at 450 MHz) operating in the 380 to 480 MHz UHF band, the ground station provides a 3.0 Mbps high data rate capability for CubeSats, which is 300 times the typical 9.6 Kbps. The ground system uses a software defined radio and front-end processing software. Service includes support for downlinking telemetry and/or uplink commanding, monitor & control capability, scheduling, and data storage. The scheduling process provides operators with a deconflicted schedule based on user requirements. This is being accomplished with minimal documentation, pre-mission testing and cost-per-pass. As of March 2020, the station supports eleven NASA funded CubeSats. An affiliation with NASA is required to use the system. This would include being a NASA sponsored mission through means such as a grant or having either an interagency or reimbursable agreement with WFF.

NASA Near Earth Network

The NASA NEN provides direct-to-earth telemetry, commanding, ground-based tracking, and data and communications services to a wide range of customers. The NASA NEN Project consists of NASA, commercial, and partner S-band, X-band, and Ka-band ground stations supporting spacecraft in low-Earth orbit, GEO, Highly Elliptical Orbit (HEO), Lunar orbit, and Lagrange point L1/L2 orbit up to one million miles from Earth. The NEN supports multiple robotic and launch vehicle missions with NASA-owned stations and through cooperative agreements with interagency, international, and commercial services. The NEN is adding additional Ka-band capability, and also recently added two 6.1-meter S-band ground stations in Florida. The Ka-band and Florida ground stations augment NEN small satellite orbital tracking and communications capacity. Table 12-4 shows the radio frequencies that the NEN supports via the National Telecommunications and Information Administration (NTIA).

Table 12-3: NEN Supported Radio Frequencies and Bandwidths

Band	Function	Frequency Band (MHz)
S Uplink	Earth to Space	2,025 – 2,110
X Uplink	Earth to Space	7,190 – 7,235 (Two NEN sites to 7,200)
S Downlink	Space to Earth	2,200 – 2,300
X Downlink	Space to Earth, Earth Exploration	8,025 – 8,400
X Downlink	Space to Earth, Space Research	8,450 – 8,500
Ka Downlink	Space to Earth	25,500 – 27,000

The NEN has been ready to provide TT&C services for CubeSats ever since they were introduced over a decade ago. Since the NEN supports primary frequency bands of S, X, and Ka it is more advantageous than using UHF bands, which are allocated as secondary frequencies and have an increased probability of local interference. The NEN provided service to its first CubeSat mission, the SeaHawk-1 CubeSat, in March 2019. It was tracked by the NEN Wallops 11 m antenna (WG1) at a data rate of 3 Mbps over X-band. This was accomplished through the small X-band antenna shown in figure 12.17. The WG1 detected good signal strength, autotracked, locked-on to collect data, and successfully completed file delivery. In June 2019, the spacecraft transmitted at 50 Mbps, which is a

Figure 12.17: SeaHawk-1 CubeSat X-band antenna. Credit: NASA.

very high data rate for a CubeSat. There are currently five in-house 6U CubeSat missions at NASA Goddard Space Flight Center (GSFC) planning to use the NEN for S-band uplink and downlink.

The NEN is exploring how to provide higher data rates for CubeSat missions with techniques such as Digital Video Broadcast Satellite Second Generation (DVB-S2). Higher data rates either increase science return or reduce the number of minutes per day of required ground station contacts. Reducing the number of minutes per day increases the number of small satellite spacecraft that the NEN may accommodate with its existing ground stations. Higher data rates also enable mother-daughter small satellite constellations, where the mother spacecraft handles the communication with Earth for multiple daughter spacecraft. The NEN is also exploring the addition of Multiple Spacecraft per Aperture (MSPA) for constellations of CubeSats and arraying of antennas for higher performance. Future larger satellite missions are planned to be supported by the NEN at 4 Gbps via Ka-band.

The NEN facilitates Commercial Services (CS) and negotiated a bulk-buy discount for all NASA missions. This allows for contacts on the NEN Contractor/University Operated and CS apertures to be at no-cost for NASA missions. The NEN does schedule CS in accordance with NASA mission defined priority. The Networks Integration Management Office (NIMO) at NASA GSFC is the liaison for customers that wish to use NEN services. NIMO has a variety of services and capabilities available and can coordinate support from providers throughout NASA, other US agencies, US commercial entities and foreign governments. Some of the services that NIMO can provide include:

- Requirements Development
- Communications Design Support & Guidance
- Optical Communications Analysis
- Network Feasibility Analysis
- Spectrum Management
- RF Compatibility Testing
- Launch Support

Network Feasibility Analysis includes determining NEN station loading as a function of the mission’s priority, and determining the availability of planned stations for the contacts requested. Prior to the mission deployment, the NEN commits to providing the requested stations and contact time as outlined in the Network Feasibility Analysis.

If interested in more information on using the NEN, please contact NIMO’s Jerry Mason.

Jerry Mason, Chief
Networks Integration Management Office, Code 450.1
Exploration and Space Communications Projects Division
Goddard Space Flight Center, Greenbelt, MD 20771
Phone: (301) 286-9515
Email: jerry.l.mason@nasa.gov

NASA Deep Space Network

The Deep Space Network (DSN) is optimized to conduct telecommunication and tracking operations with space missions in GEO. This includes missions at lunar distances, the Sun-Earth LaGrange points, and in highly elliptical Earth orbits, as well as missions to other planets and beyond. The DSN has supported, or is currently supporting, missions to the Sun as well as every planet in the Solar System (including dwarf planet Pluto). Two missions (Voyager I and Voyager II) have reached interstellar space and still communicate with the DSN.

For more information, please see:
https://www.nasa.gov/directorates/heo/scan/services/networks/dsn
https://deepspace.jpl.nasa.gov/about/commitments-office/
https://deepspace.jpl.nasa.gov

The DSN offers services to a wide variety of mission customers, as shown in table 12-5.

Table 12-4: DSN Customers, Mission Characteristics, Frequencies, and Services

Customers • NASA • Other Government Agencies • International Partners	**Mission Phases** • Launch and Early Orbit Phase (LEOP) • Cruise • Orbital • In-Situ
Mission Trajectories • Geostationary or GEO • HEO • Lunar • LaGrange • Earth Drift Away • Planetary	**Frequency Bands –** Includes Near-Earth and Deep Space Bands, Uplink and Downlink, Command, Telemetry, and Tracking Services • S-Band (2 GHz) • X-Band (7, 8 GHz) • Ka-Band (26, 32 GHz)

DSN services include:

- Command Services
- Telemetry Services
- Tracking Services
- Calibration and Modeling Services
- Standard Interfaces
- Radio Science, Radio Astronomy and Very Long Baseline Interferometry Services
- Radar Science Services
- Service Management

Custom and tailored DSN services can also be arranged for missions and customers. DSN-provided data services are accessed via well-defined, standard data and control interfaces:

- The Consultative Committee for Space Data Systems (CCSDS)
- The Space Frequency Coordination Group (SFCG)
- The International Telecommunication Union (ITU)
- The International Organization for Standardization (ISO)
- De facto standards widely applied within industry
- Common interfaces specified by the DSN

The use of data service interface standards enable interoperability with similar services from other providers.

Figure 12.18: DSN antennas and their locations. Credit: NASA.

Figure 12.18 shows the DSN antennas and their locations. Each DSN ground station in California (United States), Madrid (Spain), and Canberra (Australia) currently (June 2020) is operating four 34 m Beam Wave Guide antennas and one 70 m antenna. By the late 2020s, this is planned to increase to include one 70 m plus four 34 m antennas at each DSN site.

The DSN is capable of tracking up to four spacecraft per antenna (MSPA) if they all are within the scheduled antenna's beam. The 34 m antennas at each complex can be combined into an array, with or without the co-located 70 m antenna. The combined G/T depends on a number of factors but is approximately increased by the sum of the antenna areas from the arrayed apertures minus approximately 0.3 dB combining loss. For instance, arraying four 34 meter antennas results in an increase of 5.72 dB.

The DSN supports RF testing using the following facilities:

- Development and Test Facility (DTF-21), located near NASA Jet Propulsion Laboratory (JPL)

- Compatibility Test Trailer (CTT-22), able to come to the spacecraft site
- DSN test facility (MIL-71), located at NASA Kennedy Space Center (KSC), Florida

Morehead State University CubeSat Ground Station

Morehead State University, as an early CubeSat technology adopter, has developed ground station technologies to support LEO and interplanetary CubeSat missions. The Morehead State University Space Science Center team developed a 21-meter antenna system that has provided telemetry, tracking, ranging and commanding services for low-Earth orbit, MEO and "near-Earth" deep space CubeSat missions since it came on-line in 2006. The 21-meter antenna, shown in figure 12.19, is a unique educational tool that provides an active laboratory for students to have hands-on learning experiences with the intricacies of satellite telecommunications and radio astronomy.

Figure 12.19: The Morehead State University 21-meter Ground Station has been upgraded with support from NASA's Advanced Exploration Systems, to become the first non-NASA affiliated node on the DSN. Referred to as DSS-17, the station will support NASA Interplanetary CubeSat missions. Credit: Morehead State University.

From its inception, it was anticipated that the 21 meters would provide TT&C services for small, low power satellites performing research in the lunar vicinity, at Earth-Sun Lagrange points, at Near Earth Asteroids, and potentially out to Mars at low data rates. It was not envisioned that these small satellites would be CubeSats since the form factor was evolving simultaneously with the planning and design of the 21-meter dish. The proliferation of CubeSats and other SmallSats investigating interplanetary destinations, however, has begun to provide unique opportunities for the students and staff at Morehead State University to gain valuable experience in space operations and to vet performance of the 21 m as an operational deep space station.

An upgrade supported by NASA's Advanced Exploration Systems in 2016 turned the 21-meter antenna into Deep Space Station 17 (DSS-17), an affiliated node on NASA's Deep Space Network. The upgrade, that was undertaken in partnership with JPL, improved the performance of the station to meet DSN standards for operations. Performance metrics of DSS-17 are listed in table 12-6. This arrangement has provided another level of real-world experience to students in the space science programs at MSU who primarily operate the station. The operating philosophy is that DSS-17 serves as a Class D Station for NASA Interplanetary Class D CubeSat missions.

Students and staff at the Space Science Center at Morehead State University are developing a full motion 12-meter class antenna system that will serve as an Earth Station for low-Earth orbit satellite mission support as well as a training facility for university students to gain experience in space mission operations. The instrument was needed to fill the role previously held by the 21-meter station that is now devoted to interplanetary SmallSats. The 12-meter ground station will be staffed by university students. It will be available for a wide variety of TT&C services at S-band and X-band when it becomes operational in 2022. Figure 12.20 illustrates both 21- and 12-meter ground stations at Morehead State University.

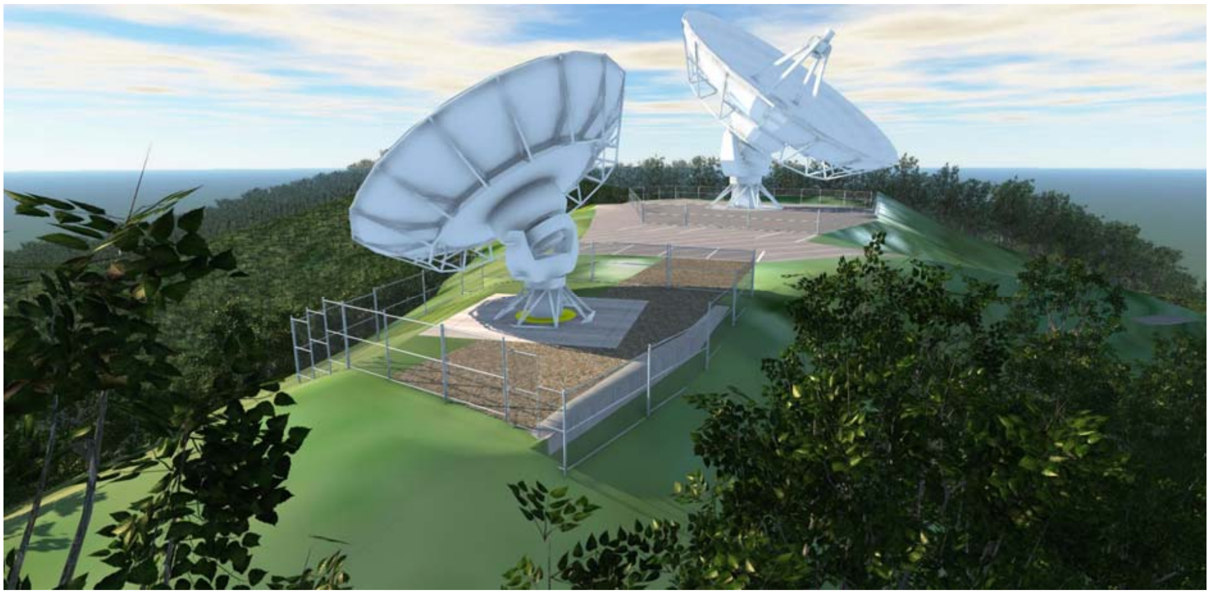


Figure 12.20: Artist's Concept of the 21-meter Ground Station (DSS-17 back) and the 12-meter LEO Ground Station (front) under development at Morehead State University. Credit: Morehead State University.

Table 12-6: DSS-17 Performance Characteristics (X-Band)	
Performance Measure	**Performance Value**
X-Band Frequency Range*	7.0 – 8.5 GHz
X-band Uplink Range*	7.145 – 7.235 GHz
X-band Downlink Range*	8.400 – 8.500 GHz
LNA Temperature	< 20 K
System Temperature T_{sys}	<100 K
Antenna Gain	62.7 dBi (@8.4 GHz)
System Noise Spectral Density	<-178 dBm/Hz
G/T at 5° Elevation	40.4 dBi/K
Time Standard	H- MASER (1ns/day)
EIRP	93.7 dBW
HPBW	0.1150 deg
SLE Compliant	Yes
CCSDS Capable	Yes
Radiometric	Angle, Doppler, Sequential Tone and PN Ranging
Ranging Precision	+/-1 range unit (0.94 ns)

12.9.2 Space Relay Network Service Providers

Space relay solutions are less common than traditional direct-to-Earth solutions, but there are a few options that exist for small satellites (see table 12-7). In order to access the space relay, a satellite operator purchases a modem from the relay manufacturer and flies that on their satellite in order to access the relay services. In general, space relays are ideal for obtaining satellite TT&C data (health and safety of the vehicle) rather than for large data downlinks.

Table 12-7: Service Providers for Space Relay Networks

Product	Manufacturer	TRL	Specifications
Simplex Data Network	Globalstar	9	LEO relay requiring either simplex or duplex data modems onboard the satellite
TDRSS Network	NASA	9	GEO relay providing S-band downlink
Fast Pixel Data Transport Network	Analytical Space	6 – 7	Developing LEO relay with hybrid RF and optical downlink
Iridium Global Network	Iridium	9	LEO relay requiring 9600 series transceivers onboard the satellite

Simplex Data Network

The Simplex Data Network by Globalstar operates with a low-Earth orbit satellite constellation that small satellites can communicate with via simplex and duplex data modems. The constellation of 48 satellite is spread on eight orbital planes with an altitude of 1,414 km and an inclination of 52°. Coverage is provided between 70° South latitude and 70° North latitude, so it does not have coverage over the poles. The satellites serve as a bent pipe for communication and do not have crosslink capability between satellites. The Globalstar system uses Code Division Multiple Access (CDMA) for its communication waveforms, which can provide a secure connection. The constellation satellites receive user spacecraft signals at L-band (1610-1626.5 Mhz) and converts it to C-band for relay to the ground station or gateway. Once the data is downlinked to the gateway, it is stored in a cloud-based network, and users can directly access the cloud to retrieve their data. Data plans are purchased on a monthly basis for this service. Data coverage is 24/7 and can be received in near real-time. If using the duplex modem configuration, commanding can also be done 24/7 unlike a traditional ground station where the satellite needs to be within its line of sight. The modem data rates are at 9.6 kbps.

The primary benefit of this service has been the ability to receive satellite health telemetry. This is particularly helpful post deployment while the ground station is searching for the spacecraft. The ability to command the spacecraft with the system has been met with mixed results. Significant lag has been experienced between when the command is sent and when the satellite receives it. For missions with low data requirements, this is an option to consider for the ground solution. Missions with high data rate requirements can still consider it is as a backup option for keeping track of satellite health when the satellite is not in contact with a ground station (2).

Tracking and Data Relay Satellite System Network

The NASA TDRSS is a communication signal relay system that provides tracking and data acquisition services. The TDRSS space segment consists of six in-orbit Tracking and Data Relay Satellite (TDRS) located in GEO. Three TDRSs are available for operational support at any given time. The operational spacecraft are located at 41°, 174° and 275° west longitude. The other TDRS in the constellation provide ready backup in the event of an operational spacecraft failure and, in some specialized cases, resources for target of opportunity activities. The system is capable of transmitting to, and receiving data from, spacecraft over at least 85% of the spacecraft's orbit. The TDRSS ground segment is located near Las Cruces, New Mexico, known as the White Sands Complex. Forward data is uplinked from the ground segment to the TDRS and from the TDRS to the spacecraft. Return data is downlinked from the spacecraft via the TDRS to the ground segment and then on to the designated data collection location.

TDRSS provides S-band and Ku-band services through the single access (SA) antennas and S-band services through the S-band multiple access (SMA) phased array. TDRSS is capable of supporting coherent range and two-way Doppler tracking as well as noncoherent one-way return-link and one-way forward-link Doppler tracking of user spacecraft. Accurate one-way return-link tracking, which can use SMA, the most available TDRSS resource, requires a stable oscillator onboard the user spacecraft as the source of frequency. Two-way and one-way return-link tracking measurements are used for ground orbit determination for navigation and precise positioning; one-way forward-link tracking is used for autonomous onboard navigation with achievable accuracies better than those of the GPS Precise Positioning System (PPS).

The NASA GSFC BurstCube 6U CubeSat mission is applying modifications to a Vulcan S-band radio in order to communicate with TDRSS. The mission is using TDRSS to obtain real-time alerts of science events captured by the spacecraft (3) (4).

Fast Pixel Data Transport Network

Analytical Space's Fast Pixel Data Transport Network will consist of a constellation of relay satellites in low-Earth orbit to provide high-speed data connections for client satellites. Client satellites will transmit the data to the relay satellite via RF, and the relay satellite will downlink that data through a combination of optical and RF communications. The network will be backward compatible with a variety of radio frequencies, meaning no additional hardware will be required onboard a client satellite. The network will also use a combination of optical and RF communications for the relay downlink, allowing higher throughput through the system than a traditional RF system. This network is not yet fully operational; a technology demonstration was launched in 2018, putting this system at a TRL level of 6 – 7 (5).

Iridium Global Network

The Iridium Global Network is a constellation of low-Earth orbit satellites that provide global communications to both users on the ground and other satellites in space. The 66 cross-linked satellites are spaced evenly on 6 orbital planes that are near polar at an 84.6 inclination and have an altitude of approximately 780 km. The service provides global coverage, including the polar regions. Due to its proximity to other low-Earth orbit "client" satellites, satellite operators can relay data through the Iridium network faster than a GEO relay network. The Iridium network uses a combination of Frequency Division Multiple Access (FDMA) and Time-Division Multiple Access (TDMA) for its communication waveforms. L-band (1616 – 1626.5 Mhz) is used for uplink and downlink between the user spacecraft and the Iridium spacecraft. Inter-satellite communication links between Iridium satellites is accomplished through Ka-band (23.18 – 23.28 GHz). Operators install an Iridium transceiver (9600 series) onboard their spacecraft in order to communicate with the Iridium network. Messages are relayed through Iridium's Short Burst Data Service, which is hosted on Iridium's cloud platform for easy user operation. For each transceiver unit, a data plan must be chosen and purchased, much like cellular phone data plans, and the plan details are linked to the unit's ID, which is referred to as IMEI (International Mobile Equipment Identity). The special feature of this system is that it has as an option for "IMEI-to-IMEI" transmission. When an Iridium IMEI is activated, five output destinations may be specified. Most vendors allow for a combination of emails addresses, fixed IP address or another device with an IMEI ID. Other vendor service options would include the real-time satellite tracking tool called GSatTrack by Global Satellite Engineering (GSE). This tool allows users to know when an Iridium satellite is approaching overhead and its coverage area. An example screenshot is shown in figure 12.21.

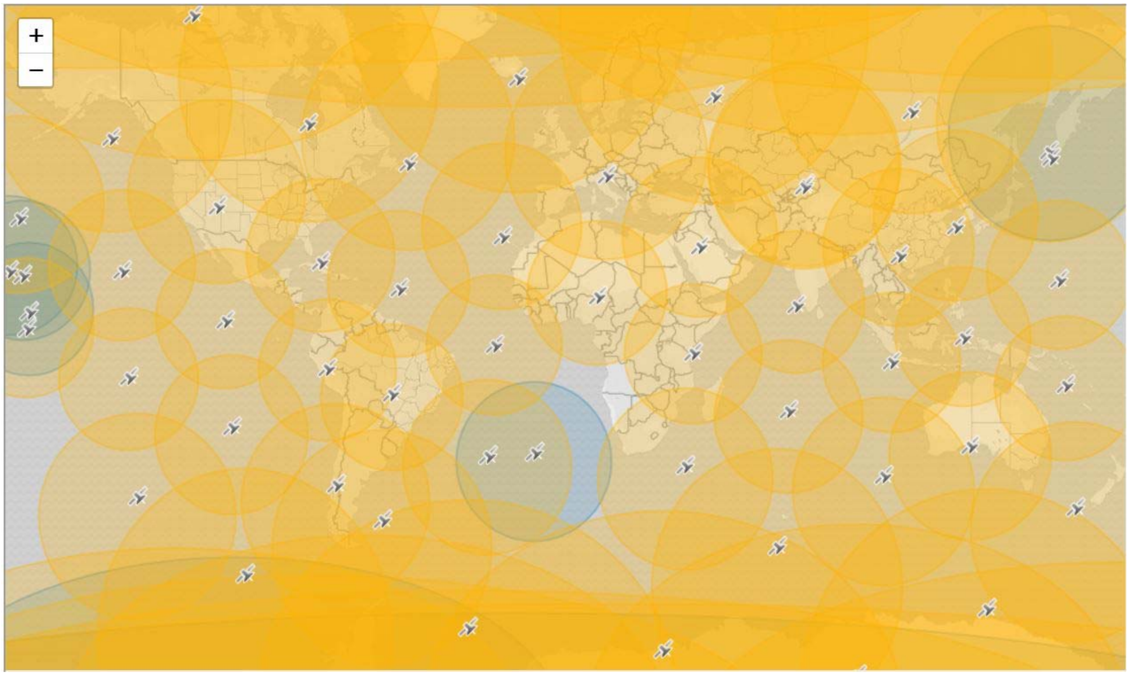


Figure 12.21 Screenshot of GSatTrack showing locations of Iridium Gen-1 satellites (blue circles) and Iridium NEXT satellites (orange circles). The size of the circle represents the coverage area. Credit: Global Satellite Engineering www.gsat.us.

As an application example, testing was completed at NASA WFF to evaluate the usefulness of short burst messages for tracking GPS location over the Iridium Network. Two transceivers were setup with one set to command and the other set in "tracking mode." The command unit sent messages containing GPS data (attitude, longitude, elevation, and velocity) and the messages were received by the tracking unit within 2 – 10 minutes of transmission. This served as a successful demonstration of being able to receive short burst, low latency messages between two units without the need for scheduling. Such an application can be valuable for missions of opportunity such as SmallSat constellations.

As of January 2019, Iridium deployed the last of its 75 NEXT satellites in conjunction with Thales Alenia Space and SpaceX. As a Public-Private Partnership (PPP), the NEXT satellites also carry hosted payloads limited to 50 kg and ~50 W of power. The satellites are replacements for the first generation and maintain interconnection with a crosslink architecture. Also in 2019, Iridium unveiled the Certus 9770 transceiver (which technology partners are beta testing and further developing), designed for speeds from 22 Kbps to 88 Kbps. It is capable of transferring IP data more than 35 times faster than previous devices (6) (7).

12.9.3 End-to-End Hardware for Ground Systems

A complete ground system can be provided as a kit with all of the necessary components bundled together and setup to work seamlessly. These end-to-end solutions include the antenna, its controller, and the RF feed with all the necessary filtering and low noise amplification for the particular wavelength of interest. They use a software defined radio or a dedicated transceiver to convert between digital packets and RF waveforms. Software is included to process the satellite position and direct the antenna to track it. Additional software is used to archive and display the information within the digital packets. Three vendors, GAUSS, Innovative Solutions In Space (ISIS) and GomSpace, listed in table 12-8 provide solutions for the low-cost CubeSat and small satellite market. One vendor, Surry Satellite Technology Limited, offers a higher end system, installation service, and personnel support. The final vendor listed, Kratos, offers a different end-to-end solution that begins with the digitized RF waveform. The Kratos Quantum software then demodulates, filters, unpacks, parses, display and archives the data (8).

Table 12-8: End-to-End Hardware for Ground Systems

Product	Manufacturer	TRL	Type of Product
Complete Ground Solution	GAUSS	9	Small satellite provider offering a complete ground solution. UHV, VHF, and S-band
Complete Ground Solution	ISIS	9	Small satellite provider offering a complete ground solution. UHV, VHF, and S-band
Complete Ground Solution	GomSpace	9	Small satellite provider offering a complete ground solution. UHV, VHF, and S-band
Surrey Ground Segment	Surrey Satellite Technology Ltd.	9	Major contractor who will install ground stations capable of S-band for U/L and D/L and X-band for D/L.
Quantum	Kratos	9	Major contractor with a complete ground solution

GAUSS Ground Station Kit

The GAUSS ground station is a turnkey solution. It can be configured with UHF, VHF and S-band on the same pointing system. An example of the associated hardware is shown in figure 12.22.

Hardware features of the systems offered include (49):

- High gain Yagi-Uda VHF and UHF antennas (>16 dBi for UHF)
- Low-noise amplifiers and band-pass filters for VHF and UHF bands
- Low-loss RF coaxial cables
- 1.5 meter parabolic dish for higher frequencies downlink (up to 6 GHz, default feed is for S-band)
- VHF: uplink and downlink up to 100 W using radio and Terminal Node Controller (TNC), software defined radio (SDR) optional
- UHF: uplink and downlink up to 70 W, using radio and TNC, SDR optional
- TX using ICOM-9100 hardware, RX recording and decoding via SDR
- Several RF and electrical fuses for lightning protection

Figure 12.22: (left) GAUSS ground station hardware, transceiver and (right) tracking antenna. Credit: GAUSS Srl.

- S-Band: downlink using SDR for recording and post-processing of I/Q RF data
- Az/El rotor for high-torque maneuvering
- Hardware components power switch on/off to minimize power consumption
- Full HD camera for instant antenna monitoring and picture logging

The features of the software that accompanies the system include:

- Automatic TLE download from publicly available repositories
- SGP4 propagator as suggested by USAF NORAD's Space-Track
- Rotor control (*compatibility with several rotor controllers, e.g. Yaesu, RF Hamdesign*)
- Assisted rotor pointing calibration and verification using Sun position
- Fully compatible with ICOM-9100 satellite radio and GAUSS USB ground dongle
- Separated Doppler shift corrections for uplink and downlink frequencies
- DUPLEX TX/RX mode
- Instant weather check and logging, in order to operate the ground station safely
- Lightning detection for safe antennas operation
- Instant logging of all subsystems operation
- Ground map with live Earth clouds
- Compatible with several TNCs (*Kantronics, Symek, Paccomm, Kenwood*)
- Email report to ground station operators
- Instant email alerts for non-nominal conditions of the satellite or GS hardware components
- Session programming for weeks of unattended ground station operations
- GUI command recording for easy session programming
- One button programming to include a whole set of commands in the session
- Manual override during pass for last-minute command addition
- Control and handling of multiple satellites using configurable priorities
- Satellite TLM decoding, graphing and archiving into a database accessible by web
- Integrated satellite payload data handling and decoding (e.g. for image file processing)
- TCP/IP connections for remote ground station & TNC operations

Innovative Solutions In Space Ground Station Kit

The ISIS small satellite ground station is a low cost, turnkey solution that is designed to communicate with satellites in low-Earth orbit that operate in either amateur frequency bands or commercial bands. The frequency bands covered are S-band, UHF, and VHF. The ground station consists of an antenna and a 19” rack which houses the transceiver, rotor control and computer which make the system very compact. Examples of these components are shown in figure 12.23. The transceiver makes use of a software defined radio (SDR) that provides flexibility to swiftly reconfigure modulation/coding/data-rate on the run. Most of the commonly used modulation schemes and coding methods are already implemented and any customization requests can also be handled (9).

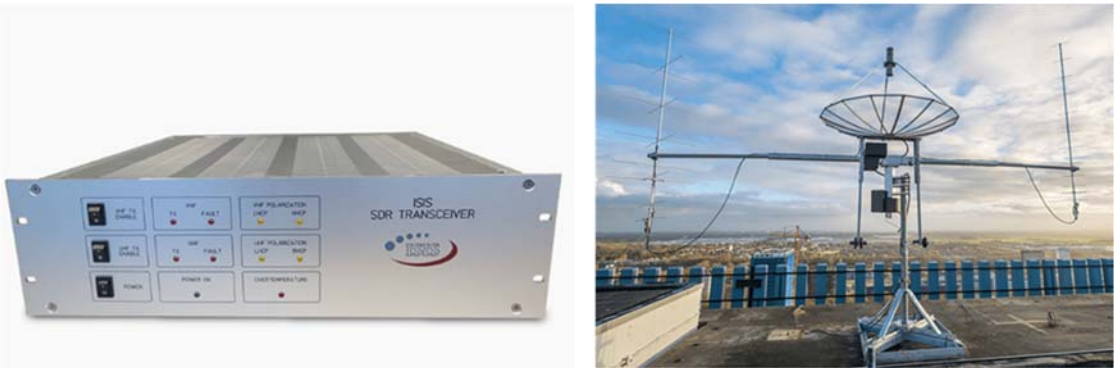


Figure 12.23: (left) ISIS ground station hardware, transceiver rack and (right) tracking antenna. Credit: ISIS.

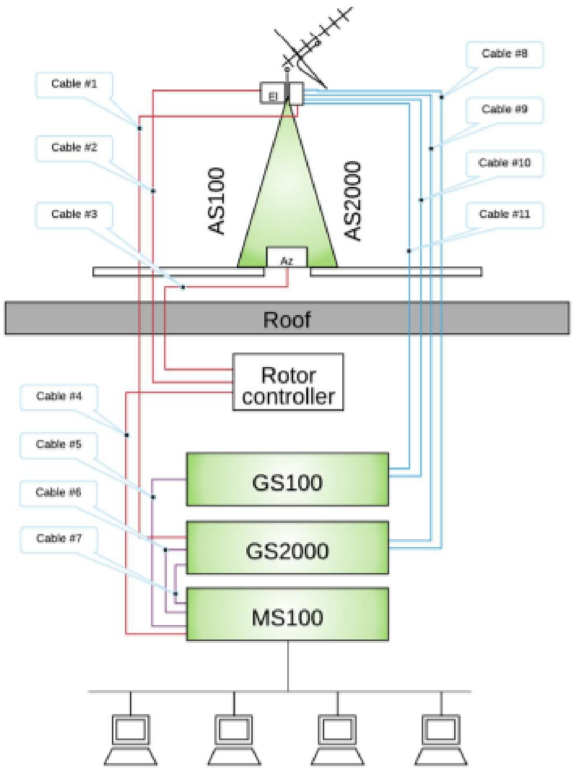
GomSpace Ground Station Kit

The GomSpace end-to-end solution is unique from other vendor offerings because a generic software defined radio is replaced with their AX100 or TR-600 radios, depending on the type of radio the in-orbit satellite uses to communicate. Using the same transceiver hardware on both sides of the link simplifies the configuration and validation testing steps in the I&T phase of the project. While the GomSpace solution does not work with satellites that do not use the GomSpace transceivers, the benefit is lower cost and simpler ground segment equipment. Figure 12.24 provides a graphic representation the ground station architecture and defines its critical components (10).

Surrey Satellite Technology Ltd. Ground Station Kit

Surrey can provide complete turnkey ground segment solutions for a range of space platforms, including all the hardware and software necessary to operate, maintain, process and archive data. Services provide by Surrey include:

- S- and X-band ground stations with full motion antenna systems from 2.4 meter to 7.3 meter in diameter, with radome options are available for harsh climates
- SSTL Pilot Satellite Control Software
- Mission planning systems
- Radiometric and geometric image processing
- Catalogue and data storage solutions
- Site surveys, ground segment installation and training
- Technical and maintenance support packages



NanoCom AS100 or AS2000

GomSpace has two rooftop antennas, the AS100 with VHF and UHF and the AS2000 with UHF and S-Band

NanoCom GS100 and GS2000

Each of the rooftop antennas has their own 19" rack mounted radio unit that contains two none flight qualified NanoCom AX100 or two TR-600 radio modules, placed on a special carrier board.

NanoCom MS100

A 19" rack mounted PC containing software relevant to controlling and communicating with a satellite. The unit has ethernet interface for remote access.

Software includes:

- Linux OS
- Rotor controller
- GSweb – tools for housekeeping (optional)
- Tracker software to control antenna movement
- Doppler compensation for the radio
- SDK

Figure 12.24: GomSpace ground station block diagram. Credit: GomSpace.

In addition, Surrey can work with customers to integrate their ground segment solutions with existing ground infrastructure or with 3rd party ground station networks (11).

Kratos Ground Station Solutions

The Kratos unique ground solution begins with their SpectraNet modem Digital IF product that converts analog signals at RF frequencies up to S-band into digital IF packets. It is the start of the Kratos digital processing product line chain. Kratos Quantum software operates on a fully digitized RF waveform. For example, a ground station service company would maintain the antennas and modems and use a very good internet connection to ship huge amount of data either into the cloud for storage and processing with the Kratos Quantum software, or to the customer MOC.

Kratos provides quantum as an integrated virtualized system supporting a satellite ground infrastructure architecture that is cloud and platform agnostic. Figure 12.25 provides a visualization for the system concept. All components are available separately to support an existing C2 solution or third-party ground network with existing signal processing and antenna resources. The quantum system includes:

(1) quantumCMD for small spacecraft C2;

(2) quantumFEP that connects C2 systems to RF signal processing equipment: handling command and telemetry stream formatting, encryption/decryption devices, CCSDS processing, and network interfaces to either quantumRadio or third-party ground antenna networks;

(3) quantumRadio, the signal processing solution when C2 and digital front-end processing are already addressed;

(4) quantumMR, a mission receiver with dual wideband receive chains, DVB-S2 and CCSDS enabled, tunable, independent IFs, LDPC/Reed-Solomon Convolutional;

(5) quantumDRA for data recording, processing and routing application supporting CCSDS/non-CCSDS header and channel data routing with IP-based interfaces;

Figure 12.25: Visualization for the Kratos quantum system concept. Credit: Kratos.

(6) quantumRX for wideband processing specifically tuned to streaming Earth observations in near-real time with 500 MHz bandwidth using Digital IF digitizers.

QuantumRadio is a purely software modem for RF signal processing on the ground or in the cloud. It can be accessed from anywhere via the web with no client software to maintain or install. QuantumRadio supports a wide range of uplink/downlink frequency bands at low to high data rates and has been tested for compatibility on a variety of widely used space radios.

By 2021, Kratos will be introducing a virtualized architecture solution called OpenSpace. As an enterprise level, end-to-end system, it will provide the SmallSat community the flexibility to scale on-demand as their operations grow in size and capability. By leveraging Digital IF over IP with time deterministic latency and software defined networks, OpenSpace will allow virtualized functions such as modems, channelizers, recorder and combiners to be orchestrated in a cloud environment. The virtual architecture will easily lend itself to upgrades and/or updates automatically, ensuring ongoing reliability and security. In addition, there will be the ability to test software releases in real-time, allowing ground equipment strings to be included in continuous integration and continuous delivery cycles. Software defined architectures are more agile, programmable, and automated, enabling the ground system to work in tandem with dynamic satellite payloads. By shifting from RF signals and analog equipment to a virtualized, IP-based infrastructure, orchestration can occur on the fly. Figure 12.26 provides an illustration of the OpenSpace architecture concept.

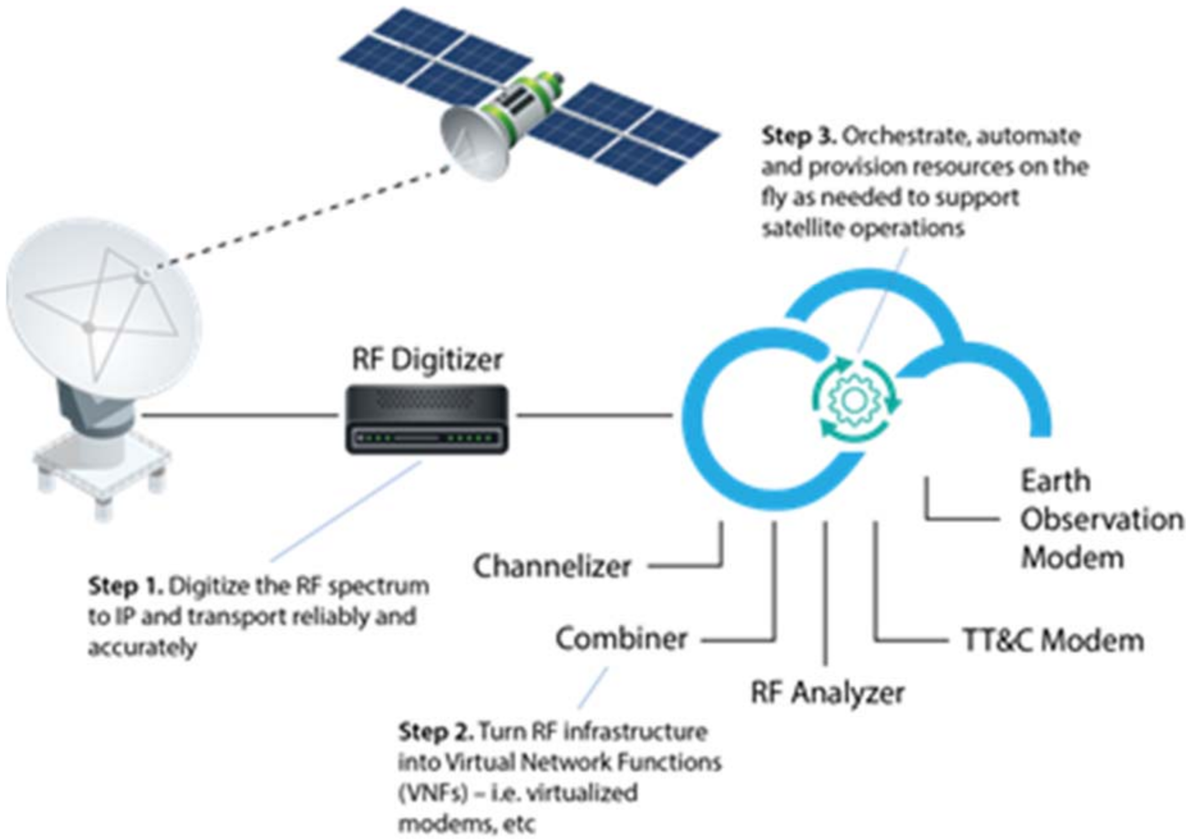


Figure 12.26: Kratos OpenSpace architecture concept. Credit: Kratos.

12.9.4 Component Hardware for Ground Systems

The hardware for ground stations consists of the tracking antenna, its feed, and the modem that converts the RF waveform into digital packets and vice versa. This section lists additional options for purchasing these components and some supporting equipment. The antennas are deferred to the prior "end-to-end" solution section because the same companies that provide a complete solution also sell the individual subsystems such as the tracking antenna. The antenna feed which consists of the RF pickup, LNA and mechanical filters is located directly on the antenna. A radome is an RF transparent enclosure that protects the antenna from weather. While there are several component hardware providers in the market, table 12-9 lists example products in each category. Often overlooked is ground compatibility testing. The GAUSS ground station dongle is a USB low-power board that integrates both a low-power UHF transceiver and a TNC, thus miniaturizing common ground station rack systems. This is useful during the satellite I&T phase to exercise commands through the satellite radio.

Table 12-9: Component Hardware for Ground Systems			
Product	**Manufacturer**	**TRL**	**Type of Product**
Tracking Antenna	See End-to-End Hardware Section 11.9.3	9	Antennas for small satellites in UHF, VHF, and S-band frequencies
Antenna Feed	See End-to-End Hardware Section 11.9.3	9	RF pickup, mechanical filters, low noise amplifier
USRP X310	NI Ettus Research	9	Open source software defined radio. DC-6 GHz with up to 120 MHz of baseband bandwidth, multiple high-speed interfaces
SpectraNet	Kratos	9	Digital IF product that converts analog signals at RF frequencies up to S-band into digital IF packets. It is the start of the Kratos digital processing product line chain.
Radome	Infinite Technologies	9	Antenna radomes
Ground Station Dongle	GAUSS	9	A USB low-power board to simulate your ground station safely in laboratory conditions. The USB dongle integrates both a low-power UHF transceiver and a TNC, thus miniaturizing common ground station rack systems
Integrated Testing Systems (EGSE) & Ground Station TT&C Modems	Celestia Satellite Test & Simulation	9	Hardware and software elements all operating within a single reference platform and environment

USRP X310 Open Source Software Defined Radio for SatCom Applications

The NI Ettus Research brand is the world's leading supplier of software defined radio platforms, including the Universal Software Radio Peripheral (USRP™) family of products. The USRP is one of the most popular open platforms for small satellite communications with options from high-performance to low-cost to highly deployable. One of the most popular hardware units for satellite communication applications is the USRP X310 with the UBX RF daughterboard. The USRP X310 is a high-performance software defined radio with the ability to transmit and receive modulated signals. With up to 160 MHz of instantaneous bandwidth and a frequency tuning range up to 6 GHz, the X310 with UBX has the raw hardware performance to cover many ground station satellite communication needs. In addition to the wideband UBX daughterboard, many narrower band options are available. The USRP family supports a wide range of software tool chains from

LabVIEW to GNU Radio with many existing IP modules for modulation and demodulation. The USRP X310 is intended for lab environments, however, it can be built in rugged weatherproof configurations. Many small satellite researchers are using the USRP as their ground station equipment for its adaptability with open source software and its embedded FPGA pre-processing capability. With a vibrant and active community around software tool chains such as GNU Radio, USRPs are being used by home hobbyists and many of the largest space vehicles developers today.

Kratos SpectraNet

SpectraNet is the only commercially available product of its kind that eliminates the distance constraints of RF transport by digitizing RF signals for transport over IP networks in a way that preserves both frequency and timing characteristics, and then uniquely restores the RF signals at their destination. By eliminating the distance constraints between antennas and signal processing equipment, this technology enables operators to deploy new ground architectures with numerous advantages, such as the ability to mitigate the effects of rain fade for Ku/Ka satellites, reduce costs by centralizing operations, simplify disaster recovery and system maintenance, optimize antenna placement and develop a migration path toward virtual ground systems. SpectralNet does all of this while protecting the operator's current investment in existing equipment. Figure 12.27 illustrates the advantage of the SpectraNet over the conventional approach.

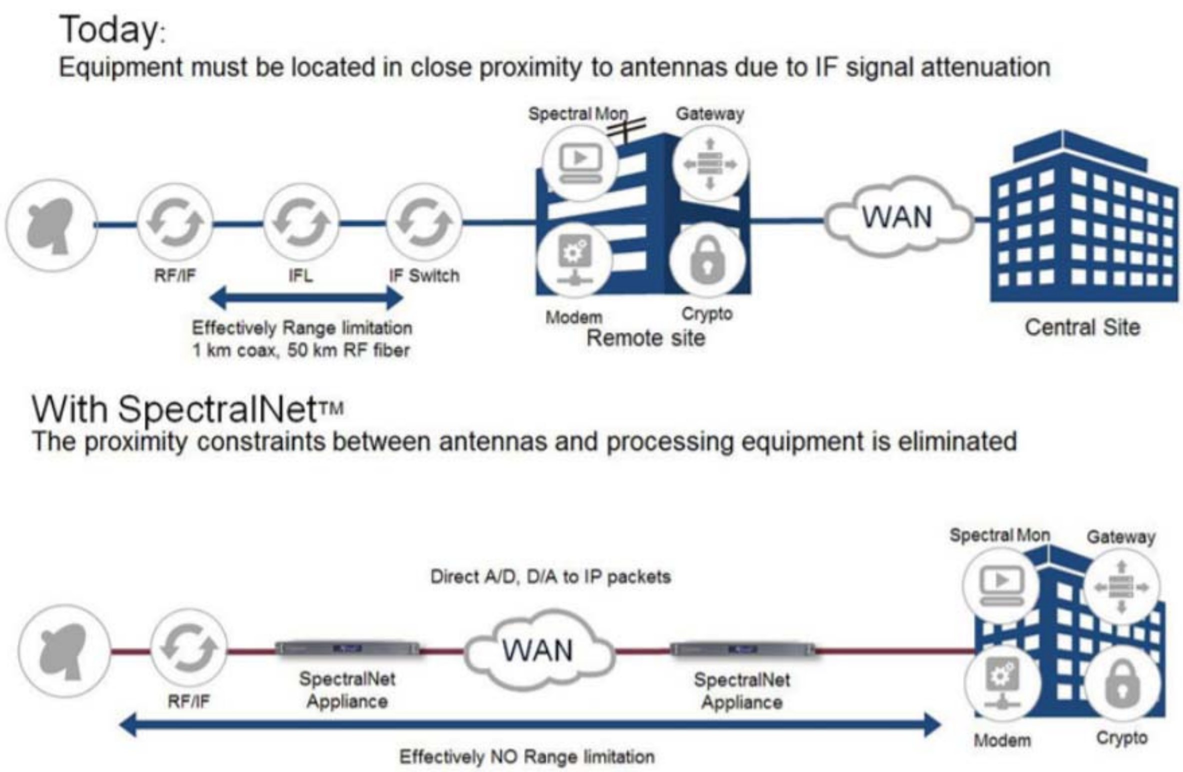


Figure 12.27: Kratos SpectraNet keeps most of the RF ground equipment remote from the ground station. Credit: Kratos.

Infinite Technologies Radomes

A successfully designed radome provides a protective cover and has minimal effect on the electrical functionality of the antenna. Figure 12.28 provides an example of a radome supplied by Infinite Technologies. Radomes provide the antenna system with a controlled environment, shielding sensitive equipment from weather related stresses such as wind, snow, ice, salt spray, etc. A radome can increase the useful life of the antenna and decrease overall maintenance costs for the system. Consideration for a radome should be given early in the design phase of the system, as a radome will allow for lighter duty and less expensive components such as drive motors and foundations due to the elimination of wind loads on the antenna. Also, the controlled environment inside the radome provides greater system availability allowing the antenna to operate in more adverse environmental conditions with minimal signal degradation. A radome will also provide maintenance personnel protection from weather during antenna maintenance (12).

For a radome to be a benefit, the unique attributes of the system being protected must be taken into consideration. A well-designed radome addresses these factors and can avoid negatively affecting the performance of the antenna system. Careful selection of a radome can improve overall system performance and readiness by:

- Allowing operation in severe weather by protecting the antenna from wind, rain, snow, hail, sand, salt spray, insects, animals, UV damage, windblown debris, and wide temperature fluctuations
- Providing security for the antenna system and protecting it from observation, vandalism etc.
- Providing a controlled environment which minimizes downtime, extends component and system operating life
- Permitting the use of more economical antenna pedestals, foundations, and drive system components

Figure 12.28: Infinite Technologies small radome. Credit: Infinite Technologies.

GAUSS UHF Mini Ground Dongle

GAUSS UHF Mini Ground Dongle, shown in figure 12.29, is a USB low-power board to simulate a ground station safely in laboratory conditions and expedite assembly, integration, and test procedures. The USB dongle integrates both a low-power UHF transceiver and a TNC, thus miniaturizing common ground station rack systems. It was designed to have easy access to TT&C testing during final verifications and pre-integration periods, but it can also be used on a ground station if an external power amplifier is added. It is fully compatible with the GAUSS UHF Radios. The dongle comes with multi-platform software and can be used with any PC/Mac. A special bundle includes both the radio and the Mini Ground Dongle for quick system deployment (13).

Figure 12.29: GAUSS UHF USB Mini Ground Dongle. Credit: GAUSS.

Integrated Testing Systems (EGSE) & Ground Station TT&C Modems

Celestia Satellite Test & Simulation BV (C-STS) provides ground-based solutions in the domains of satellite simulation, testing, communication, and data processing. Established in 1985, Satellite Services B.V. (SSBV) was acquired by Celestia Technologies Group in 2016 and re-branded to Celestia Satellite Test & Simulation B.V. to continue as a competence center for EGSE and TT&C solutions. Celestia STS has more than 30 years of experience in the space industry. More than 300 EGSEs and TT&C modems were delivered to space agencies, large system integrators, and specialized flight-equipment manufacturers around the World.

On-board computers, mass memory units, and transponders are tested every day with C-STS equipment. Celestia EGSE solutions have been used in more than 80% of all European Space Agency (ESA) missions. Celestia STS testing equipment is available in standard functionality, or configured to meet specific customer needs. System options include:

- Telemetry and Telecommand Processing System
    - TM acquisition and simulation
    - TC generation and acquisition
    - Bit error rate tester
    - TC authentication
    - TM/TC deciphering (API/DLL/LAN)
    - Includes control and monitor software for data processing and visualization
- Wizardlink High Rate Interface System
    - Up to 4 Wizardlink channels in parallel
    - Up to 2Gbps data rate per channel
    - Includes software for high speed ingest, processing, data archiving, and export
- LVDS High Rate Interface System
    - Up to 4 parallel LVDS inputs and outputs
    - 8-bit parallel up to 1Gbps per channel
    - Teaming of 2 LVDS input and output channels to 16-bits
    - 16-bit parallel up to 2Gbps per channel

- Includes software for high speed ingest, processing, data archiving, and export
- TT&C Integrated Modem and Baseband unit
    - Single or dual channel modulation and demodulation
    - Ranging measurement
    - Doppler simulation
    - Bit error rate tester
- Level Zero Processor Software for High Speed Data Processing
    - Data directly from the local disk drive or shared network drive
    - Processing of TM data from bitstream to frame and packet level
    - Configurable frame and packet checking rules
    - Configurable frame and packet output data storage and sorting
    - Live frame and/or packet distribution via LAN
    - Real-time statistical analysis, error checking, and reporting
- Optical Digital Convertor
    - Processing of optical detector signals to simulate optical communications

Efforts are on-going to improve product capability with a focus on modular, flexible, scalable multichannel systems that take advantage of the latest technologies. New modem and interface platform designs are to be launch by the end of 2020.

12.9.5 Ground Software

Software dominates the ground segment, replacing hardware solutions wherever possible. Advancements have been enabled by the speed of the personal computers, the bandwidth of the internet, and the security and availability of cloud storage and cloud computing. The remaining essential hardware for ground stations are the tracking antennas, feeds, modem and data storage drives. Everything else in between can be software. For example, computers are sufficiently capable that the FEP can be software, as can the radio. Software outside the RF chain perform significant supporting tasks. They include visualizing and calculating the satellite location in orbit and controlling the tracking antenna. Command and control software manages command scripts to be sent to the satellite and can display and analyze telemetry. Many software are open source and free. Other software are purchased from companies with a long history in ground segment solutions who had previously provided hardware products to do the tasks (table 12-10).

Table 12-10: Software for Ground Systems

Product	Manufacturer	TRL	Type of Product
softFEP	AMERGINT	9	Emulation ground systems software
quantumFEP	Kratos	9	Software that performs data formatting and interface conversion for commands and telemetry, with full support for NSA Type 1 and AES encryption/decryption devices
Gpredict	Alexandru Csete	9	Open source software that tracks satellites and provides orbit prediction in real-time. Radio and antenna rotator control for autonomous tracking

GNU Radio	GNU Project	9	Free software development toolkit that provides signal processing blocks to implement software-defined radios and signal processing systems
HWCNTRL	DeWitt & Associates	9	Ground station control program with an automation software package

AMERGINT softFEP

AMERGINT softFEP applications are deployed virtually on cloud architectures or hosted on dedicated servers. The applications perform control center data formatting and interface conversion for commands and telemetry, with full support for NSA Type 1 and AES encryption/decryption devices. SoftFEP applications are built on a proven library of more than 1,000 software devices. This allows each softFEP application to be tailored to the requirements specific to the ground system. Processing chains configured via Python scripts move satellite downlink data from Earth receipt for processing and uplink data to the radiating site. Deploying softFEP on multiple virtual machines (VMs) or within the cloud is inherent in the product architecture. Virtualized softFEP deployments support a wide range of ground system architectures while taking advantage of cloud-computing benefits. When applications are deployed in VMs, they can be hosted locally or run remotely in a cloud and interoperate across network connections. Customers have deployed their softFEP applications as independent network gateways, black front-end processors, red front-end processors, and data recorders, flowing data between the VMs as a satellite contact is processed (14).

Kratos quantumFEP

The quantum FEP satellite front-end software provides the digital processing and network connectivity needed between the Command & Control (C2) system and the RF signal processing equipment. All of the digital processing functions in a typical small satellite ground system are included: command and telemetry processing, recording, AES COMSEC security, CSSDS processing, packet level FEC, and network gateway interface support. Monitoring and control can be done using the HTML5 user interface or using REST or GEMS APIs. Figure 12.30 provides an illustration for quantuFEP system architecture (15).

Key features of quantumFEP are:

- Can be used on bare metal machines, a private cloud, or with cloud provider
- Suitable for all types of SmallSat programs – CubeSats, NanoSats, MicroSats, and SmallSats
- Compatibility tested with widely used ground modems
- Built-in test functions reduce Integration and Test (I&T) effort – ultimately reducing cost
- Configurable as mission requirements change or as new missions come online
- Commercial AES Encryption/Decryption standard feature with built in AES Key Manager
- Standard TCP/IP, GEMS, REST and VITA-49 interfaces make integration a snap
- Pure Software Implementation for signal processing functions
- Access and control from anywhere through the web with no client software to install or maintain

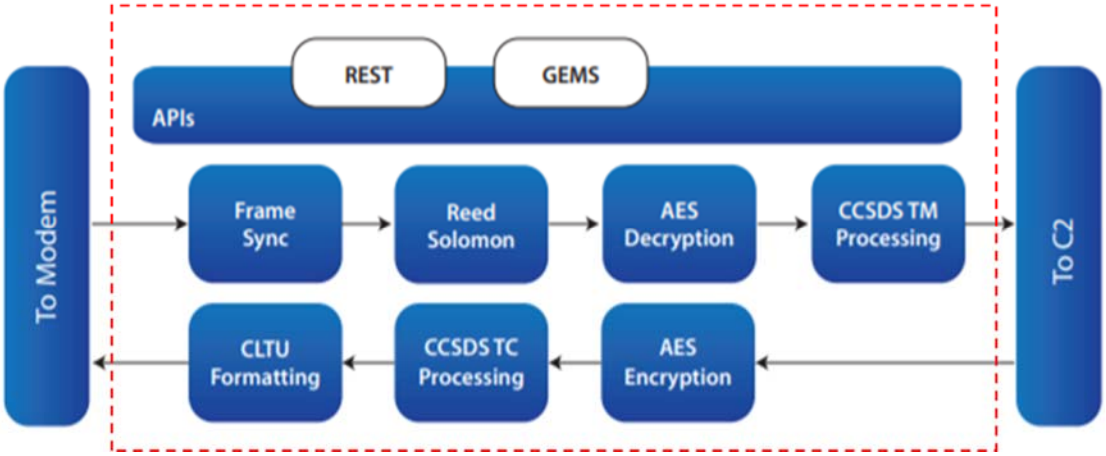


Figure 12.30: Kratos quantumFEP system architecture. Credit: Kratos.

Gpredict

Gpredict is a real-time satellite tracking and orbit prediction application. It can track a large number of satellites and display their position and other data in lists, tables, maps, and polar plots (radar view) as shown in figure 12.31. It can also predict the time of future passes for a satellite, and provide detailed information about each pass. Gpredict is different from other satellite tracking programs in that it allows the satellites to be grouped into visualization modules. Each of these modules can be configured independently from others, allowing unlimited flexibility in the look and feel of the modules. It will also allow satellite tracking relative to different observer locations at the same time (16). The following are key features of the software:

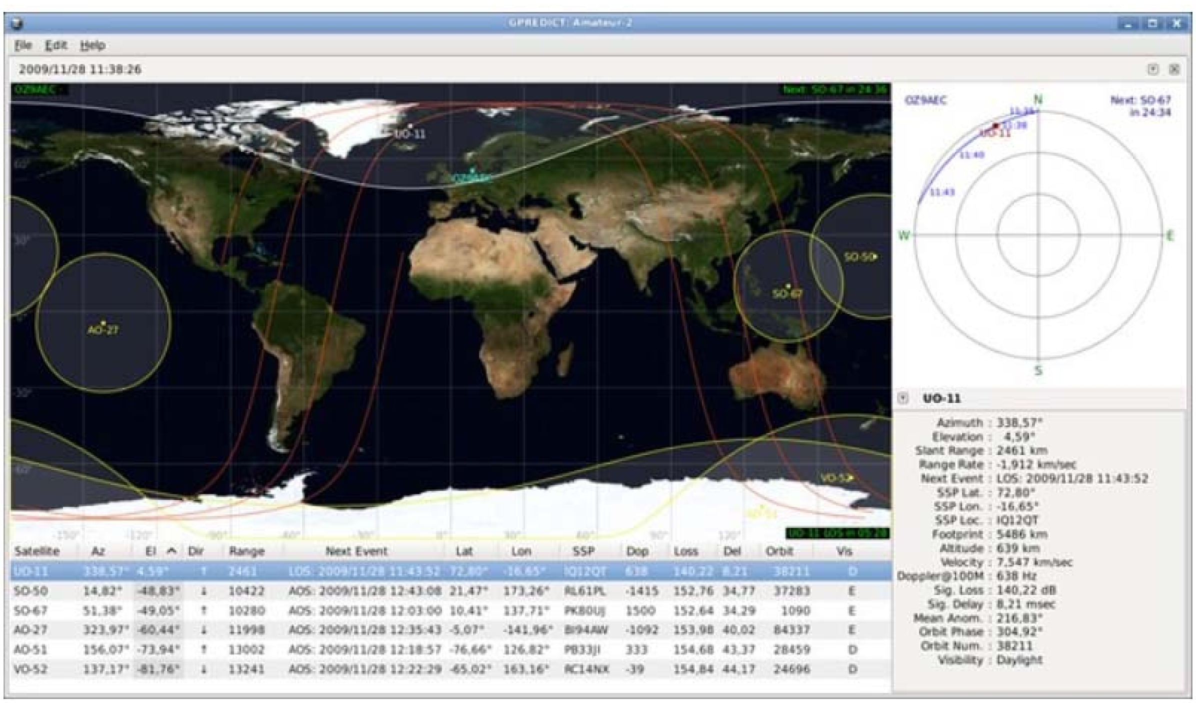


Figure 12.31: Gpredict graphical display with multiple satellites. Credit: Gpredict.

- Fast and accurate real-time satellite tracking using the NORAD SGP4/SDP4 algorithms
- No software limit on the number of satellites or ground stations.
- Appealing visual presentation of the satellite data using maps, tables and polar plots (radar views).
- Allows satellites to be grouped into modules, each module having its own visual layout, and being customizable on its own. Of course, several modules can be used at the same time.
- Radio and antenna rotator control for autonomous tracking.
- Efficient and detailed predictions of future satellite passes. Prediction parameters and conditions can be fine-tuned by the user to allow both general and very specialized predictions.
- Context sensitive pop-up menus allow future passes to be quickly predicted by clicking on any satellite.
- Exhaustive configuration options allowing advanced users to customize both the functionality and look & feel of the program.
- Automatic updates of the Keplerian Elements from the web via HTTP, FTP, or from local files.
- With a robust design and multi-platform implementation, Gpredict can be integrated into modern computer desktop environments, including Linux, BSD, Windows, and Mac OS X.
- As free software licensed under the terms and conditions of the GNU General Public License, it can be freely used, learned from, modified, and re-distributed.

GNU Radio

GNU Radio is a free & open-source software development toolkit for developing radio systems in software as opposed to completely in hardware. It can be used with readily-available low-cost external RF hardware and runs on most modern computers to create software-defined radios. It can also be used without hardware in a simulation-like environment.

GNU Radio performs all of the signal processing. It can be used to write applications to receive data out of digital streams or to push data into digital streams, which are then transmitted using hardware. GNU Radio has filters, channel codes, synchronization elements, equalizers,

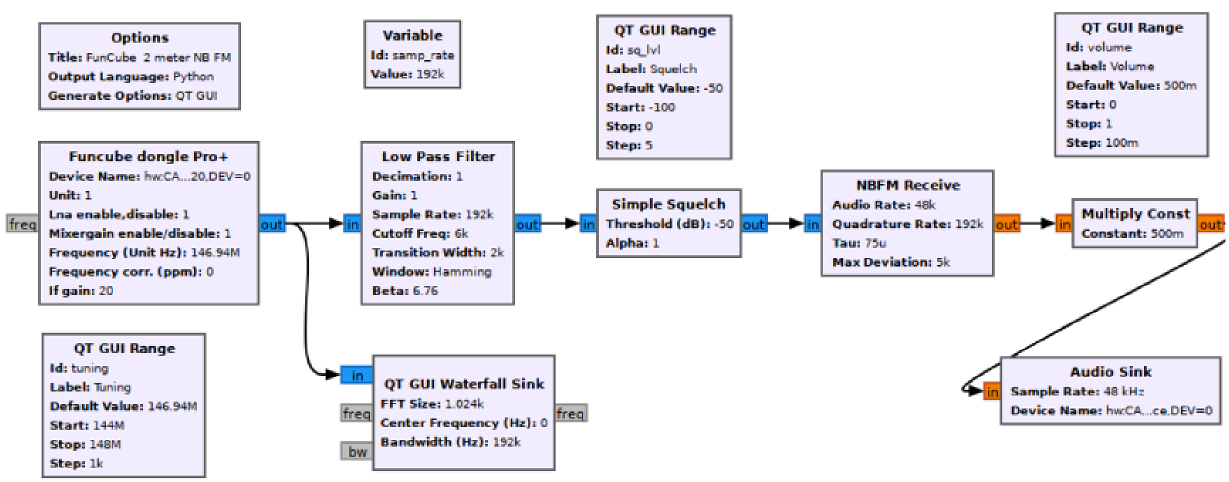


Figure 12.32: GNU Radio block diagram example for a 2-meter NBFM receiver. Credit: GNU Radio.

demodulators, vocoders, decoders, and many other elements (referred to as *blocks*) typically found in radio systems. More importantly, it includes a method of connecting these blocks and then manages how data is passed from one block to another. Extending GNU Radio is also quite easy; if a specific block is found to be missing, it can be quickly created and added.

Since GNU Radio is software, it can only handle digital data. Usually, complex baseband samples are the input data type for receivers and the output data type for transmitters. Analog hardware is then used to shift the signal to the desired center frequency. That requirement aside, any data type can be passed from one block to another–be it bits, bytes, vectors, bursts or more complex data types. Figure 12.32 shows an example GNU Radio block diagram (17).

HWCNTRL

HWCNTRL is a satellite ground station control program that is installed in more than 30 sites throughout the world. This automation software package has the ability to support multiple antennas and instruments simultaneously. Satellite passes are generated by user request based on the ephemeris set, and users can select specific passes to be added to the schedule. Scheduled events can be single-use or reoccurring on a daily or weekly basis. A control/status screen is accessible for each instrument in the system, and the user can view and change the settings of any instrument through these screens (18).

12.9.6 Mission Operations & Scheduling Software

The following section provides an overview of mission operations and scheduling software products that can be integrated into a MOC, see table 12-11. While the specific aspects of each of these products is discussed below, they all have some common features. In general, these software applications cover functions related to mission scheduling and tasking, commanding and telemetry, and monitoring and control. Many of them also have automation features that enable “lights-out” operations or reduced manpower requirements.

All of these products are highly customizable. They can not only adapt to multiple missions, satellites, and ground stations, but these products also allow for customized visualizations, analyses, and user interface views. Additionally, many of these products are cloud-based or have a web interface to enable easier access for an operator from almost anywhere.

Table 12-51: Mission Operations and Scheduling Software

Product	Manufacturer	TRL	Type of Product
COSMOS	Ball Aerospace	9	Open source command and control system that can be used in all phases of testing and operations
Galaxy	The Hammers Company	9	Command and telemetry system that has been available since 2000
Major Tom	Kubos	8+	Cloud-based command and telemetry system that can interface with some COTS flight software

Orbit Logic Family of Products	Orbit Logic	9	Group of mission planning and scheduling products for both aerial and satellite imaging applications
ACE Premier Family of Products	Braxton Technologies	8+	Group of hardware and software components for end-to-end Satellite Operations Center (SOC)
Mission Control Software	Bright Ascension	8+	Monitoring and control interface with "lights-out" automation features built-in

COSMOS

COSMOS is a free, open-source command and control system providing commanding, scripting, and data visualization capabilities for embedded systems and systems of systems. COSMOS is intended for use during all phases of testing (board, box, and integrated system) and during operations. COSMOS is made up of 15 applications that can be grouped into four categories: real-time commanding and scripting; real-time telemetry visualization; offline analysis; and utilities. Figure 12.33 shows how the all of the application relate to one another and to the targets that are being controlled. Any embedded system that provides a communication interface can be connected to COSMOS. All real-time communications flow through the command and telemetry server, ensuring all commands and telemetry are logged. Additionally, program specific tools can

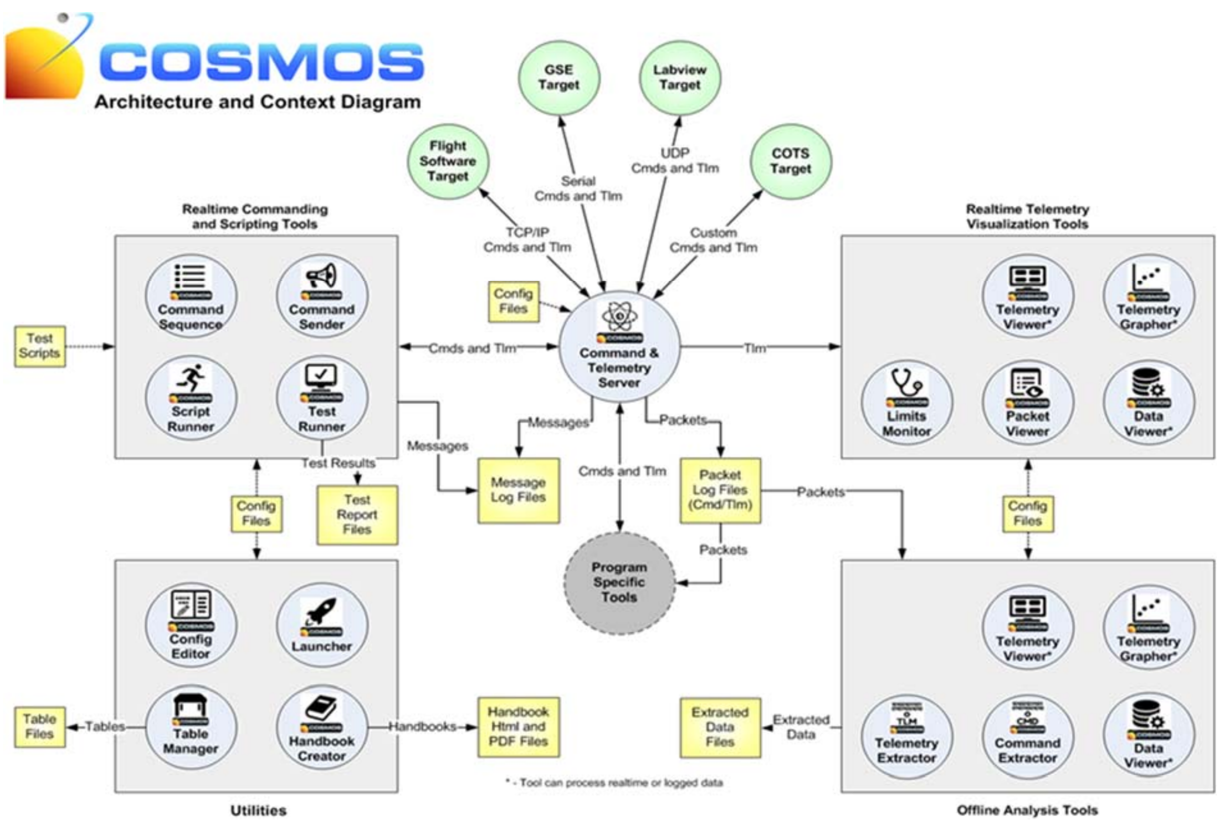


Figure 12.33: COSMOS architecture and context diagram. Credit: Ball Aerospace.

be written using the COSMOS libraries, and these tools can interact with the command and telemetry server as well (19).

Galaxy

Galaxy is a command and telemetry system that is derived directly from the ITOS telemetry and command system developed by the Hammers Company with NASA Goddard Space Flight Center (GSFC). It has been available commercially since 2000. Galaxy can accept telemetry from, and send commands to, multiple spacecraft and ground stations simultaneously. Users can customize Galaxy for a particular mission via a database in which they provide telemetry and command specifications. Users can design telemetry displays, plots, sequential prints, configuration monitors, and spacecraft commands and table loads in simple text files stored on the computer's file system. Most displays can be viewed remotely over the web or by using remote Galaxy instances. Additionally, Galaxy is CCSDS compliant, and it can communicate over a wide variety of transports and protocols including TCP/IP networking, synchronous and asynchronous serial ports, SpaceWire, MIL-STD-1553, and the GMSEC message bus (20).

Major Tom

Major Tom is a commanding and telemetry system that allows operators to use the same tool, workflow, and processes during development, testing, and operations. Key features include simplified dashboards for commanding and telemetry data; an API that allows an operator to build custom automation; and the ability to support multi-satellite operations. Major Tom leverages a cloud-based deployment for simplicity and can be integrated with some COTS ground stations and flight software, including Kubos's own KubOS open-source flight software. Figure 12.34 provides a screenshot of the user interface (21).

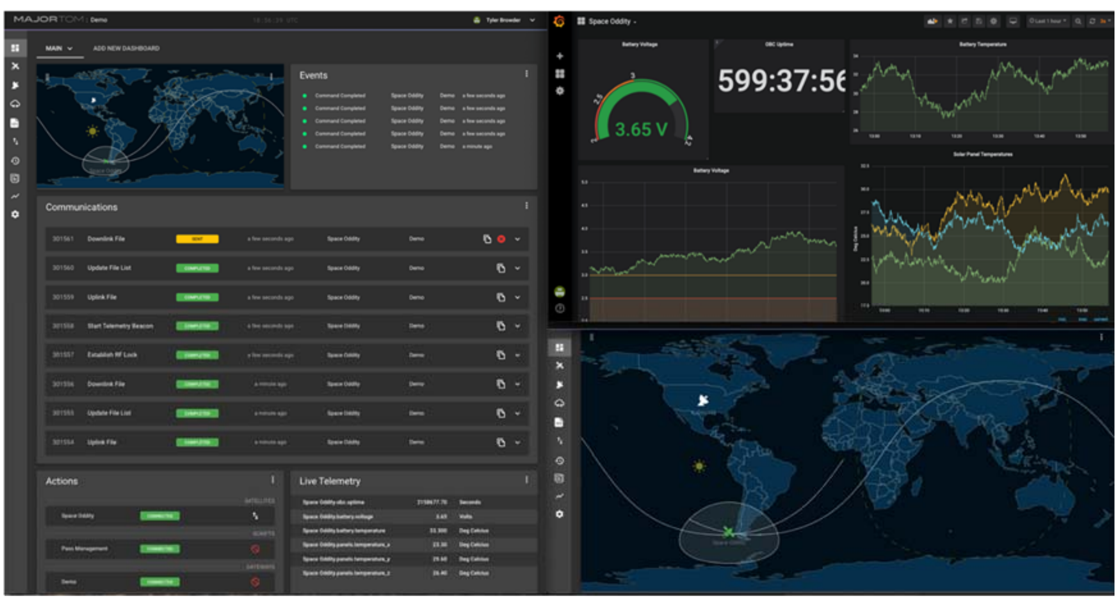


Figure 12.34: Major Tom user interface screenshot. Credit: Kubos.

Orbit Logic Family of Products

Orbit Logic specializes in mission planning, scheduling, and space situational awareness software. The software suite consists of multiple applications that support analysis and operations for aerial and satellite imaging and space-to-ground networking. The mobile, web, desktop, and onboard scheduling applications have a variety of features, including: configurable systems, constraints, and goals; high performance algorithms; deconflicted scheduling plans; visualizations and animations on the user interface, and flexible process flows and automation. Figure 12.35 provides a screenshot for Orbit Logic's Collection Planning and Analysis Workstation (CPAW) (22).

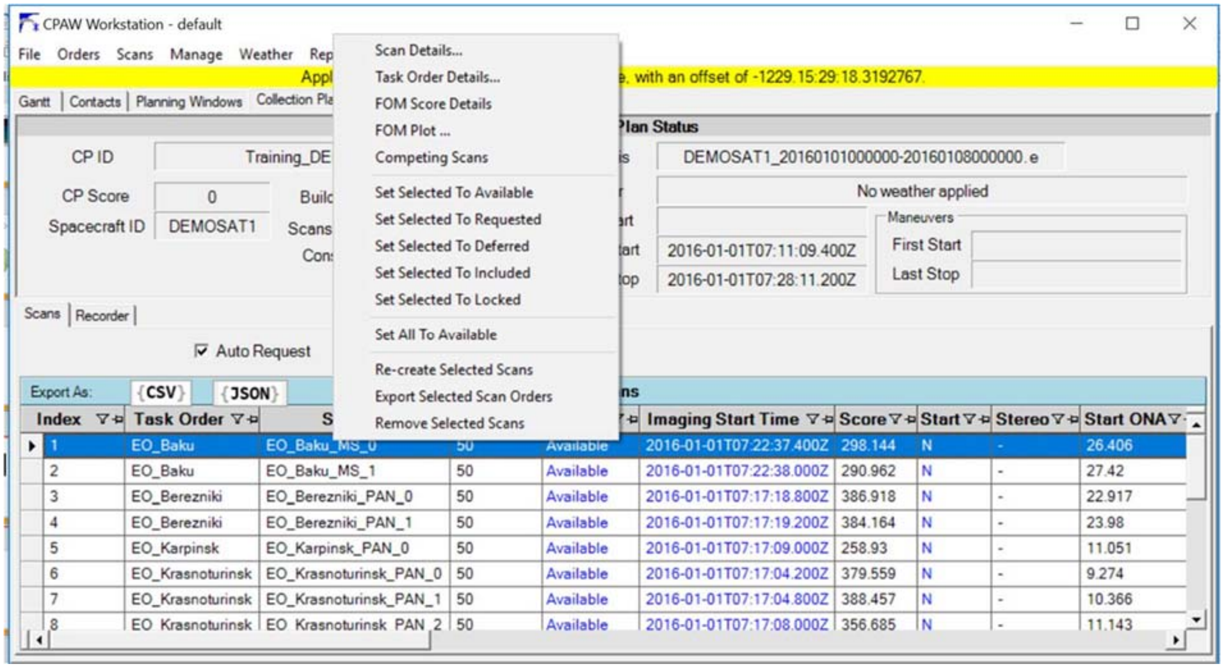


Figure 12.35: Orbit Logic CPAW couples spacecraft model and scheduling features to optimize data collection plans. Credit: Orbit Logic.

ACE Premier Family of Products

The ACE Premier family of products from Braxton Technologies includes the hardware and software components necessary for a satellite MOC. Key applications include command and control, scheduling and resource optimization, flight dynamics and mission planning, situational awareness, factory compatibility testing, front-end communications processors, crypto integration and controllers, and spacecraft and ground simulation. These products can be delivered through COTS point solutions with mission-unique plug-ins, or as a turn-key system (23).

Bright Ascension Mission Control Software

Bright Ascension's Mission Control Software (MCS) ground software provides a monitoring and control interface to implement changes during development and flight. An example of the interface is shown in figure 12.36. MCS consists of an integrated graphical environment with dedicated views and layouts that can be created, saved, and customized for different stages of the mission. MCS also supports a wide range of ground station interfaces and protocols to fit both in-house and commercial ground stations. Additionally, MCS includes automation features to enable unattended (or "lights-out") operations (24).

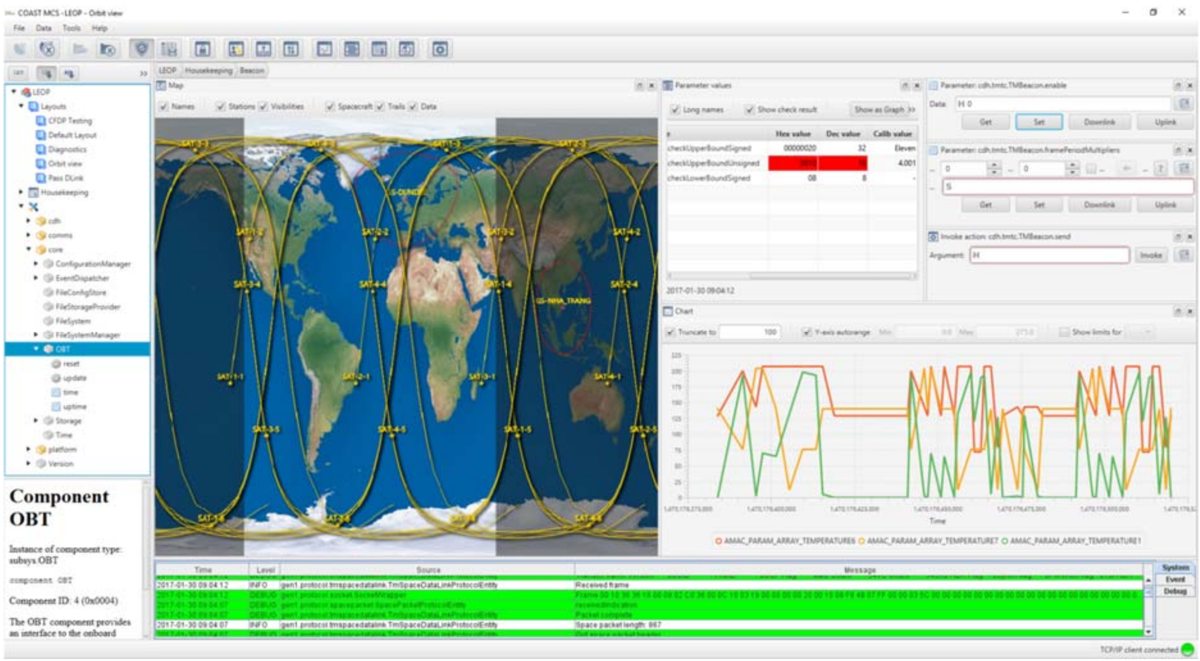


Figure 12.36: Bright Ascension Mission Control Software interface screenshot. Credit: Bright Ascension.

12.10 On the Horizon

Ground data systems have to continue to evolve in order to keep up with the furious pace of small satellite technology. Advancements in onboard processing and data storage are going to demand more capability in getting data to the ground. Mass production of small satellites is quickly becoming a reality and large constellations are now starting to find their way to orbit. This will require ground system technology that can communicate with multiple satellites simultaneously. Optical communications and phased array ground systems are emerging solutions to these needs. While both technologies have seen years of investment, they are now just starting to find their way into the ground networks. While it may still be years before becoming a staple for these networks, the following sections provide insight to the state of these technologies and where they are headed in the future.

12.10.1 Optical Communications

Increasing demand for data from NASA missions has led to a migration over the past few decades to increasingly higher radio frequency (RF) bands (X, K, and Ka) and ultimately to the optical and near-infrared regime. Optical communications are expected to increase data rates by two orders of magnitude (or more) over traditional RF links. The next generation systems will incorporate optical communications, and a number of early flight demonstrations and uses of optical communications in the coming decade are expected to be transformational for NASA and other space organizations. Whereas Ka-band frequencies go up to 40 GHz frequency, the optical signal reaches up to 200,000 GHz. Higher frequencies have the potential for huge increases in data rates, theoretically proportional to frequency-squared if all other factors are equal. At optical wavelengths, other factors, such as atmospheric losses, receiver sensitivity, aperture, and power, must also be considered, but nonetheless, optical communications offer the potential for orders of magnitude improvement in data throughput.

The term "optical communication" refers to the use of light as a medium for data transmission. For space applications, lasers are being used as the light source. Laser systems with dynamic systems such as fast-steering mirrors are used to accurately point the laser on the spacecraft to the ground terminal. Other methods using laser arrays for beam pointing are also being developed in order to reduce the need for complex dynamic systems. Data is transmitted in the form of hundreds of millions of short pulses of laser light every second. The light is made of photons and the optical ground terminals are setup to collect the light at the photon level. In fact, the ground terminals are designed for an environment where relatively few photons may be received from the transmitter spacecraft, especially from deep space. Direct photon detection with Pulse Position Modulation (PPM) is used instead of the common RF technique of direct carrier coherent modulation to convey information. PPM modulation uses a time interval that is divided into a number of possible pulse locations, but only a single pulse is placed in one of the possible positions, determined by the information being transmitted. In order to detect extremely faint optical signals with relatively few photons through the atmosphere, optical ground stations can use a superconducting nanowire single photon detector (SNSPD), which, to increase the sensitivity of the nanowires, uses a 1-Kelvin cryocooler. A real-time signal processing receiver uses time-stamped photon arrivals to synchronize, demodulate, decode, and de-interleave signals to extract information code-words. Hence, while the specific technologies employed differ in some respects from those used in radio frequency ground terminals, the higher-level functions performed by the optical communication ground terminal are similar.

Optical communication is attractive for mission designers using small, resource-constrained spacecraft, because it offers a path to relatively high data rates with relatively small and low power spacecraft equipment. The same volume and power savings can be experienced on the ground terminal side as well. This is driven by the size of the wavelengths. Because RF wavelengths are longer, the size of their transmission beam covers a wider area, therefore, the capture antennas for RF data transmissions must be very large. Laser wavelengths are 10,000 times shorter, allowing data to be transmitted across narrower, tighter beams. This results in the ability to deliver the same amount of signal power to much smaller collecting areas. The reduction in antenna size applies for ground and space receivers, which allows for size and mass reductions on the spacecraft side.

In 2013, NASA made great strides with its optical communication demonstration on the Lunar Atmosphere and Dust Experiment Explorer (LADEE) mission. The pivotal NASA Lunar Laser Communications Demonstration (LLCD) was able to achieve 622 Mbps from a lunar distance. Building on this success, there is a need for low size, weight, and power (SWaP) optical flight terminals for SmallSats and a ground infrastructure of Optical Ground Stations (OGS).

Optical Ground Stations and Future Demonstrations

Optical ground stations (OGS) contain notably different equipment than RF stations, including an optics assembly, photon counter assembly (usually involving a photon counting nanowire detector and cryostat), and signal processing assembly with time-to-digital converter. Since optical communications use a frequency higher than RF, (e.g. 1,550 nm downlink and 1,065 nm uplink wavelengths), the optical dishes can be smaller than RF antennas. To receive optical signals from a low-Earth orbit, 40 – 60 cm telescopes are sufficient. For successful deep space optical communications, calculations show that 3 m, 4 m, or even 8 m diameter ground apertures are required, depending on the distance from Earth. For these size apertures, when a dedicated 3 m – 8 m OGS is not available, partnerships can be formed with large astronomy telescopes. For example, the Deep Space Optical Communications (DSOC) demonstration launches in 2022 and JPL-designed OGS equipment is being housed at the Palomar Observatory (Hale 5-m telescope). It is also important for OGS to have spatial diversity. Weather, atmospheric conditions, turbulence, and aerosols in the air are able to degrade the laser propagation. Because certain types and depth of cloud covers can cause signal loss, probability of link success increases with multiple diverse locations.

For interoperability between SmallSats and public and private optical ground stations, a common communications standard is key. The Consultative Committee for Space Data Systems (CCSDS) is a member driven international organization, which provides recommendations for communications standards, including optical communications. Adhering to these standards by both SmallSats and ground stations allows the bring-your-own-receiver model to work.

Figure 12.37 JPL's OCTL showing a 1-meter optical aperture. Credit: NASA JPL.

JPL is operating the Optical Communications Telescope Laboratory (OCTL) at Table Mountain, CA, with a 1-m telescope, as shown in figure 12.37. This dish was used for the LADEE mission and offered great performance from a lunar distance.

ESA has a 1-m OGS with a 0.7° field of view at the Teide Observatory in Tenerife, Spain that was originally built for the observation of space debris. Figure 12.38 shows the ESA-OGS and its telescope.

Figure 12.38: (left) ESA-OGS at the Teide Observatory and (right) its 1-meter telescope on an English equatorial mount. Credit: (left) European Space Agency/D. Lopez and (right) European Space Agency.

The National Institute of Information and Communications Technology (NICT) operates several OGS that collectively form the IN-orbit and Networked Optical Ground Stations Experimental Verification Advanced Testbed (INNOVA). The INNOVA testbed includes a 1.5 m telescope and three 1-m telescopes. The 1.5 m was first constructed in 1988 in Koganei, Tokyo, Japan, and has a focal ratio of f/1.5 and a 1.5 arcminute detector field of view. The 1 m telescopes have a focal ratio of f/12, multiple focus options, and have demonstrated closed-loop tracking for low-Earth orbit satellites to within 10 arcseconds. The three stations are located in Koganei, Kasima, and Okinawa. Figure 11.39 shows an image of the 1 m OGS in Koganei, Japan.

The Deutsches Zentrum fur Luft- und Raumfahrt (DLR) German Aerospace Center is another organization active in optical communications. About 25 km west of Munich, Germany is their Optical Ground Station Oberpfaffenhofen (OGS-OP) that houses a 40 cm Cassegrain telescope. The German Aerospace Center has also developed a transportable optical ground station (TOGS). It has a 60 cm deployable telescope in a Ritchey-Chretien-Cassegrain configuration with a focal ratio of f/2.5. The telescope is supported by an altazimuth mount on a structure with four adjustable legs for leveling the mount and compensating for rough terrain. It has been successfully used to track the OPALS instrument on the ISS and serves as the primary ground station for the OSIRIS payload on the BiROS satellite. The German Aerospace Center OGS-OP and TOGS are shown in figure 12.40.

Figure 12.39: NICT 1 m OGS in Koganei, Japan. Credit: NICT.

The Aerospace Corporation has an optical ground terminal in El Segundo, CA. It is a 40 cm diameter, 3 m focal length Ritchey-Chrétien telescope with a Si-APD detector. The OGS and associated telescope are shown in figure 12.41. This ground

Figure 12.40: (left) OGS-OP and (right) TOGS. Credit: German Aerospace Center. https://creativecommons.org/licenses/by/3.0/de/legalcode.

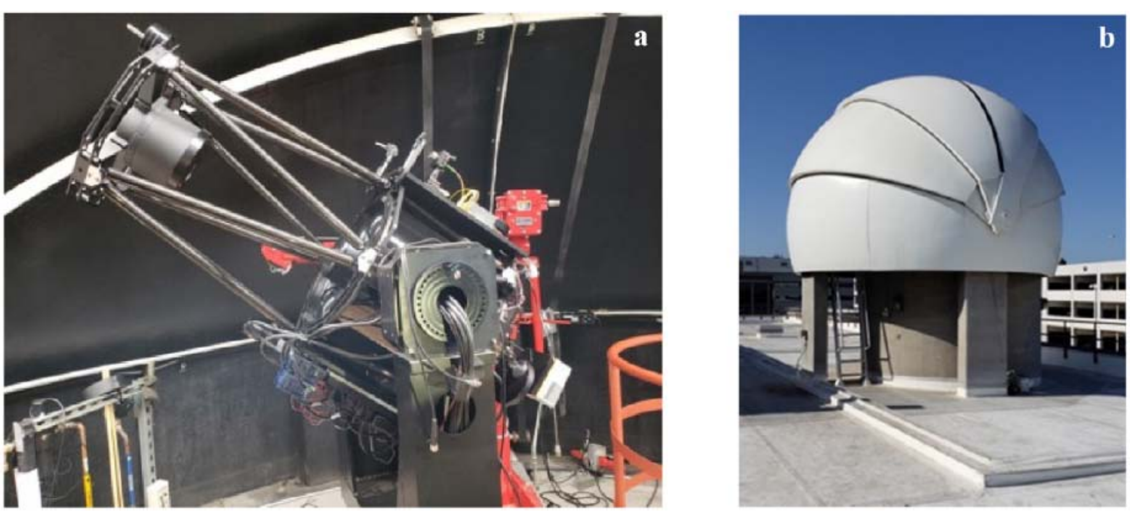


Figure 12.41: (left) The Aerospace Corporation manned OGS and (right) 40 cm telescope located in El Segundo, CA. Credit: The Aerospace Corporation.

station is fully operational and validated, as a CubeSat optical link from low-Earth orbit to earth of 200 Mbps was demonstrated in 2017 by the NASA sponsored OCSD mission. The 1.5U, 2.5 kg satellite used a 2 W, 1,064 nm laser transmitter 8 x 8 x 2 cm in size with a 0.06° FWHM beamwidth. While many optical communications demonstrations use a ground laser beacon to meet stringent pointing requirements, Aerospace demonstrated beaconless optical communications by body-steering the satellite open-loop at the optical ground station. Designing the laser transmitter with twice the divergence of the OCSD pointing capability eliminated the cost and complexity of a ground reference beacon. The optical communication engagements were optimized by limiting to 30° – 70° elevation and typically lasted 2 – 3 minutes. The best engagement on this mission demonstrated 200 Mbps and an average range of 725 km lasted 115 seconds and had a BER of ≤ 1E-6 for 92% of the time. This same CubeSat optical transmitter on the AeroCube-11 mission in 2019 demonstrated a 1 GByte data transfer in a single optical pass. As of 2020, the El Segundo station must be manned during operation, which is inconvenient. For that reason and for geographic diversity, an unmanned station is being developed and is planned for deployment in Hawaii and New Mexico in 2021. The unmanned optical ground station has an automated dome that protects the telescope.

NASA has several exciting Optical Communications demonstrations in the pipeline, including O2O and the Laser Communications Relay Demonstration (LCRD). LCRD is supported by OGS1 at OCTL, and OGS2 in Hawaii. Currently, the Science Enabling Technology for Heliophysics (SETH) deep space demonstration mission is being proposed. The mission plans to transmit optically from an ESPA class SmallSat and yield data rates greater than 10 Mbps from a distance of 15 million km. The OGS in this case will be the 4.3 m Lowell Discovery Telescope (LDT), housing the transportable optical ground receiver elements designed for DSOC.

Optical Ground Stations in Development

Internationally, optical ground station nodes in Australia and New Zealand are being funded as of 2020. The plan is to tie these stations together to produce a communication network, which can support optical, RF, and future quantum communications (SPIE 2020). Kongsberg Satellite Services AS (KSAT) announced in April 2020 the plans to build a commercially available optical ground station with a 50 cm telescope, selecting Nemea, Greece as the site due to its moderate weather in the summer with 95% availability.

In the United States, NASA's JPL operates the Deep Space Network (DSN) infrastructure, supporting 2-way RF communications and ranging services. Therefore, a novel design idea was approved to augment a DSN RF antenna by installing optical segments at its center, making it a dual-purpose, RF-Optical hybrid antenna**.** The operational RF-Optical hybrid will ultimately include 64 mirrors each of diameter 1.3 m, installed as a segmented 8 m optical receive aperture/mirror physically inside one of the new Deep Space Network (DSN) 34 m radio frequency ground terminals (DSS-23, in California). The installation is being implemented in several phases.

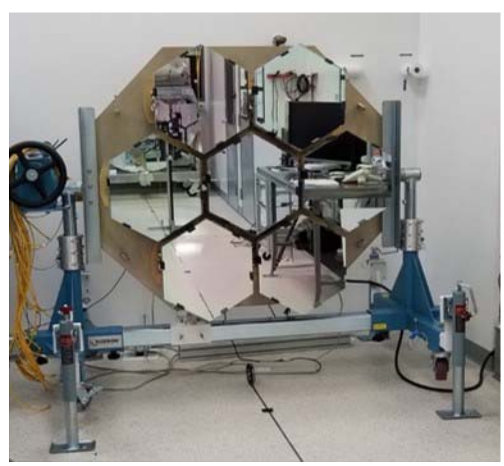


Figure 12.42: Prototype 7-segment mirror in lab testing at JPL. Credit: JPL.

First Phase: before building the operational terminal, JPL is first developing a 7-mirror prototype, shown in figure 12.42, for field testing on the DSN R&D 34 m antenna (DSS-13) at Goldstone, California. Each of these seven mirrors for the prototype is 0.5 m diameter, for a combined equivalent area of about 1.3 m. The complete 7-element prototype system will be installed in the second half of FY20 in DSS-13 with the field testing carried out through end of FY21.

Second Phase: this phase includes procurement and assembly of the first 16-segment portion of the 64-segment operational system. This 16-segment portion will use 16 full-size 1.3 m mirrors, for an equivalent receive optical area of 4 m. The 16-segment system will be installed into DSS-23, a new operational 34 m radio antenna under development now in Goldstone, California. It will be ready for a year of field tests on DSS-23 starting in mid-FY24.

Third Phase: this phase includes completion of the full 64-segment aperture on DSS-23, as illustrated in figure 12.43, including a full year of field tests. This 8 m equivalent optical ground aperture will be operational in October 2027.

DSS-23 will then be capable of a full set of RF services with the 34 m antenna in addition to high-rate optical communications with its 8 m optical assembly. The RF services on DSS-23 will be operational starting in late 2024. Before the full operational readiness dates for optical communications, the above partial optical systems will be usable at various times for best effort demonstration optical communications passes in the near-Earth or Lunar regimes, as well as for deep space missions, such as Psyche, which will carry a full-fledged DSOC flight terminal.

Figure 12.43: Artist overlay of built DSN RF antenna and planned optical segments at its center. Credit: NASA.

The approach of using the R&D DSS-13 antenna for the early optical ground terminal prototyping and field testing, followed by deployment and final testing in the operational DSN aperture, enables a cost-effective implementation that minimizes schedule as well as development risk for the entire effort. There will be a single operational optical receiver on DSS-23 as the prototype system on the R&D antenna is very limited in capability. The DSS-23 optical receiver is the same design that JPL is delivering to the Palomar Observatory for use with the DSOC optical communications technology demonstration on the NASA Psyche mission. This receiver is also being installed in ground terminals at White Sands and other locations for other near- and deep-space missions, as well as Artemis. One exciting implication of this 8 m equivalent optical aperture is that it meets the requirement for Human Exploration of 230 Mbps downlink data rate from Mars.

12.10.2 Phased Array Ground Stations

Phased array ground stations use phased array antennas consisting of multiple smaller antenna elements that are electronically connected at a site. These antenna elements each have computer-controlled phase delays that can be manipulated to increase the overall antenna gain in one or more specified directions. A phased array can be “electronically steered,” as opposed to mechanically pointed. In addition to optimizing antenna gain (for transmit or receive, or both) in specified directions, phased arrays can communicate with multiple spacecraft at once, and at multiple frequencies. Phased arrays have a long tradition of use for military applications, where the ability to rapidly point, steer, or scan can be essential. Past and current generations of Global Positioning Satellites (GPS) have transmit phased arrays of a dozen or more elements to optimally control their Earth-directed beams. Phased arrays on the ground can be optimized to increase gain in the direction of one or more SmallSats, which may be very resource constrained and hence can benefit from the increase in sensitivity of relatively small ground antenna system elements.

The number of NASA sponsored SmallSat missions is expected to continue to grow rapidly in the next decade and beyond. In response to this trend, the NASA NEN is working to better understand the characteristics and requirements of these missions and how it can evolve its service offerings to provide effective and efficient support with reduced network loading and lower cost to customers. The NEN and collaborating universities are investigating whether new service offerings such as multiple spacecraft per aperture (MSPA), ground-based phased array antennas, ground-based antenna arraying, and other emerging capabilities are cost effective and could be technically supported to benefit these SmallSat missions.

According to the NEN's investigation, some mission planners are moving towards formation flying SmallSats for multiple reasons, including lower price cost per launch, the inherent redundancy multiple spacecraft provide, and for specific scientific objectives. The use of MSPA and/or ground-based phased array antennas could instead be used to support multiple SmallSats simultaneously from a single asset. Additional ground-based antenna arrays could increase the achievable data rate by two times or more for longer distances from Earth.

The NEN is currently considering partnerships with industry and universities to conduct future demonstrations of Ground Based Phase Array (GBPA) technology. Similar to MSPA technology, GBPA could afford the NEN the ability to support multiple spacecraft simultaneously from a single system. The goal of a future demonstration would be to develop a GBPA that is equivalent to at least a 6 m antenna and capable of supporting five to six satellites simultaneously. Future demonstrations can begin to investigate a comparison between a GBPA and the traditional multiple aperture approach in the areas of performance, capability, cost, and operations.

ATLAS Space Operations, Inc. has designed a mobile, rapidly deployable, ground-based electrically-steered array (GBESA) RF antenna system for satellite communications applications, as shown in figure 12.44. ATLAS LINKS array technology consists of an array of receivers, each with multiple antennas that can receive signals from multiple sources across the entire sky without requiring moving parts or phase shift hardware. In a GBESA, phase shifts and gain changes due to spatial effects are compensated for in software. When configured as an array, the ATLAS LINKS system has the ability to process multiple satellite signals simultaneously. The array has overlapping views of the entire sky which are then combined using spatial filters to reconstruct a signal as if the array were electrically pointed at a target. The number of digitally formed beams depends upon the computing power rather than the number of antennas and phase shift hardware. It is the algorithm combination of phase and gain diversity that distinguishes a GBESA from a phased array, where the former has the potential to match the performance of parabolic dish antennas. The lack of moving parts and the ease of assembly gives

Figure 12.44: ATLAS ground based electrically steered array antenna system. Credit: NASA.

LINKS antenna array a distinct advantage over large dish antennas. COTS components were used for its manufacturing, which makes it highly cost competitive as well.

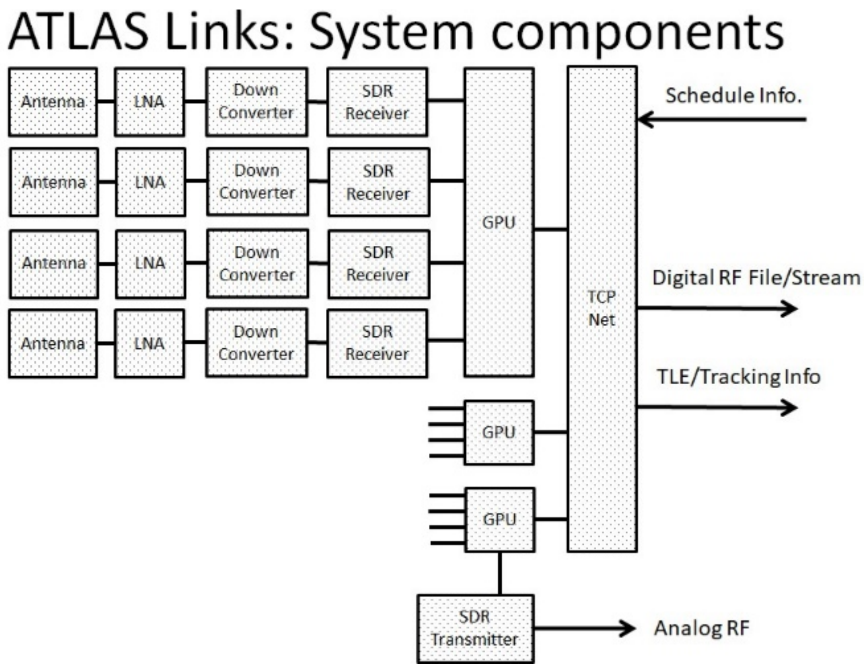


Figure 12.45: ATLAS LINKS single element system components diagram. Credit: ATLAS Space Operations.

As shown in figure 12.45, each antenna unit consists of log-periodic antennas, software defined radios, and a down converter for processing of higher frequency signals. A four-antenna unit along with a CPU/GPU box with power and USB cables makes up one element. Mechanically, the arrangement is compact, enabling whole sky coverage from a human-portable unit. The design follows the computing-at-the-edge paradigm by combining the signals from all four antennas into a single output stream that is then fed as digital data to the next 4-antenna element. Each element holds its own schedule and can record satellite passes even if the network is down.

A two-radio system was tested at the NASA Goddard Compatibility Test Lab in early 2018. Signal strength and noise levels were varied to emulate a wide range of satellite/ground ranges and geometries. A PRN BERT signal was generated and split using two channel simulators that provide delay and attenuation to match the properties of a satellite signal traveling to two ground antennas. The two outputs of the channel simulators, collectively termed “reference” signals, were independently measured for BER and Eb/N0. The one output of the LINKS array was also assessed, with comparison results shown in figure 12.46.

Each of the two reference signals are plotted with X’s. Their shape adheres well to the theoretical BPSK BER curve (not shown). The LINKS results, displayed as diamonds, shows a different curve as opposed to the observed reference. The LINKS system combines power, as does a phased array, and also reshapes the noise distribution. The spatial filter process inherent to LINKS redistributes the random noise power giving it an asymmetrical, non-Gaussian distribution. Further, the LINKS time alignment algorithm works holistically to both align signals and cancel noise. Redistribution removes energy between the I/Q constellation points, reducing false positive bit assignments, improving BER. Evidence of the reshaping is seen where LINKS achieved a perfect BER with 4 dB lower Eb/No (a nominal value of 1×10^{-8} is chosen for plotting purposes) than any reference signal. LINKS is a GBESA, being unlike a phased array in that it brings not only phase but also gain information to the combining process resulting in improved BER vs Eb/No curve.

ATLAS performed a demonstration at NASA WFF in April 2018 with a four-element (16 radio) array, as shown in figure 12.47, where it successfully downlinked satellite passes from four

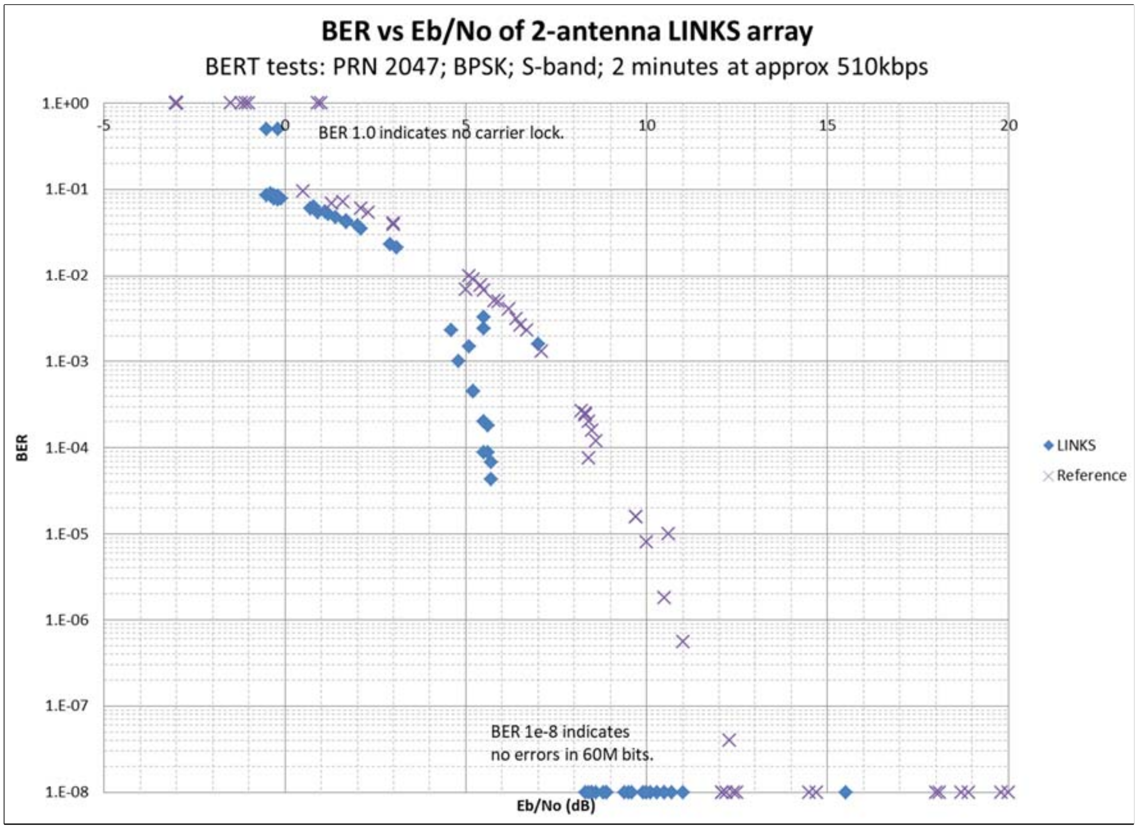


Figure 12.46: BER vs Eb/NO chart of ATLAS LINKS for S-band coded downlink. Credit: ATLAS Space Operations.

Figure 12.47: (left) ATLAS LINKS Demonstration at NASA Wallops Flight Facility and (right) ATLAS T2 Array. Credit: ATLAS Space Operations.

representative satellites. ATLAS is currently working with the Department of Defense's Defense Innovation Unit (DIU) to further test and develop LINKS. The competitively awarded rapid prototyping program will run through the summer of 2020.

In addition to ATLAS, there are a number of other companies working to lead the way in phased array technology development. ALCAN Systems is developing a fully electronically steerable flat panel antenna. The main advantage of the technology is the use of liquid crystal within the antenna. This enables the product to be lower cost and perform at lower power. The current focus is to accommodate Ka-band for supporting satellite constellations in low-Earth orbit and MEO, but other bands are possible. The antenna is a modular design such that it can be combined and achieve higher gain/throughput based on customer needs. The single antenna can achieve throughputs in excess of 400 Mbps. It has a size of 55 x 99 x 9 cm, weighs less than 20 kg, consumes less than 100 W, and can operate across a wide scan angle of +/- 55°. ALCAN is working with its partners to build a mass-production supply chain and assembly capability for the antenna, targeting first customer deliveries by Q4 2021.

C-COM Satellite Systems is also developing a Ka-band flat panel antenna that is fully electronically steered. Their solution uses 4x4 groups of modular antennas, which can be scaled up to 16x16 or larger arrays of antennas. Their objective is to be able to replace a mechanically steered parabolic antenna of 70 – 75 cm in diameter. This would require a flat panel to be constructed of 4,000 elements for Tx and Rx. The advantage of their technology is that it is modular and can be scaled to any size depending on application requirements. It is also conformal and can follow the shape of the surface from which it's intended to operate. The antennas are also smaller, lighter, and can easliy be used on the move. 4x4 sub arrays, as shown in figure 12.48, have been tested successfully and C-COM has recently received a patent for their unique method of calibrating the arrays. Development is ongoing with goals for commercialization by the end of 2020.

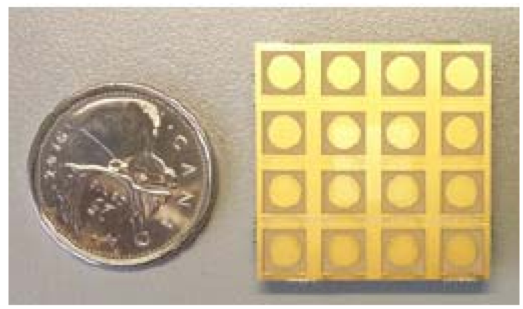


Figure 12.48: C-COM 4x4 Rx module with 16 elements. Credit: C-COM.

Phasor, who was recently acquired by Hanwha Systems, is working towards the commerical introduction of its "Release One" technology-based products that showcase flat panel electrically steered arrays (ESA). Their systems are designed for the enterprise-grade SATCOM mobility markets in the commerical Ku-band. Their ESAs will work with satellites in any network configuration and support tradiational GEO and nontraditional low-Earth orbit and MEO satellite constellations. Their technology is solid-state with no moving parts. The arrays use a unique and patented ASIC-based beam-forming technology and software defined systems approach that allows for very high performance, a very low profile, and a scalable, modular aperture to accommodate aperture sizes of various dimensions. The design can match the performance of a 2.4 m dish or greater and deliver G/Ts greater than 20 dB/K and EIRPS of greater than 70 dBW.

ThinKom Solutions Inc has a patented phased array technology called VICTS, which stands for Variable Inclination Continuous Transverse Stub. VICTS delivers all the benefits of conventional mechanical and electrically steered phased array antennas but without their well-known drawbacks and limitations. This technology provides gap-free pole-to-pole coverage, high beam agility for network flexibility, a low profile antenna radome, low prime power consumption, and a high spectral efficiency. The VICTS antennas are fully proven with over 5,000 daily commerical flights on 1,300+ commerical aircraft. They are also interoperable with low-Earth orbit, MEO, and GEO satellite constellations. In the first quarter of 2020, ThinKom completed a series of interoperability tests that demonstated compatibility of its VICTS technology on their Ku-band Ku3030 system, shown in figure 12.49, with a low-Earth orbit satellite network. The switch time between individual satellite beams was less than 100 milliseconds and handoffs between satellites were completed in less than one second. Switches between low-Earth orbit and GEO satellites were also achieved with similar results. The measured terminal performance showed throughput rates in excess of 350 Mbps downlink and 125 MBps uplink at latencies of less than 50 ms. Tests have also been successfully conducted over the past 12 months with their Ku- and Ka-band COTS phased array aero antennas across commerical and military bands and a wide range of GEO and non-geostationary satellites. In all cases, the antennas have consistently demonstrated high throughput operation and rapid reliable handoffs, including both intra- and inter-satellite switching.

Figure 12.49: ThinKom Ku-band ThinAir Ku3030. Credit: ThinKom.

12.11 Summary

The ground segment serves as the gateway to getting valuable data collected by the satellite into the hands of the user. It is a critical component of the satellite system that requires attention at the earliest stages of mission planning. Understanding what ground solution best meets the needs of the mission has a direct impact on the spacecraft design, concept of operations, launch schedule, mission operations cost, and expected data volume for processing. Much effort also goes into preparing for the interaction between the satellite and ground network. Developing software and simulations, drafting operations manuals, conducting operations rehearsals, and performing compatibility tests are all par for the course. Post launch, the ground station also plays a key role in locating and commissioning the spacecraft.

The primary ground system options to consider are either operating your own ground station and managing its legal, maintenance, and labor factors, or purchasing time on an established turnkey network that shares resources amongst a number of users. The former may best serve a professional institution that has a consistent influx of satellite missions to manage, or the university environment because it is an excellent learning platform for students, while the latter may best serve a customer solely interested in obtaining data. The two options can also be combined to meet broader mission needs. With the sharp increase in small satellites and the possibility of thousands more, the market for turnkey solutions is plentiful and competitive with companies like Amazon getting into the mix. This environment is favorable to the community as it drives down cost, provides an array of service options, and spurs innovation.

In looking forward to the future of ground systems, the clear objective is how to more efficiently bring the data down. Great strides are being made with optical communications where it is possible to have increases in data per pass that are orders of magnitude above what can be achieved with RF communications. Optical communication technology is now being infused into ground system architectures, and flight hardware is becoming miniaturized enough to fit within small satellites. Phased array antenna technologies continue to advance with the goal of becoming more affordable. The ability of these systems to quickly change beam directions and acquire multiple targets will be critical for communicating with constellations of small satellites.

Even with the implementation of these advanced technologies, RF systems are expected to continue being part of the architecture. Optical communications have precise pointing requirements, sensitivity to weather, and other operational considerations that present risk to a mission. RF systems are a suitable mitigation to support emergency situations and safe modes.

They can provide a path to transmitting critical commands even if the spacecraft is not capable of orienting itself as long as there is a low gain antenna-radio system onboard and a large ground antenna with a high-power transmitter available.

While the tried and true RF ground system solution remains the workhorse for small satellites, the innovative nature of the small satellite platform will soon challenge the community to adapt to systems capable of handling hundreds of satellites and high data volumes. Efforts are ongoing to keep pace, but only time will tell whether ground systems will advance or impede the small satellite revolution.

For feedback solicitation, please e-mail: arc-sst-soa@mail.nasa.gov. Please include a business e-mail so someone may contact you further.

References

(1) Amazon. AWS Ground Station Features. *AWS.* [Online] 2020. https://aws.amazon.com/ground-station/features/.

(2) Globalstar. GLOBALSTAR SATELLITE IoT. *Globalstar.* [Online] 2020. https://www.globalstar.com/en-us/.

(3) Teles, J., Samii, M. V. and Doll, C. E.: "*Overview of TDRSS."* Advanced Space Res. Vol. 16. pp. 1267-1276, s.l. 1995.

(4) NASA. Tracking and Data Relay Satellite (TDRS). *Tracking and Data Reply.* [Online] 09 17, 2017. https://www.nasa.gov/directorates/heo/scan/services/networks/tdrs_main.

(5) Analytical Space. UNLOCK THE POWER OF DATA FROM SPACE. *Analytical Space.* [Online] 2020. https://www.analyticalspace.com/.

(6) Iridium. Global Network. *Iridium.* [Online] https://www.iridium.com/network/globalnetwork/.

(7) GSAT. Iridium Satellite Location Map Tool . [Online] 2020. https://www.gsat.us/tools/iridium-satellite-location-map-tool.

(8) GAUSS SRL. Ground Station. *Group of Astrodynamics for the Use of Space Systems (G.A.U.S.S. Srl).* [Online] 2020. https://www.gaussteam.com/services/ground-station/.

(9) Innovative Solutions in Space. Ground Stations. *Innovative Solutions in Space: Ground Stations.* [Online] 2020. https://www.isispace.nl/products/ground-stations/.

(10) GomSpace. Ground Systems. *GomSpace.* [Online] 2020. https://gomspace.com/shop/subsystems/ground-systems/default.aspx.

(11) Surrey Satellite Technology Ltd. Ground Segment. [Online] 2020. https://www.sstl.co.uk/media-hub/featured/ground-segment.

(12) Infinite Technologies Incorporated. RADOMES FUNCTION. *Radomes & Composite Structures.* [Online] 2020. https://compositeradomes.com/radomes/what-is-a-radomes-function/.

(13) GUASS SRL. GAUSS UHFMini Ground Dongle Datasheet. 2020.

(14) Amergint Technologies. softFEP Datasheet. 2020.

(15) Kratos. Software Front End Processer Datasheet. 2020.

(16) Csete, Alexandru. About Gpredict. [Online] http://gpredict.oz9aec.net/.

(17) GNU Radio. GNU Radio - Main Page. *Wikipedia.* [Online] https://wiki.gnuradio.org/index.php/Main_Page.

(18) DeWitt, Henry. Satellite Ground Station Control. *DeWitt & Associates.* [Online] 2020. http://www.dewitt-assoc.com/groundStation.html.

(19) Ball Aerospace. The User Interface for Command and Control of Embedded Systems. *COSMOS.* [Online] 2020. https://cosmosrb.com/.

(20) The Hammers Company. Galaxy. [Online] 2020. https://hammers.com/galaxy.

(21) Kubos. Major Tom. [Online] 2020. https://www.kubos.com/majortom/.

(22) Orbit Logic. Orbit Logic. [Online] 2020. https://www.orbitlogic.com/index.html.

(23) Braxton. ACE Premier™ Family of Products. [Online] 2020. https://www.braxtontech.com/products-services.

(24) Bright Ascension. Mission Control Software. [Online] 2020. https://www.brightascension.com/products/ground-control-software/.

(25) IceCube — 874 GHz submillimeter wave radiometer mission on a 3U CubeSat. [Online]. https://directory.eoportal.org/web/eoportal/satellite-missions/i/icecube

(26) Near Earth Network (NEN) CubeSat Communications. NASA Technical Reports Server. [Online] January 1, 2017, https://ntrs.nasa.gov/search.jsp?R=20170000974.

(27) Shannon Terry, A.I. Solutions, Inc. What are Space Ground Systems. [Online] https://ai-solutions.com/about-us/news-multimedia/what-are-space-ground-systems/.

(28) Streamlining Ground Station Network Compatibility Test for Small Satellites. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180003437.pdf

(29) Important Questions and Answers: Satellite Access. Satellite Communication, Chapter: Satellite Communication - Satellite Access. [Online]

http://www.brainkart.com/article/Important-Questions-and-Answers--Satellite-Access_11944/ [Accessed: 2020]

(30) “Real-time Earth: A Hybrid Ground & Space Communications Network for Smallsats”. Viasat. [Online] 2018.

https://www.viasat.com/sites/default/files/media/documents/viasat_real-time_earth_brochure.pdf [Accessed: 2020]

(31) antenna-theory.com. Yagi-Uda Antenna. [Online] 2018. http://www.antenna-theory.com/antennas/travelling/yagi.php [Accessed: 2020]

(32) “The Parabolic Reflector Antenna (Satellite Dish)” (2011).

http://www.antenna-theory.com/antennas/reflectors/dish.php [Accessed: 2020]

(33) Bill Sepmeier. “Understanding and Performing Satellite Link Budgets”. NSN Network Services.

http://tiij.org/issues/issues/spring97/communications/nsn/linkbudget.html

(34) Bernardo Schneiderman. Industry Trends - News Analysis - Market Intelligence and Opportunities Executive Roundtable: Flat Panel Antennas. September 3, 2019.

http://satellitemarkets.com/people/executive-roundtable-flat-panel-antennas [Accessed 2020]

(35) 15 June 2020 by Alcan Systems. ALCAN announces electronic beam steering ground antenna for LEO and MEO satellite service use at a low price of EUR 1,500. Spacewatch.global: Space: Entrepreneurship.

https://spacewatch.global/2020/06/alcan-announces-electronic-beam-steering-ground-antenna-for-leo-and-meo-satellite-service-use-at-a-low-price-of-eur-1500/ [Accessed: 2020]

(36) ThinKom PR, April 30, 2020 In Press Releases, ThinAir ThinKom Completes Successful Antenna Interoperability Demonstrations on Ku-Band LEO Satellite Constellation

https://www.thinkom.com/ku-band-leo-interoperability/ [Accessed: 2020]

(37) Craig Bamford January 8, 2020. C-COM Finding its Place in Phased Array Satellite Communications Market.

https://spaceq.ca/c-com-finding-its-place-in-phased-array-satellite-communications-market/ [Accessed: 2020]

(38) Florian Moll, Amita Shrestha, Christian Fuchs. Ground stations for aeronautical and space laser communications at German Aerospace Center. Publisher: Proc. SPIE 9647, Advanced Free-Space Optical Communication Techniques and Applications.

https://core.ac.uk/reader/31021696

(39) ESA Optical Ground Station. Lasted updated: 13 November 2019. Accessed: 2020

https://en.wikipedia.org/wiki/ESA_Optical_Ground_Station

(40) NASA. Lunar Laser Communication Demonstration: NASA’s First Space Laser Communication System Demonstration Fact Sheet

https://www.nasa.gov/sites/default/files/llcdfactsheet.final_.web_.pdf

(41) Space Optical Communications Using Laser Beams. NASA Fact Sheet.

https://technology.nasa.gov/patent/TOP2-248

(42) NASA. July 15, 2018. “LLCD: 2013-2014”. [Accessed: 2020]

https://www.nasa.gov/directorates/heo/scan/opticalcommunications/llcd/

(43) Fuchs, Christian & Giggenbach, Dirk: "Optical Free-Space Communication on Earth and in Space Regarding Quantum Cryptography Aspects." 10.1007/978-3-642-11731-2_11. 2009.

https://www.researchgate.net/publication/225003843_Optical_Free-Space_Communication_on_Earth_and_in_Space_Regarding_Quantum_Cryptography_Aspects?enrichId=rgreq-4e72ce313bd72420b09642379fcbc0f9-XXX&enrichSource=Y292ZXJQYWdlOzIyNTAwMzg0MztBUzoxMDQ4MTA5OTcwOTIzNTNAMTQwMjAwMDI5NzQ1OA%3D%3D&el=1_x_2&_esc=publicationCoverPdf

(44) Kathleen Michelle Riesing, Portable Optical Ground Stations for Satellite Communication. Doctor of Philosophy in Aeronautics and Astronautics, MASSACHUSETTS INSTITUTE OF TECHNOLOGY. June 2018.

https://dspace.mit.edu/bitstream/handle/1721.1/119269/1061557727-MIT.pdf?sequence=1&isAllowed=y

(45) Scott Schaire, Serhat Altunc, Yen Wong, Obadiah Kegege, Marta Shelton, George Bussey, Marcus Murbach, Howard Garon, Yudhajeet Dasgupta, Steve Gaines, Edward McCarty, Sean McDaniel, Wesley Faler, Peter Celeste. Trish Perrotto, Booz Allen Hamilton, Matt Batchelor: "Investigation into New Ground Based Communications Service Offerings in Response to SmallSat Trends." 32nd Annual AIAA/USU Conference on Small Satellites. 2018.

(46) Khan, Khudeja: "Data Communication With A Nano-satellite Using Satellite Personal Communication Networks (s-pcns)." Electronic Theses and Dissertations, 2004-2019. 3588. 2008.

(47) Samuel Sanders Visner: "Cyber Best Practices for Small Satellites." International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

(48) Kul Bhasin, Pete Vrotsos, Eli Naffah: "Commercial Communication Services For Nasa Space Missions: Capability Assessment, Opportunities And Challenges."

https://www1.grc.nasa.gov/wp-content/uploads/Ka-Band-Conference_-Commercial-Communication-Services-for-NASA-Space-Missions.pdf

(49) GAUSS Srl. “Ground Station & Software.” https://www.gaussteam.com/wordpress/wp-content/uploads/2018/01/Flyer_GroundStation_Software_1.pdf

13.0 Identification and Tracking Systems

13.1 Introduction

In the past, most launches involved a single, large satellite launching on a dedicated launch vehicle. Small satellites as secondary payloads were sometimes 'dropped off' along the way to the primary payload's orbit, or they rode along to the final orbit with the primary payload. In either case, it usually was not that difficult to distinguish between primary and secondary payloads via size and operational parameters.

Recently, however, multi-manifest or "rideshare" launches have become more common, and consolidators (1) (2) (3) are bundling CubeSats and other smaller payloads together with larger payloads to fill up the excess capacity of almost any given launch vehicle. For technical and cost reasons, such launches generally deploy small satellites and CubeSats into very similar orbits over a short time window. Such "batch" launches give rise to "CubeSat confusion" (4); by launching CubeSats close in space, they become hard to distinguish from each other; by launching them close in time, existing space traffic management/space situational awareness systems do not have time to react to the addition of so many new space objects all at once (5) (6). At times it can take weeks to months to sort out which object is which and some may never be uniquely identified at all.

Due to their standardized shape and size, CubeSats look very similar to one another, especially when they are in orbit hundreds of kilometers away. If there are unidentified objects from a launch, then the possible number of associations of object identification (IDs) to tracked objects scales as n (n-factorial, where n is the number of unidentified space objects from the launch)! For example, if there are just two objects, say a payload and an upper stage, there are two ways in which you can associate the IDs with the tracked objects, and even that can be a challenge (7). However, if there are 10 unidentified objects, there are 3,628,800 possible combinations; with 20 this rises to 2.4×10^{18} combinations. The magnitude of the problem gets big quickly.

Small satellites can improve their chances of being identified and tracked through good coordination with tracking agencies pre-launch, through community sharing of Two-Line Element set (TLE) and other position data in clearly-defined, consistent formats, and through careful consideration of deployment direction and timing (8). Good design choices can also improve the chances of small satellites surviving launch and early orbit (9) and can even make use of in-space commercial radio networks as a "back-up" method of communicating should primary systems fail (10). However, despite improvements in both design and coordination, many small satellites still go unidentified. This has led to the introduction of tracking aids – independent systems that help owners and trackers identify small satellites and CubeSats, in some cases even if the satellite itself is malfunctioning.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

13.2 Tracking Aids

Tracking aids come in several categories, each with its own benefits and drawbacks (11). Table 13-1 discusses the broad categories available, with representative examples discussed below.

Size, weight, and cost vary for each of the examples, but all can be considered compatible with a CubeSat mission; see the references for detailed information on size, weight, and power (SWaP) and cost.

Table 13-1: Types of Tracking Aids			
Technology scheme	**Description and reference mission**	**TRL**	**Reference**
CubeSat position and ID via radio	A position, navigation, and timing (PNT) receiver is attached to a CubeSat, along with a radio to transmit the information via a LEO communications provider (or directly to the ground); example: BlackBox, Blinker.	7	(12) (13)
Coded light signals from light source on exterior of CubeSat	Exterior-mounted LEDs with large-aperture telescopes to receive the signal or diffused LED lasers with ground-based photon-counting cameras.	7 – 6	(14) (15)
Radio Frequency interrogation of an exterior Van Atta array	For example, exterior mounted radio frequency identification (RFID) tag & commensurate radar.	7	(16)
Laser interrogated corner cube reflectors (CCR)	One or several small CCRs can be attached to CubeSat exterior; ground-based laser and receiver telescope needed to distinguish number of CCRs.	7	(17)
Passive augmentations to visibility	Use of high-albedo paint or tape or other methods to increase visibility.	9	

13.3 Devices that Communicate Position and ID via Radio

The most comprehensive (but also potentially the most complex and SWaP-intensive) option involves equipping a small satellite with an independent PNT receiver and independent radio capable of transmitting that data to an independent communications provider. An example technology is the Black Box system (figure 13.1), described by NearSpace Launch, Inc., in a

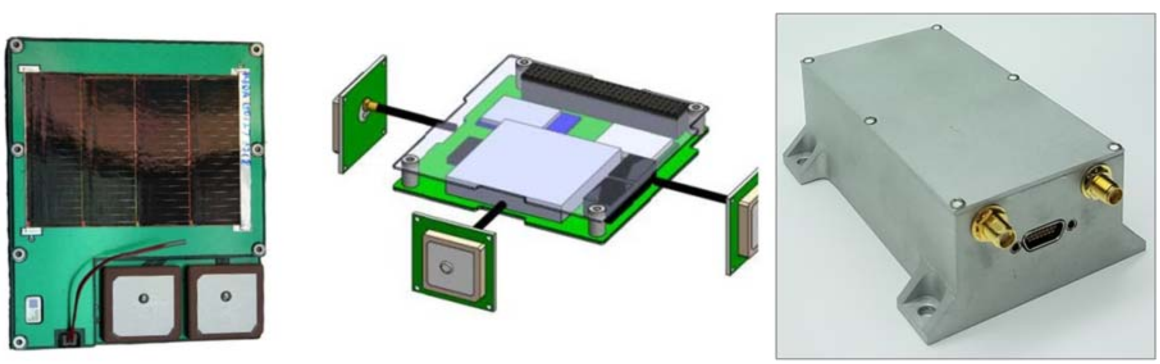


Figure 13.1: (left) Thin Patch or Stamp Black Box for side mounting. (Middle) PC104 Black Box for internal stack mounting. (Right) Standard Black Box for larger satellites. TRL 9: flown on spaceflight launch. Solar array and antennas not shown. Credit: NearSpace Launch, Inc.

recent conference paper (18). This system comes in several form factors for mounting internally or externally to a small satellite or CubeSat. The patch antenna shown in the first image is approximately 10 cm by 8 cm and can weigh as little as 22 grams; larger systems such as the one shown in the third image have flown and are considered TRL 9. These systems combine a low-power Global Positioning System (GPS) receiver with a low-power radio capable of communicating with a low-Earth orbit communication provider (in the case of Black Box, the Global Star network) and which operates independently from the spacecraft's regular command and telemetry links. Externally-mounted versions often include solar cells for independent power generation.

A similar concept under development is The Aerospace Corporation's 'Blinker' (13), in which a Global Positioning System (GPS) receiver and low-power radio are externally mounted to a CubeSat. GPS positions ("tags") are recorded, stored, and then radioed when the satellite is over an Aerospace Corporation ground station (which is separate and independent from the CubeSat's mission ground station). Research and development are being conducted to automatically convert the GPS tags into ephemeris information that can be directly ingested by space situational awareness centers (in this case the 18th Space Control Squadron via Space-Track.org).

The advantages to such a system are that it provides the most complete data on a satellite's position, and requires no specialized ground equipment (other than the equipment used by the communications provider). Some such systems are independently powered and can provide data even if the host satellite never powers up, though others are dependent on spacecraft power to function. These systems are the most complex of the tracking aids described, however, and despite their relatively small size, are still the most SWaP-intensive of the options examined. Systems that rely on power from the host vehicle are also useless if the host vehicle suffers a power anomaly.

13.4 Devices that use Coded Light Signals

Slightly less complex are devices that make use of coded light signals for identification. An example of such a device is the Extremely Low Resource Optical Identifier (ELROI) beacon shown in figure 13.2, under development by Los Alamos National Lab (19). Devices such as ELROI use exterior-mounted light-emitting diodes or diode lasers that blink in a prescribed sequence that uniquely identifies the satellite. The ELROI system is designed to be independently powered by a small solar cell and battery, and packaged into a system as small as a Scrabble tile, though only larger systems – with power provided by the host satellite – have flown.

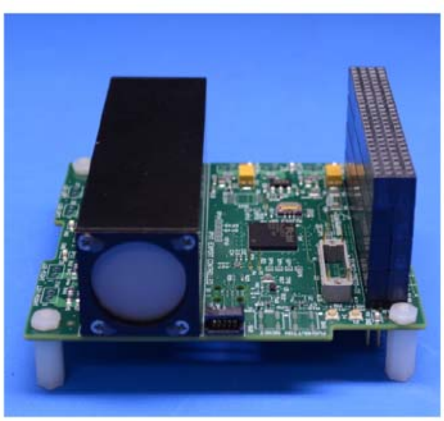



Figure 13.2: (left) ELROI PC104 beacon unit that was installed on NMTSat.d (right) Two ELROI beacon units delivered for a launch in 2021. Credit: Los Alamos National Laboratory.

The emitters on such devices can be regular Light Emitting Diodes (LEDs) or diffused diode lasers, but require specialized ground equipment – either a large-aperture telescope or a photon-counting camera – and the ability to track the object as it passes overhead. Figure 13.3 shows how the system works for ELROI. A photon-counting camera attached to a telescope tracks the signal from a diode laser and decodes the ID of the host satellite from the on/off pattern of the flashes.

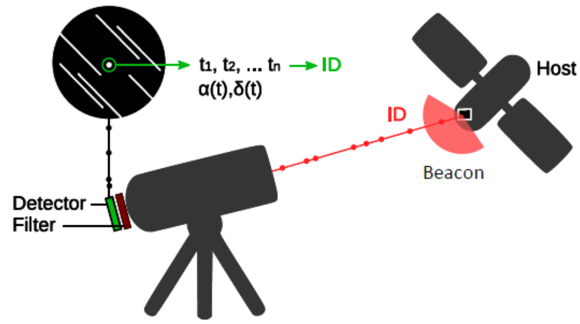


Figure 13.3: ELROI Optical Detection System. Credit: Los Alamos National Laboratory.

Another similar system, proposes to use red, blue, and green LED lights on specific faces of the satellite, which blink in a unique pattern, and standard astronomical optical telescopes to track and identify the LED flash pattern (14).

LED-based identification systems have the advantage of being relatively simple and capable of identifying satellites uniquely. However, all systems flown to date have required power from the host satellite, leading to issues with detection (19) if the host satellite does not power up. Current implementations are also relatively large, though future systems are expected to be much smaller and may include independent power. LED-based systems require relatively clear skies for identification, and dedicated ground equipment (telescope and sensor). The light sources are too faint to allow blind searching of the sky for the satellite; orbital information from a SSA provider is also required to find and track the CubeSat, although the process of tracking the satellite via an optical telescope allows the orbital ephemeris to be updated. Issues with attitude control on the host satellite can also complicate the identification process.

13.4.1 Van Atta Arrays and RF Interrogation Receivers

Another method for increasing the trackability and possible identification of small satellites involves devices that respond when interrogated by an RF signal of appropriate wavelength. One such system, the CubeSat Identification Tag (CUBIT) shown in figure 13.4, is similar to the RFID devices used in proximity badges (16). Built by SRI International and partnered with NASA Ames, CUBIT responds with a short burst of information when interrogated by a radio signal of the correct frequency. CUBIT is relatively small and designed to be independent of host vehicle power. The implementations that have flown contain a small battery suitable for 30 days of in-orbit life, which covers the most critical early orbit identification period. The device is separated into an internally-mounted electronics unit attached to an exterior antenna to minimize the exterior footprint of the unit. Two units have flown and been successfully demonstrated in space on board TechEdSat-6 in 2017 and TechEdSat-7 in 2020. A relatively large ground architecture (in CUBIT's case, a 30 m antenna and an array of antennas) are required to interrogate the system and successfully acquire the low-power response.

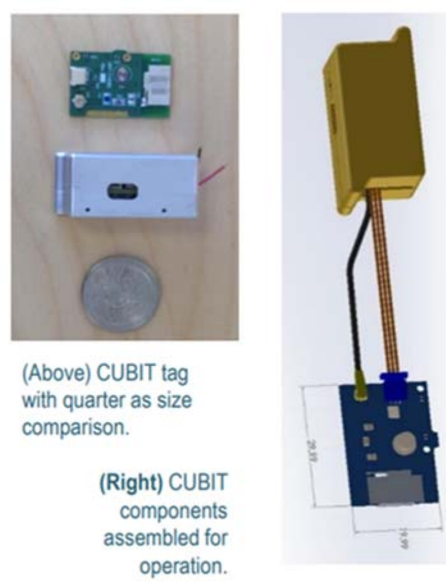


Figure 13.4: CUBIT. Credit: SRI International.

Another example of an RF-interrogated device is a Van Atta array, a passive device which re-radiates RF energy back toward the source of that energy (20). One such device, the Nanosatellite

Tracking Experiment (NTE) consists of a 64-element Van Atta array of tiny, paired antennas tuned to a Ku-band RF frequency, as shown in figure 13.5 (21). When interrogated at the proper frequency range, the incident RF field received by each antenna is fed to a corresponding antenna via a passive transmission line, where it is re-radiated. This significantly increases the radar cross-section of the object, allowing it to be more easily tracked. Unique identification is difficult, however. A satellite carrying a Van Atta array device will be distinguishable from one not carrying such a device, or from one carrying a device tuned to a different frequency band, but two satellites carrying the same Van Atta array will return the same signature. The RF interrogation also requires a ground source of the appropriate frequency. However, Van Atta array devices are entirely passive and extremely low SWaP, making them easy to include on small satellites and CubeSats. NTE devices have flown in space but results from those flight experiments have not been published to date. A unique identification capability is presently under development, with in-orbit testing anticipated in 2021 (22).

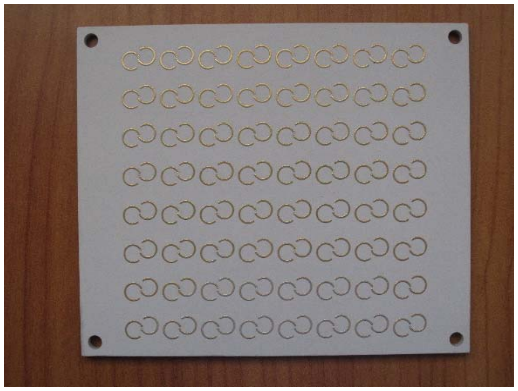


Figure 13.5: NTE Van Atta array retro-reflector in the Ku-band, fits standard 1U panel, tuned to HAX RADAR frequency. Credit: Naval Information Warfare Center.

13.4.2 Laser-Interrogated Corner Cube Reflectors

Corner cube reflectors, long used in the space industry, are just special mirrors designed to reflect laser light back in the direction from which it arrived. They require no internal energy source. When illuminated by a laser, they provide a return signal that can be detected on the ground by a fast camera, as seen in figure 13.6. Putting a different number of CCRs on a set of CubeSats allows the ground station to differentiate between the CubeSats (i.e., a CubeSat with one CCR will produce a different return signal from another with a two CCRs or three CCRs, etc.). One can

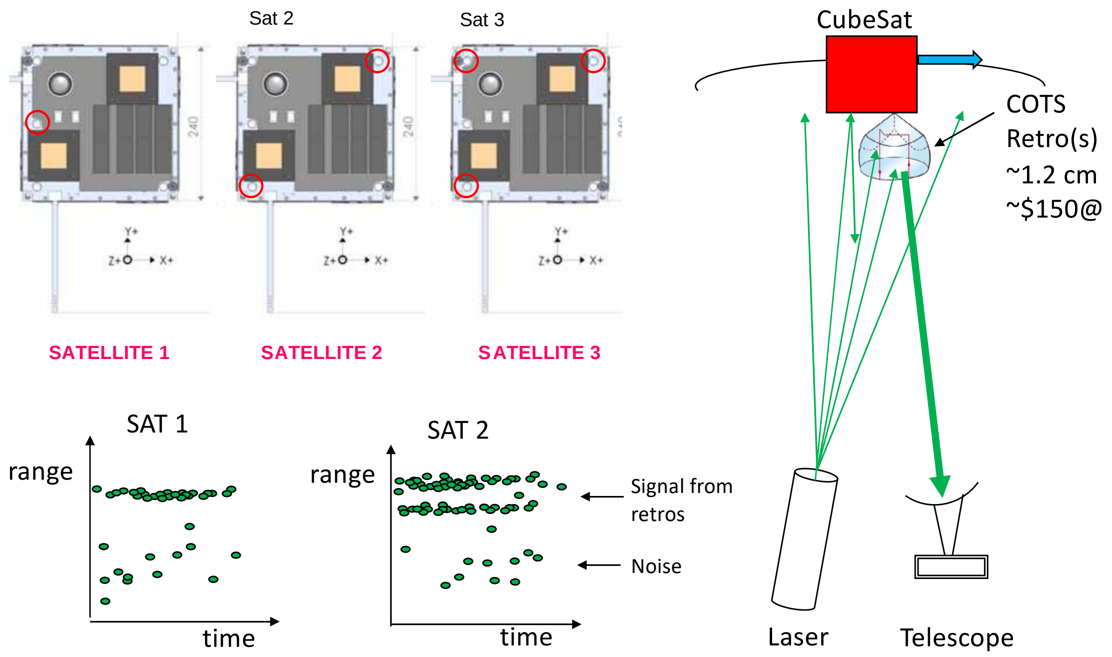


Figure 13.6: Corner Cube Reflectors. Credit: The Aerospace Corporation.

use a laser and telescope system like those employed by the International Laser Ranging Service (ILRS) (23), which are high TRL and have been operating for decades. Precise orbital information is required to lase the CubeSat and receive a return, and the number of satellites that can be uniquely identified is limited by the number of corner cube reflectors that can be attached.

13.4.3 Passive Increase in Albedo

The simplest method of increasing trackability of satellites involves using high-albedo paint, special tape, or other simple methods to increase the optical or radar visibility of a small satellite, allowing it to be more easily detected by ground-based systems (24). White-colored thermal paint has been used for years to increase the ability of satellites to reject heat, and helps make the satellites more visible and more trackable. Additionally, CubeSats often deploy a mission-specific configuration of wire antennas and/or cylindrical boom structures which can serve as unique identifiers using ground-based optical or radar characterization (25). Such approaches are simple, require little to no SWaP, and are readily available, but don't uniquely identify the satellite, and are limited in their effectiveness.

13.5 Identification and Tracking Ground Systems

Initially established in 2005, the Joint Space Operations Center (JSpOC) was performing space surveillance and providing foundational SSA for the US Department of Defense as well as for other agencies and space entities. Since July 2016, that role is provided by the 18th Space Control Squadron (18 SPCS) which assumed all functions including D/T/I artificial objects in Earth orbit and maintain the space catalog which is publicly available on space-track.org. 18 SPCS is co-located with the Combined Space Operations Center at Vandenberg Air Force Base in Southern California. As part of their activities, they provide launch support and conjunction assessment (which identifies close approaches between launch and other catalogued in-orbit objects), collision avoidance and reentry assessment. This is achieved via the US Space Surveillance Network (SSN) that is formed by several sensors around the world (28). 18 SPCS is capable of tracking more than 23,000 objects in orbit and of providing data and analytics of pieces as little as 10 cm. They issue TLEs that are updated on a regular basis and can be utilized to compute predicted orbit ephemeris and conjunction analyses.

The US Air Force next generation SSA system, known as the Space Fence provides higher resolution for tracked objects. It was declared operational in March 2020 and can track objects below the previous 10 cm limit. It is located in Kwajalein Island, in the Republic of the Marshall Islands and consist of a S-band radar system to track objects primarily in low –Earth orbit, although it can track objects in medium Earth orbit (MEO) and geostationary orbit (GEO) as well. Data obtained with the Space Fence will feed the US SSN. The 20th Space Control Squadron based in Huntsville (Alabama) manages the Space Fence and provides the data to the 18 SPCS to complete the space catalogue (29). Another major antenna in the SSN is the Haystack Ultrawideband Satellite Imaging Radar (HUSIR), which is the highest-resolution, long-range sensor in the world. HUSIR generates simultaneously X and W band images that can provide valuable information about the size, shape an orientation of Earth orbiting objects (30).

The NASA Goddard Conjunction Assessment Risk Analysis (CARA) team acts as an important intermediary between CSpOC and the satellite missions. CARA usually gathers daily orbit ephemeris and covariance files from the teams and provides the data to CSpOC for screening and close approach assessment. CARA provides capabilities to NASA missions beyond the CSpOC level of support, including operations concept development, probability of collision computation, high interest event notification, or conjunction geometry analysis among other functions. Since 2012, the French Space Agency (CNES) utilizes the equivalent CAESAR team for their missions (31)(32).

Besides government assets, several commercial entities are providing tracking information to stakeholders. Those include Analytical Graphics, Inc. (AGI) which provides data from a network of commercial sensors and through its Commercial Space Operations Center. ExoAnalytic has a global telescope network (EGTN) formed of over 25 observatories and 275 telescopes tracking orbiting objects in GEO, highly elliptical orbit (HEO), and MEO. The EGTN is able to collect both angles and brightness measurements. They also maintain a proprietary catalog of satellites and space debris that are regularly tracked and cataloged. This includes a historical archive of over 100 million object measurements (26).

LeoLabs is another important commercial entity providing detailed information for spacecraft tracking. They use a group of distributed Earth-based, phased-array radars to make a COTS satellite tracking service targeted to the specific requirements of low-Earth orbit smallsat operators. They currently have two radar stations in the United States and another one in New Zealand. The planned capability for 2020 – 2021 includes six radars strategically located around the world, which would have the capability to robustly track objects down to 2 cm in size. The predicted performance also includes a revisit time of over 10 observations per day for specific objects, and a low-Earth orbit catalog of over 250,000 pieces. Through their LeoTrack platform, they are able to use their radar data to perform precision tracking and curated orbit information products for satellites as small as 1U. Their system includes an open source GUI capable of displaying all the catalog in real time, as well as, fundamental orbit information about each individual object**.**

13.6 Future Efforts

Many in the community are aware of the "CubeSat confusion" issue, and there is a ground-swell of desire to make progress with mitigating this problem. Regulators have recognized the issue (27), and one of the consolidators, SpaceFlight, Inc., has announced a mechanism by which they may take tracking and identification technologies into space as hosted payloads aboard some of their upcoming dispenser satellite flights to increase their TRLs (28). The Aerospace Corporation is planning to sponsor and conduct a virtual “Industry Day” in the near future, to bring together regulators, consolidators, CubeSat Owner/Operators, and industrial and academic technology solution providers to discuss this matter and try to affect a solution.

On the horizon, High Earth Robotics plans to create the Argus constellation – twelve optical 6U HERO-1 nanosatellites with space telescope payloads in GEO that can identify objects, take high resolution images of damaged satellites, and help identify solutions to avoid further decomposition. The constellation is intended to be resilient to interference and communications link interruption (29).

13.7 Conclusion

Small satellites and CubeSats are likely to increase in popularity, and multi-manifest launches provide a very cost-effective way to get large numbers of satellites to space. Improving the ability to identify and track similar satellites in space – especially those deployed in batches from a single launch vehicle – can help both small satellite owners and the entire space enterprise avoid the pitfalls of “CubeSat confusion.”

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

References

(1) https://spaceflight.com, accessed March 3, 2020.

(2) https://nanoracks.com/rideshare-habitat-building-demonstration/, accessed March 3, 2020.

(3) https://www.kirtland.af.mil/About-Us/Fact-Sheets/Display/Article/826059/space-test-program/, accessed April 8, 2020.

(4) Skinner, M.A.: "*CubeSat Confusion: how to avoid 'dead on arrival'*." IAC-20-A6.7.9, International Astronomical Congress 71st meeting, 12-14 October 2020, The CyberSpace edition.

(5) Klotz, Irene: "*SpaceX Rideshare Mission Spawns 12 Orphan CubeSats*." Aerospace Daily and Defense Report, 8/12/2019.

(6) Grush, Loren: "*Why the Air Force Still Cannot Identify more than a Dozen Satellites from One December Launch: The case of the unknown satellites*." The Verge, https://www.theverge.com/2019/4/2/18277344/space-situational-awareness-air-force-tracking-sso-a-spaceflight-CubeSats

(7) Bloch, J. et al.: "*The ALEXIS Mission Recovery*." 17th annual American Astronomical Society (AAS) guidance and control conference, Keystone, CO (United States), <https://www.osti.gov/biblio/142518>, 1994.

(8) Braun, B. & S. Herrin: "*The More, the Messier: ORS-3 lessons for multi-payload mission deployments*." 1-10. 10.1109/AERO.2016.7500582. 2016.

(9) Venturini, C.C.: "*Improving Mission Success of CubeSats*." Aerospace Report number TOR-2017-01689, June 12, 2017, https://www.nasa.gov/sites/default/files/atoms/files/improving_mission_success_of_CubeSats_-_tor-2017-01689.pdf, accessed May 15, 2019.

(10) Voss, H.D., et al.: "*Globalstar Communica0on Link for CubeSats: TSAT, GEARRS1, and GEARRS2*." 29th AIAA/USU Conference on Small Satellites, Logan UT, August 9, 2015.

(11) Skinner, M.A.: "*Making Small Satellites Visible: Nanosat tracking and identification techniques and technologies."* IAC-19-A6.7.5, International Astronomical Congress 70th meeting, October 21-25, 2019, Washington DC, United States.

(12) Voss, H.D., Dailey, J.F., Orvis, M.B.: "*'Black Box' Beacon for Mission Success, Insurance, and Debris Mitigation*." SSC18-PII-11, 32nd Annual AIAA/USU Conference on Small Satellites, Logan UT. 2018.

(13) Abraham, A.J.: "*GPS Transponders for Space Traffic Management*." Center for Space Policy & Strategy, Aerospace Corporation, April 2018.

(14) Cutler, J., Seitzer, P., Lee, C.H., *et al*.: "*Improved Orbit Determination of LEO CubeSats: Project LEDsat*." AMOS Technologies Conference, 19 – 22 September 2017, Maui, Hawai`i.

(15) Palmer, D.M., Holmes, R.M.: "*ELROI: A License Plate for Your Satellite*." Journal of Spacecraft and Rockets, Vol. 55, No. 4. pp. 1014-1023. 2018.

(16) Phan, Samson: "'*Spaceflight Industries' SSO-A Flight Launches with SRI International's CUBIT Technology Onboard, Developed to Track and Identify Low Earth Orbit Satellites*." https://www.sri.com/blog/spaceflight-industries-sso-flight-launches-sri-internationals-cubit-technology-onboard, retrieved 10/30/2019.

(17) Kirchner, G., Grunwaldt, L., Neubert, R., Koidl, F., Barschke, M., Yoon, Z., Fiedler, H., Hollenstein, C.: "*Laser Ranging to Nano- Satellites in LEO Orbits: Plans, Issues, Simulations*." 18th International Workshop on Laser Ranging, Fujiyoshida, Japan. 2013.

(18) Voss, H.D. et. al.: "'*Black Box' RF Sat-Link for Space Debris, Mission Success and Risk Mitigation*." First International Orbital Debris Conference, Sugar Land, TX. 2019.

(19) Palmer, D.M., et. al.: "*Progress Towards the ELROI™ Satellite License Plate."* SSC20-VI-05, 34th Annual Conference on Small Satellites, Logan, UT. 2020.

(20) Bird, Dudley: "*Design and Manufacture of a Low-Profile Radar Retro-Reflector*." Paper presented at the RTO SCI Symposium on "Sensors and Sensor Denial by Camouflage,

Concealment and Deception", held in Brussels, Belgium, April 19-20, 2004, and published in RTO-MP-SCI-145.

(21) Lane, D. et. al.: *"Nanosatellite Tracking using Passive Retro-Reflectors."* SSC20-WKIV-04, 34th Annual Conference on Small Satellites, Logan, UT. 2020.

(22) Lane, ibid.

(23) ILRS, https://ilrs.gsfc.nasa.gov/technology/laserRanging/index.html, accessed April 14, 2020.

(24) Hall, D.: "*Optical CubeSat Discrimination*." AMOS Technical Conference, September 2008.

(25) Chong, Chee-Yee, and Shozo Mori: "*Metrics for feature-aided track association*." 2006 9th International Conference on Information Fusion. IEEE. 2006.

(26) ExoAnalytics Solutions. Space Domain Awareness (SDA). ExoAnalytic. [Online] 2020. [Cited: 03 18, 2020.] https://exoanalytic.com/space-domain-awareness

(27) US Federal Communications Commission, "*Orbital Debris in the New Space Age, Report and Order and Further Notice of Proposed Rulemaking."* FCC-20-54, paragraph 62, April 24, 2020.

(28) Sorensen, J.: "*SpaceFlight Inc. Unveils Next-gen Orbital Transfer Vehicle to Fly Aboard Next SpaceX Rideshare Mission*." July 15, 2020. https://spaceflight.com/spaceflight-inc-unveils-next-gen-orbital-transfer-vehicle-to-fly-aboard-next-spacex-rideshare-mission/

(29) HEO Robotics. HEO Robotics engages in space demonstration with Royal Australian Air Force. *HEO Robotics:Achievements.* [Online] 2019. [Cited: 03 18, 2020.] https://www.heo-robotics.com/post/heo-robotics-engages-in-paid-demonstration-with-royal-australian-air-force.

14.0 Deorbit Systems

14.1 Introduction

The threats of space debris are increasing due to the launch of several multi-satellite constellations, particularly in low-Earth orbit. The lifetime requirement for any spacecraft in low-Earth orbit is 25 years post-mission, or 30 years after launch if unable to be stored in a graveyard orbit (1).

The rate of decay of these spacecraft depends on several factors. In particular, the orbit allocation and the ballistic coefficient play a fundamental role on the ability to comply with regulations. Estimates of the accumulation of orbital debris suggest more than 750,000 particles with a diameter 1 – 10 cm, and over 29,000 pieces with diameters >10 cm, are in orbit between geostationary and low-Earth orbit altitudes (2). 94% of all launches generate space debris, and 64% of that debris consists of fragments that have a collective mass of 7,500 metric tons (2). Figure 14.1 is a representation of the debris around Earth. The objective of the NASA Orbital Debris Program along with the Inter-Agency Space Debris Coordination Committee (IADC) is to limit the creation of space debris. They have mandated that all spacecraft must either deorbit within a given amount of time or move into a graveyard orbit for safe storage (3). Small spacecraft missions typically stay in low-Earth orbit, as it is a more accessible and less expensive orbit to reach. There are lots of rideshare opportunities to low-Earth orbit through several commercial launch providers. The close proximity to Earth can relax spacecraft mass, power and propulsive constraints. Additionally, the radiation environment in low-Earth orbit is relatively benign for altitudes below 1000 km. Small spacecraft launched at or around the International Space Station (ISS) altitude (400 km) naturally decay in well under 25 years. However, at orbital altitudes beyond 800 km, there is no guarantee that a small spacecraft will naturally decay in 25 years due to uncertainties in atmospheric density and the differences in ballistic coefficient, as seen in figure 14.2.

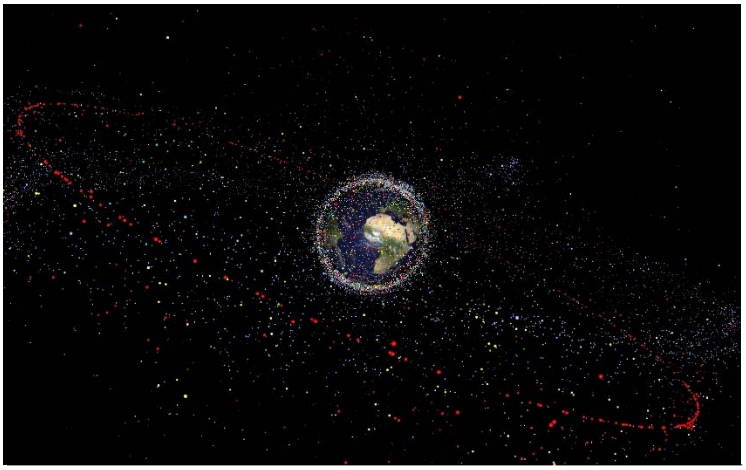


Figure 14.1: Distribution of space debris. Credit: European Space Agency.

In this image, a representative 6U CubeSat with 0.06 m^2 drag area and 14 kg of dry mass decays at different rates depending on several initial circular orbits. The results differ from those achieved with another representative spacecraft of 100 kg and 0.5 m^2 of drag area, showing the important effect the ballistic coefficient plays in the orbit propagation. The majority of launched small spacecraft do not carry on-board propulsion, making them unable to achieve graveyard orbits for decommissioning. Therefore, they need to rely on deorbit techniques such as increasing the drag area by rotating the spacecraft with their Attitude Determination and Control System (ADCS) module if they are in low altitudes. For some spacecraft, their exposed drag area is not enough to meet the 25-year requirement. They can use deorbit devices such as drag sails (passive systems) or even hire external deorbit services (active systems), in order to deorbit.

Passive deorbit systems have gained maturity since the last iteration of this report, and there are more devices with high Technology Readiness Levels (TRL ≥ 8) that are guaranteed to satisfy

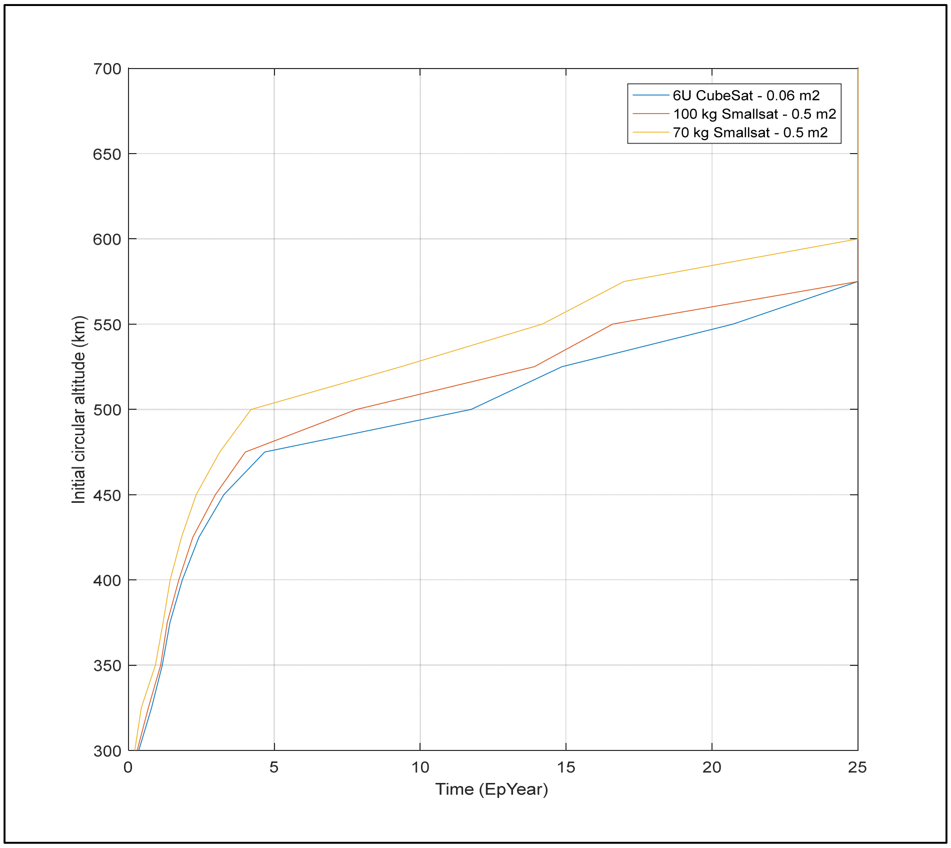


Figure 14.2: Initial orbit altitudes yield different lifetimes depending on the ballistic coefficient of the spacecraft. Three representative area-to-mass ratios are shown. Note that the propagation stops at 25 years, but the initial altitudes yield even longer times. Credit: NASA.

the 25-year requirement. Several missions have demonstrated the capability of some of these devices, and an increasing number of small spacecraft have been carrying them.

Traditionally passive systems were the main option for deorbiting due to their increased simplicity. However, recently active methods are gaining traction. On one hand, active deorbiting requires attitude control and, in some case, also surplus propellant post-mission, such as a steered drag sail that relies on a functioning attitude control system, or in actuators for pointing the sail. On the other hand, some of the new active deorbiting solutions include a separate spacecraft that is capable of attaching to the defunct satellite to bring it down to lower orbits where the satellites can complete the deorbit using their own drag decay. Some recent small spacecraft like the European RemoveDebris mission have even implemented a variety of active and passive deorbit systems within the same mission. This technology demonstration mission included both active and passive systems such as a net experiment, a harpoon, and a more traditional drag sail. The mission tested these systems to prove feasibility of such technologies in space by deploying two separate 2U CubeSats from the main spacecraft to simulate space debris. After the mission was completed, the passive system was deployed and is currently deorbiting the main satellite to burn in the atmosphere.

Propulsive devices have also been used for deorbiting techniques, however this approach is still considered risky due to potential failure or malfunction of either the spacecraft (up until its final stage of decommission) or the propulsive capability itself. Even if the spacecraft carries enough excess propellant for its own active decay approach, it also needs adequate attitude control capability after the mission. This method requires continuous operation until the reentry takes place, making it inconvenient and costly for a small spacecraft mission (4). Overall, active deorbiting methods are still challenging for small spacecraft, as this demand increases design complexity and uses valuable mass and volume. This report studies the state-of-the-art for both systems, excluding spacecraft that carry their own propulsive means. For those systems, please refer to the Propulsion chapter located in this report.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that TRL designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

14.2 State-of-the-Art – Passive Systems

Passive deorbit methods require no further active control after deployment. Recent developments have increased the number of available options with flight heritage. This chapter will emphasize recent developments rather than past missions. In addition, the chapter aims to discuss devices used exclusively for deorbit purposes, excluding technologies such as solar sails that are used for other propulsive applications.

Drag devices represent the most common deorbit device for satellites orbiting in low-Earth orbit. They present an advantage due to simplicity and by not occupying large volumes while stowed. For certain area-to-mass ratios in altitudes equal or lower than 800 km, drag devices can be deployed to increase the drag area for faster deorbiting in compliance with the 25-year requirement. Recently, this technology has been implemented in several small spacecraft missions, and several companies and institutions are developing prototypes that are increasingly more mature, providing solutions to the space debris problem for missions that do not have resources for an active system. Table 14-1 displays current state-of-the-art technology for passive deorbit systems. These are the most developed technologies for deorbiting systems as of 2020.

Table 14-1: Drag devices Deorbit Systems

Product	Mission host and launch mass (kg)	Device mass (kg)	Initial orbit	Launch Year	Deploy-ment Year	Drag area (m^2)	Manufacturer	TRL	Ref.
NanoSail-D2	FASTSAT (4.2)	N/A	650 km 72 deg inc	2010	2011	10	NASA MSFC/ARC	9	(1)
Drag-Net	ORS-3 Deployed a Minotaur Upper Stage (100)	2.8	N/A	2016	2016	14	MMA Design	9	(5)

Icarus-1	SSTL TechDemoSat-1 (157)	3.5	635 km	2014	2019	6.7	Cranfield Aerospace Solutions	9	(6)
Icarus-3	Carbonite-1 (80)	2.3	650 km 98 deg inc	2015	Future (in-orbit)	2	Cranfield Aerospace Solutions	8	(6)
DOM	ESEO (45)	0.5	572 km × 588 km 97.77 deg	2018	Future (in-orbit)	0.5	Cranfield Aerospace Solutions	8	(6)
Terminator Tape	Prox-1 (71)	0.808	717 km 24 deg	2019	2019 (deployed as of July 2020, to be fully deorbited)	10.5	Tethers Unlimited, Inc.	9	(7)
DragSail	InflateSail (3.2)	N/A	505 km 97.44 deg	2017	2017	10	Surrey Space Centre	9	(8)
Exo-Brake	TechEdSat 5 (3.4)	TBC	405 km 51.5 deg	2014	2015	0.35	NASA	9	(9)
removeDebris	100	N/A	405 km 51.5 deg	2018	2019	16	Surrey Space Centre	8	(10)
CanX-7	3U CubeSat (3.6)	0.800 (4 modules of 0.200)	688 km 98 deg	2016	2017	4	UTIAS-SFL	9	(11)

14.2.1 Main High TRL Drag Devices

Several small spacecraft missions have built and launched passive deorbit technologies in the past using a drag sail or boom. The NanoSail-D2 mission, which was deployed in 2011 from the minisatellite *FASTSat-HSV* into a 650 km altitude and 72° inclined orbit, demonstrated the deorbit capability of a low mass, high surface area sail (4). The 3U spacecraft, developed at NASA Marshall Space Flight Center (MSFC), reentered Earth's atmosphere in September 2011. The mission was the continuation of a previous effort from NASA's MSFC and Ames Research Center

(ARC). The precursor mission, NanoSail-D did not have the chance to deploy due to a launch failure onboard a Falcon 1 rocket in 2008.

More recent missions have increased the technology readiness level of these devices since then. CanX-7, still in orbit at an initial 800 km SSO, deployed a drag sail in May, 2017. The sail was developed and tested at University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS-SFL) Figure 14.3).

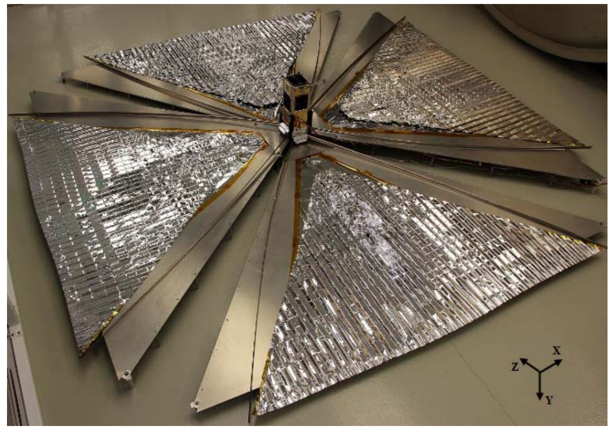


Figure 14.3: CanX-7 deployed drag sail during testing. Credit: Cotten et al. (2017).

The CanX-7 deorbit technology consists of a thin film sail that is divided in four individual modules that each provide 1 m^2 of drag area. These sail sections are deployed mechanically with spring booms, which help to preserve the geometry. Each module also has electronics for individual telemetry and command. This feature allows different sections to be controlled separately to mitigate risk of a single failure, and to allow custom adaptability to various spacecraft geometries and ballistic coefficient requirements for other missions. For the 2017 deployment, all four segments functioned successfully. The deorbit performance was measured after a month. The deorbit profile showed that the effects of the sail segments accounted for an altitude decay rate at the time of measurement of 20 km s^{-1} per year, which results in a significant increase from the previous 0.5 km s^{-1} per year. These rates are expected to increase as the atmospheric density increases exponentially with lower altitudes (11).

The Technology Educational Satellite, TechEdSat-n, program at NASA ARC has contributed significantly to the development of drag devices. It consists of a series of nanosatellite technology demonstrations in collaboration with several universities including San Jose State University and the University of Idaho. One of the main goals of the program is to test and improve deorbiting techniques, and in particular developing a unique targeting capability with their own drag device design known as the Exo-Brake. The Exo-Brake deorbit system is an atmospheric braking system that distinguishes itself from other drag devices since it is more akin to a parachute instead of a solar sail due to its primary tension-based elements. This becomes fundamental for accurate deorbit targeting since the device must retain its shape without collapsing during those critical reentry moments occurring at the atmosphere interface altitude of 100 km, known as the Von Karman line (12).

The Exo-Brake was first implemented as a passive orbit device on the TechEdSat missions TES 3, TES 4, and TES 5. Recent CubeSats have also used it for controlled mission deorbiting. The Exo-Brake development is funded by the Entry Systems Modeling project within the NASA Space Technology Mission Directorate's (STMD) Game Changing Development (GCD) program. The latest two of the four TechEdSat spacecraft using a passive Exo-Brake are TechEdSat-5 and TechEdSat-7; TechEdSat-5 was deployed from the ISS in 2017 and demonstrated this deorbiting capability after 144 days in orbit. TechEdSat-5 orbited at 400 km altitude when the Exo-Brake was enabled. TechEdSat-7 is a 2U CubeSat expected to launch on the first Virgin Orbit launch. It carries a fixed and high packing density exo-brake intended for traditional reentry disposal without modulation (12). The most recent TES mission that incorporates an active deorbiting design, TechEdSat-10, was deployed from the ISS on July 13th, 2020, see figure 14.4.

The Surrey Space Centre based in the United Kingdom has developed the DragSail technology, which was implemented in a family of missions. The Inflatesail 3U CubeSat first demonstrated this technology. The European Commission QB50 program and the DEPLOYTECH partnership that included DLR and NASA Marshall Space Flight Center, among others, funded it. This mission was launched in 2017 and included a mast/drag-sail technology that successfully deorbited the satellite in just 72 days. This achievement was the first time a spacecraft has deorbited using European inflatable and drag-sail methods (8).

Figure 14.4: TechEdSat-10 deployment from the ISS in July 2020. Credit: NASA.

The RemoveDebris mission was developed under the European Commission FP7 program by a consortium of several institutions such as Airbus and the Surrey Space Centre. The mission consisted of a small spacecraft of 100 kg that was deployed from the ISS in 2018. One of the experiments it carried was a passive drag augmentation device consisting of a sail. The sail was deployed in March 2019, however, trajectory data showed it only happened partially since no significant altitude change was measured. The lessons learned from this incident were implemented in another version for the Space Flight Industries' SSO-A mission that incorporated two of these sails. In that case, the assembly did not include an inflatable boom (10).

As part of the ESA CleanSat program, Cranfield Aerospace Solutions in the United Kingdom has also developed a variety of drag augmentation systems. The first demonstrated technology was the Icarus-1, which flew in the TechDemoSat-1 mission from SSTL, launched in 2014, see figure 14.5. Another version also flew in the Carbonite-1 spacecraft, launched in 2015. The concept is similar to other drag devices in which the drag increases by deploying a membrane sustained by rigid booms. The Icarus technology consists of a thin aluminum structure located around the satellite side panel that contains four stowed Kapton trapezoidal sails and booms. The mass of the system is 3.5 kg for about 5 m^2 of sail area for the Icarus-1, and 2.3 kg for 2 m^2 for the Icarus-3. Both sails deployed successfully and are expected to deorbit both spacecraft in less than 10 years. The second technology developed by Cranfield Aerospace Solutions is a De-orbit mechanism (DOM) device which consists of a version of the drag sail presented in a smaller cuboid outline. The mechanical system varies from Icarus since the sails are triangular and the booms work as tape springs themselves. This system flew in the European Student Earth Orbiter on a 45 kg satellite that carried several student payloads. Among them, the Cranfield University DOM module will deorbit the spacecraft after decommissioning. The sail has an area of 0.5 m^2 with a mass of 0.5 kg (6).

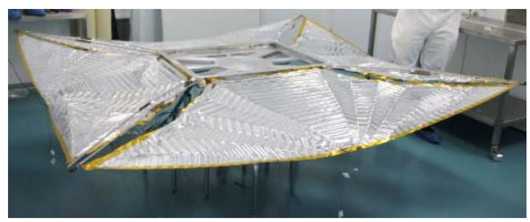


Figure 14.5: Icarus-3 drag sail implemented in the Carbonite-1 mission. Credit: Cranfield Aerospace Solutions.

MMA Design LLC, a company from Colorado, has patented the dragnet deorbit system. The 2.8 kg module (figure 14.6) deorbited the ORS-3 Minotaur

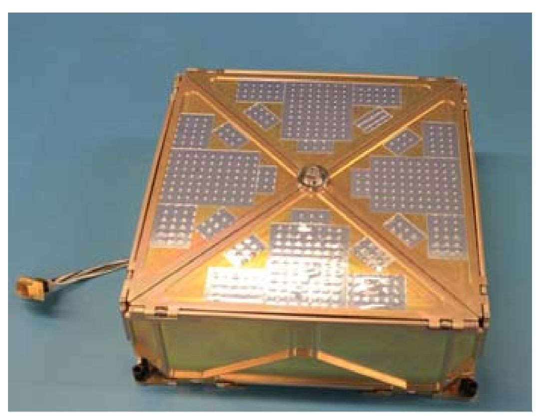


Figure 14.6: DragNet module. Credit: MMA Design LLC.

Upper Stage in 2.1 years after launch in November 2013. DragNet features four stowed thin membranes that deploy through a single heater-powered actuator. The sail has an area of 14 m^2 that can effectively deorbit a 180 kg spacecraft at an altitude of 850 km in less than 10 years (5).

14.2.2 Deployable Booms

Composite Technology Development, Inc. has developed the Roll-Out DeOrbiting device (RODEO) that consists of a lightweight film attached to a simple, ultra-lightweight, roll-out composite boom structure (figure 14.7). It was successfully deployed on suborbital RocketSat-8 on August 13, 2013 (13).

Figure 14.7: RODEO stowed. Credit: Composite Technology Development, Inc.

AAC Clyde Space collaborated with the University of Glasgow to construct the Aerodynamic End-of-Life Deorbit system for CubeSats (AEOLDOS), where a lightweight, foldable “aerobrake” made from a membrane is supported by boom-springs that open the sail to generate aerodynamic drag against the upper atmosphere (14). There is no current update to this system as of October 2020.

14.2.3 Electromagnetic Tethers

In addition to drag sails, an electromagnetic tether has proven to be an effective deorbit method (figure 14.8). This technology uses a conductive tether to generate an electromagnetic force as the tether system moves relative to Earth’s magnetic field. Tethers Unlimited developed Terminator Tape that uses a burn-wire release mechanism to actuate the ejection of the Terminator’s cover, deploying a 70 m long conductive tape at the conclusion of the small spacecraft mission (7). There are currently two main modules. The first, NSTT for NanoSats has a mass of 0.808 kg. The second, CSTT, is made for CubeSats and has a mass of just 0.083 kg. Figure 14.9 shows an image of both systems respectively (15). The 70 m long NSTT has been implemented in the 71 kg Prox-1 satellite, launched in mid-2019 by the Air Force Research Laboratory. Tethers Unlimited is also working with Millennium Space Systems, RocketLab, and TriSept Corp. on an experiment called DragRacer, which will consist of a satellite with the Terminator Tape, and another without, in order to characterize the tape performance (16). The AeroSpace Corporation 2 kg and 1.5 Aerocube 5A and 5B CubeSats, launched in 2015, also incorporated a version of the Terminator Tape and are still on orbit as of July 2020.

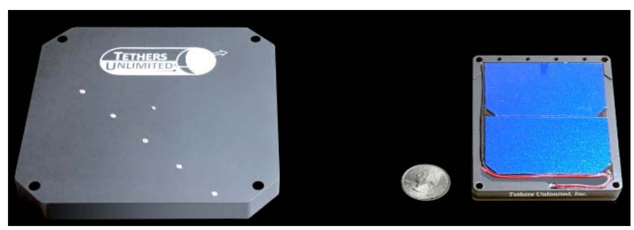


Figure 14.8: Image of the NSTT (left) and the CSTT modules. Credit: Tethers Unlimited.

On the horizon, two universities are developing innovative new drag devices for upcoming missions. The University of Florida is developing the Drag Deorbit Device (D3) 2U CubeSat which provides attitude stabilization and modulation of the satellite drag area at the same time, making

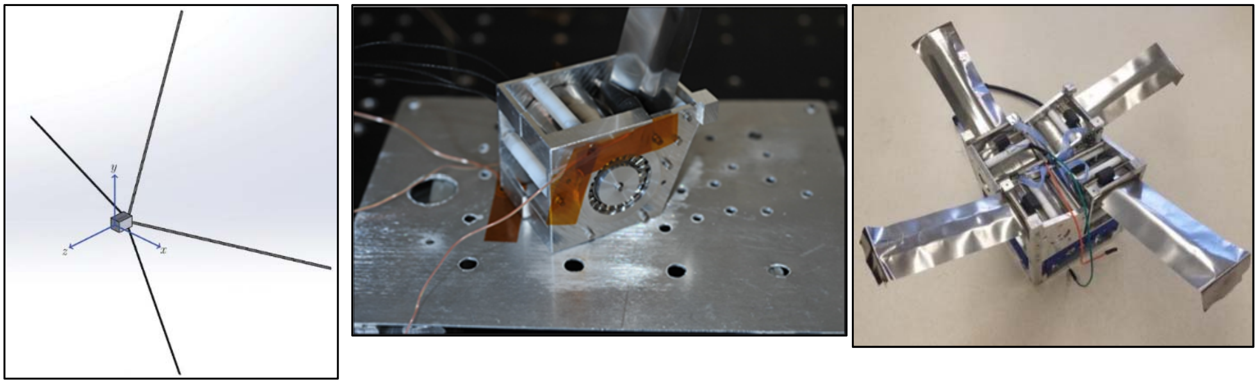


Figure 14.9: D3 CAD design (left), boom inside thermal vacuum chamber (center), and prototype design (right). Credit: Omar et al., 2019, and Martin et al., 2019.

the overall solution an alternative to regular ADCS units. Four 3.7 m long tape spring booms form the D3, which is capable of deorbiting a 15 kg satellite from an altitude of 700 km. A final design has been already been tested and simulated, including thermal vacuum and fatigue testing (17) (18). Figure 14.9 shows two images of the final design. The mission has been selected by NASA through the CubeSat Launch Initiative, which includes eligibility for placement on a launch manifest (19).

Purdue University is developing the other system on the horizon and it consists of a drag device that can deorbit a satellite placed in a Geosynchronous Transfer Orbit (GTO). The Aerodynamic Deorbit Experiment will be the technology demonstration of this concept, and it will consist of a 1U CubeSat. It will be deployed from a Centaur upper stage in a future Atlas V rocket from United Launch Alliance. Once deployed, the device will occupy an area of about one m^2 in order to decrease the ballistic coefficient of the spacecraft and reduce the perigee altitude during each pass. Consequently, the expected lifetime of the ADE mission will be 50 – 250 days instead of the estimated seven years (20).

14.3 State-of-the-Art – Active Systems

Several companies have been increasingly offering active spacecraft-based deorbit systems. Space startups such as AstroScale, ClearSpace, and D-orbit have long-term plans and have already started initial technology demonstrator missions. These systems consist of separate, dedicated spacecraft that attach to decommissioned satellites to place them into decaying or graveyard orbits. In December 2019, Iridium stated that they would like to pay for an active deorbit system to remove 30 of their defunct satellites (21). In addition, NASA STD-8719.14A stipulates that all spacecraft using controlled reentry processes have to be within 370 km of the target when landing (10). Therefore, future concepts such as sample return missions are going to need active reentry devices to satisfy these requirements.

This section covers some of the main stakeholders in the industry that are working towards the implementation of active space debris removal, as well as some other promising technologies that can potentially be used for actively deorbiting spacecraft in the future.

14.3.1 TechEdSat Series Exo-Brake

The Exo-brake introduced earlier in the passive systems also has active control capability. The TechEdSat-6 mission was the first one implementing this technology, on a 3.5U CubeSat with a mass of 3.51 kg that deployed its Exo-Brake from the rear of the satellite. It targeted a reentry over Wallops Flight Facility by modulating the drag device to adjust the ballistic coefficient as orbital determination about the satellite state became available over time. Figure 14.10 shows a

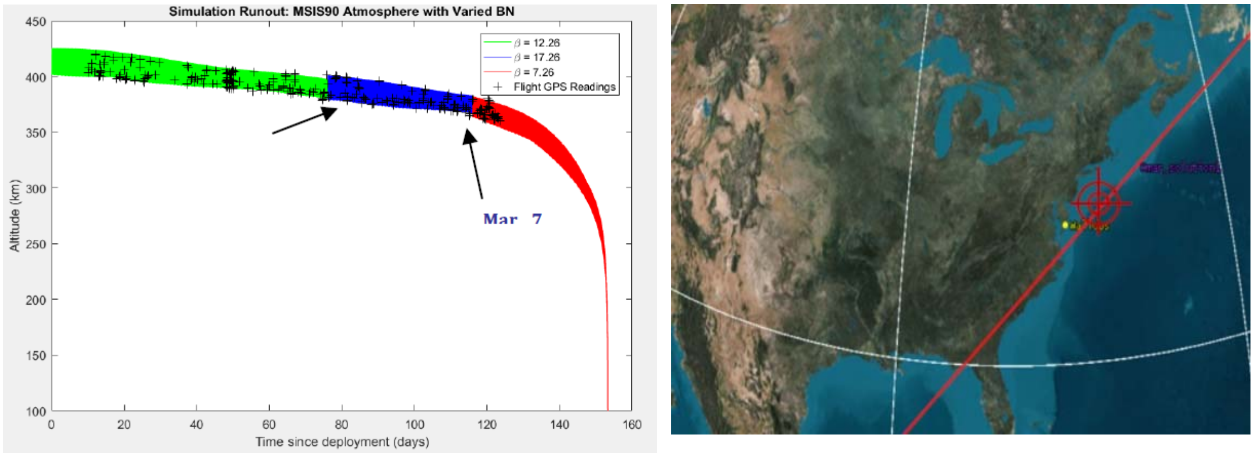


Figure 14.10: Targeting of the TES 6 Exo-Brake is achieved by modifying the drag area of the modulating Exo-brake. (Left) the plot includes actual GPS readings and the approximate ballistic coefficient achieved at different parts of the mission. Credit: Murbach et al., 2019. (Right) the reentry location and final ground track of TES 6. The spacecraft overshot but still demonstrated the capability to target a particular location by modifying its ballistic coefficient. Credit: NASA.

representation of the actual deorbit targeting capability of the TES 6 when the Exo-Break modified the ballistic coefficient. The Iridium gateway enabled the command of the brake, which proved to significantly affect the reentry time and consequently, the location of the Wallops target area. The spacecraft overshot the intended target range slightly as shown in the second image, since it could not achieve a lower 4 – 5 kg m^{-2} ballistic coefficient configuration, which would have yielded suitable results if placed at 300 km. However, the mission demonstrated successfully the reentry experiment and the command/control capability by overflying Wallops right before reentering. This technology was going to be demonstrated again in the TechEdSat-8 mission. Although the Exo-Brake was successfully deployed, a power system failure occurred before the targeting process started. The TES 8 Exo-Brake was an improved version of the previous TES 5 and TES 6 devices. The ballistic coefficient range was larger (6 – 18 kg/m^2) which allows better control authority for targeting. TES 10 and upcoming TES 11 are also incorporating this design (12).

14.3.2 RemoveDebris Consortium Partners

The RemoveDebris mission carried two 2U CubeSats that were ejected from the mothership to simulate space debris and demonstrate active deorbit capabilities. The first CubeSat, known as DebrisSat-1, deployed at a very low velocity from the main spacecraft and subsequently inflated a balloon that provided a larger target area. A 5 m diameter net was ejected from the main spacecraft just 144 seconds after deployment, capturing the CubeSat at a distance of ~11 m from the mothercraft. The object, once enveloped in the net, re-entered the atmosphere in March 2019 (10). The RemoveDebris mission also carried another active debris technology consisting of a harpoon. In this scenario, a target platform attached to a boom was deployed from the main spacecraft. The mothership then released the harpoon at 19 m/s to hit the platform in the center. Once that occurred, the 1.5 m boom that connected the two objects snapped on one end. However, a tether secured the target in place, avoiding the creation of new debris. This resulted in the first demonstration of a harpoon technology in space. The harpoon target assembly had a dry mass of 4.3 kg (10).

14.3.3 Astroscale

Astroscale is a company founded in Japan and with offices in the UK, the US, and Singapore. Their two main objectives are to provide services to address the end-of-life (EOL) scenario of newly launched satellites, and to proactively remove existing space debris. They collaborate with a variety of governmental and international organizations around the world (such as the US government, ESA, the European Union or the United Nations) in order to position themselves as leaders of a more sustainable low-Earth orbit environment.

As part of the EOL campaign, the ELSA-d mission, which is scheduled to launch in 2020, will consist of two spacecraft, with one acting as a 'servicer' and the other as a 'client'. They will have launch masses of 180 kg and 20 kg respectively. The concept of operations is to perform rendezvous maneuvers by releasing the client from the servicer repeatedly in order to demonstrate the capability of finding and docking existing debris. The technology demonstrations will include search and inspection of the targets, as well as rendezvous of both tumbling and non-tumbling cases (22).

Regarding their active debris removal campaign, Astroscale is also working with national space agencies to incorporate solutions to remove critical debris such as rocket upper stages or defunct satellites. This campaign started with a partnership with the Japanese Space Agency (JAXA) in February 2020. This collaboration will result in the implementation of the Commercial Removal of Debris Demonstration project (CRD2) which consists of the removal of a large space debris object performed in two mission phases. Astroscale will be involved in the first part, with a satellite that identifies and acquires data from an upper stage rocket object from Japan. The company is responsible for manufacturing and operating the satellite to complete these tasks, with a planned demonstration in 2022 (22) (23).

In June 2020, Astroscale acquired the intellectual property of the Israeli company Effective Space Solutions. This company developed the Space Drone servicing vehicle, which is capable of providing active debris removal. The Space Drone will mature into an Astroscale program (24).

14.3.4 ClearSpace

ClearSpace is a Swiss company founded as a spin-off from the Ecole Polytechnique Federale de Lausanne (EPFL) research institute. Their plans also include service contracts for active debris removal. One of their proposed missions, ClearSpace One, which has been backed by ESA, will find, target, and capture a non-cooperative, tumbling 100 kg VESPA (Vega Secondary Payload Adapter) upper stage. The chaser spacecraft will be launched into a 500 km orbit for commissioning and initial testing before raising its altitude to 660 km where the VESPA is located, where it will attempt rendezvous and capture. ClearSpace One will use a group of robotic arms to grab the upper stage and then both spacecraft together will be deorbited to a lower orbit for a final disintegration in the atmosphere. The mission is planned to launch in 2025 to help establish a market for in-orbit servicing and debris removal (25).

14.3.5 Momentus

Momentus is a company founded in 2017 and based in California that operates space transportation systems that can propel or deorbit other spacecraft. Their Vigoride platform is capable of carrying satellites with masses up to 250 kg. With a wet mass of 215 kg, it is capable of providing up to 1.6 km s^{-1} for 50 kg payload, through a water plasma propulsion system (26). Although the main objective of this system is to provide enhanced propulsive capability to their customers, the platform is suitable for active deorbiting. Momentus has booked several Vigoride missions on Falcon 9 launches through 2020 and 2021.

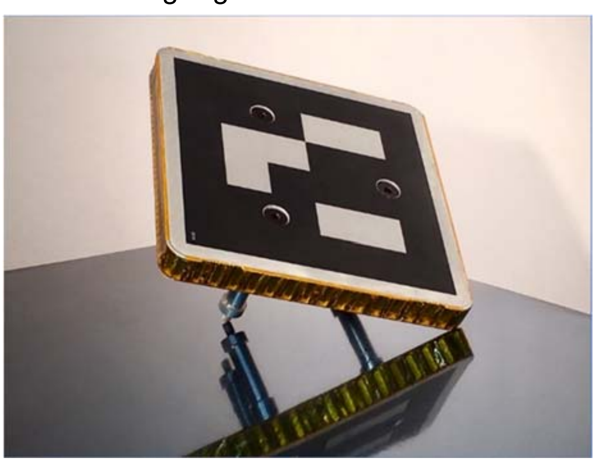
14.3.6 D-orbit

D-orbit is a space transportation company founded in 2011 in Italy, with subsidiaries in Portugal, the United Kingdom, and the United States. It provides transportation services onboard their ION CubeSat carrier platform that can provide precision deployment and is able to host satellites from 1 to 12U. Two initial flights are already scheduled for 2020 onboard the ArianeSpace Vega SSMS POC flight and the SpaceX Falcon 9. The first mission will carry 12 Doves from the Earth-observation company Planet, and future versions of this technology will consider other applications such as retrieving orbiting spacecraft to deorbit them. In addition, D-orbit provides an external solid motor booster specifically for deorbiting purposes. This independent module, known as D-Orbit Decommissioning Device (D3) shown in figure 14.11, is a proprietary solution that is optimized for end-of-life maneuvers (27).

Figure 14.11: D-Orbit D3 module. Credit: D-orbit.

14.3.7 Altius Space Machines

In 2019, the satellite constellation company OneWeb signed a partnership with Altius Space Machines from Boulder, Colorado, to include a grappling fixture on all their future launched satellites in an effort to make space more sustainable. The Altius DogTag consists of a universal interface for small satellites that is inexpensive and lightweight. The fixture design enables various grappling techniques to enable servicing or decommissioning. It uses magnetic capabilities as its primary capture mechanism but is also compatible with other techniques in an effort to accommodate other potential customers and act as a standard interface (28). More specifically, it is compatible with magnetic attraction, adhesives, mechanical, and harpooning captures. Figure 14.12 includes an image of the prototype and a table with DogTag main features.



Bounding Volume	150mm x150mm x 65mm
Total Mass	250g
Mounting Interface	3x M5x0.8 threaded inserts on an 84.5mm bolt-hole circle
Compatible Gripping Methods	Magnetic Capture Adhesive Capture - Electrostatic - Gecko - Hot-Melt - Chemical Mechanical Capture - Pinch-Grasp - Snare Penetrating Capture (Harpoon)

Figure 14.12: DogTag prototype. Credit: Altius Space Machines.

14.5 Summary

The new space paradigm and the increasing population of spacecraft in low-Earth orbit requires deorbiting systems that can satisfy space debris requirements. Small spacecraft deorbit systems have matured significantly over the past few years. Several passive systems have flown on various missions and increased to TRL 9 after successful technology demonstrations. Drag sails are the main technology, and several companies have already commercialized and sold these products. Other systems such as electromagnetic tethers, deployable booms, or the NASA Exo-brake have also already been prototyped and demonstrated in space. In addition, active systems that include commanded and modulated systems, as well as independent servicing spacecraft, are also maturing and will play a fundamental role in the upcoming years. A version of the Exo-brake with pointing capabilities has been demonstrated in the TechEdSat-6 mission, while the RemoveDebris mission has successfully tested two different active methods, a net and a harpoon, for future implementation in active debris removal operations. Companies such as Astroscale, Momentus, D-Orbit, or ClearSpace are already developing and planning to launch servicing spacecraft that can attach to decommissioned satellites to bring them down to a graveyard orbit or disintegrate in the atmosphere. In conclusion, this technology has increased significantly in maturity since the last iteration of this report, and is expected to grow as the demand for deorbiting services increases with additional launches.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

References

(1) NASA. Process for Limiting Orbital Debris. *standards.nasa.gov.* [Online] 2012.

(2) Williams, M.: "Eye-Opening Numbers On Space Debris." [Online] March 21, 2017. [Cited: July 12, 2018.] https://phys.org/news/2017-03-eye-opening-space-debris.html.

(3) NASA. *Process for Limiting Orbital Debris.* s.l. : NASA-STD-8719.14B, 2019.

(4) Bonin, G., et al.: *"The CanX-7 Drag Sail Demonstration Mission: Enabling Environmental Stewarship for Nano- and Microsatellites."* 2013, 27th Annual AIAA/USU Conference on Small Satellites.

(5) MMA Design. dragNET™ De-Orbit System. *MMA Design: Products.* [Online] 2020. https://mmadesignllc.com/product/dragnet-de-orbit-system/.

(6) *Development Of Commercial Drag-Augmentation Systems For Small Satellites.* Palla, Chiara, Kingston, Jenny and Hobbs, Stephan. Damstadt : ESA Space debris Office, Ed. T. Flohrer & F. Schimtz, 2017.

(7) R. P. Hoyt, I. M. Barnes, N. R. Voronka, and J. T. Slostadin: "*The Terminator Tape: A Cost-Effective De-Orbit Module for End-of-Life Disposal of LEO Satellites."* 2009. AIAA Space 2009 Conference.

(8) Underwood, Craig, et al.: "*Inflatesail De-Orbit Flight Demonstration Results And Follow-On Drag-Sail Applications."* s.l. : Acta Astronautica, 2019, Vols. 162, pages 344-358. ISSN: 0094-5765.

(9) Murbach, M., et al.: "*TechedSat 5/PhoneSat 5 (T5/P5)."* Logan UT: Conference on Small Satellites, 2016.

(10) Aglietti, Guglielmo, et al.: "*The active space debris removal mission RemoveDebris. Part 2: in orbit operations."* s.l. : Acta Astronautica, Elsevier, 2020, Vols. 168, pp. 310-322.

(11) Cotten, Brad, Bennett, Ian and Zee, Robert E.: "*On-Orbit Results from the CanX-7 Drag Sail Deorbit Mission."* s.l.: 131stAnnual AIAA/USUConference on Small SatellitesSSC17-X-06, 2006.

(12) Murbach, M., et al.: "*The Exo-Brake as an Inexpensive Means of Achieving Sample Return from Low Earth Orbit – Recent Flight Tests."* Washington, D.C. : 70th International Astronautical Congress (IAC), 2019.

(13) Turse, D., et al.: *"Flight Testing of a Low Cost De-Orbiting Device for Small Satellites."* 2013. Proceedings of the 42nd Aerospace Mechanisms Symposium.

(14) P. Harkness, M. McRobb, P. Lutzkendorf, R. Milligan, A. Feeney, and C. Clark: "*Development status of AEOLDOS: A deorbit module for small satellites."* 2014.

(15) Hoyt, Robert, et al.: "*The Terminator Tape: A Cost-Effective De-Orbit Module for End-of-Life Disposal of LEO Satellites."* 2020.

(16) Caleb Henry: "Tethers Unlimited says early results of deorbit hardware test promising." *Space News.* [Online] 01 23, 2020. https://spacenews.com/tethers-unlimited-says-early-results-of-deorbit-hardware-test-promising/.

(17) Omar, Sanny, et al.: "*CubeSat Mission to Demonstrate Aerodynamically Controlled Re-Entry using the Drag De-Orbit Device (D3)."* Logan UT: 32nd Annual AIAA/USUConference on Small Satellites, 2018.

(18) Martin, Tanya, Omar, Sanny and Bevilacqua, Riccardo: "*Controlled Spacecraft Re-Entry of a Drag De-Orbit Device (D3)."* s.l.: University of Florida, Journal of Undergraduate Research, Vol. 21., 2019.

(19) NASA. NASA Announces Tenth Round of Candidates for CubeSat Space Missions. [Online] 03 14, 2019. https://www.nasa.gov/feature/nasa-announces-tenth-round-of-candidates-for-cubesat-space-missions.

(20) Long, A. C. and Spencer, D. A.: "*A Passively Stable Pyramid Sail for the Deorbit of Small Satellite Constellations."* s.l.: 68th International Astronautical Congress, 15th IAA Symposium on Space Debris (A6) Space Debris Removal Issues, 2017.

(21) Caleb Henry: "Iridium Would Pay To Deorbit Its 30 Defunct Satellites — For The Right Price." *Spacenews.* [Online] 12 30, 2019. https://spacenews.com/iridium-would-pay-to-deorbit-its-30-defunct-satellites-for-the-right-price/.

(22) Blackerby, Chris, et al.: "*The ELSA-d End-of-life Debris Removal Mission: Preparing for Launch."* Washington D. C., 70th International Astronautical Congress (IAC), 2019.

(23) Astroscale. End of Life (EOL). *Astroscale.* [Online] 10 2019.

(24) Sandra Erwin: "Astroscale Moving Into GEO Satellite Servicing Market." *Spacenews.* [Online] 06 03, 2020. https://spacenews.com/astroscale-moving-into-geo-satellite-servicing-market/.

(25) ClearSpace One. Find: How do we locate satellites or debris? *ClearSpace Today.* [Online] 2020. [Cited: 03 28, 2020.] https://clearspace.today/546-2/.

(26) Momentus. Vigoride User Guide. 2020.

(27) Martin, Tanya, Omar, Sanny and Bevilacqua, Riccardo: "*Controlled Spacecraft Re-Entry of a Drag De-Orbit Device (D3)."* University of Florida: Journal of Undergraduate Research, Vol. 21, 2019.

(28) Maclay, Timothy, et al.: "*The development of commercially viable ADR services: Introduction of a small-satellite grappling interface."* s.l.: First International Orbital Debris Confeference, 2019.

(29) ExoAnalytics Solutions. Space Domain Awareness (SDA). *ExoAnalytic.* [Online] 2020. [Cited: 03 18, 2020.] https://exoanalytic.com/space-domain-awareness.

(30) HEO Robotics. HEO Robotics engages in space demonstration with Royal Australian Air Force. *HEO Robotics:Achievements.* [Online] 2019. [Cited: 03 18, 2020.] https://www.heo-robotics.com/post/heo-robotics-engages-in-paid-demonstration-with-royal-australian-air-force.

Summary

This report has provided an overview and assessment of the state-of-the-art for small spacecraft technology at a particular point in time. However, the reader should be aware that the pace of technology advancement for SmallSats in general is still rapidly accelerating. As CubeSats become larger and SmallSats become smaller, technology maturation and miniaturization will further increase capabilities. While still fairly dominated by the CubeSat platform, the SoA report is starting to reflect increased interest in larger SmallSat systems. This is due in part to an increase in launch opportunities and launch vehicle capabilities, as rideshares and small dedicated launchers further reduce the cost of access to space. Small spacecraft that are larger and more capable than traditional CubeSats, but can also use rideshares and small dedicated launchers are, therefore, receiving more attention from space scientists and mission designers.

This report will be regularly updated as emerging technologies mature and become state-of-the-art. Any current technologies that were inadvertently missed will be identified and included in subsequent versions. This report is also available online located at: https://sst-soa.arc.nasa.gov. Ongoing reader and technology inputs can be made by reaching out to the editor of this report at arc-sst-soa@mail.nasa.gov.

16.0 Glossary

(3DOF)	Three Degrees Of Freedom
(ACS3)	Advanced Composite Solar Sail Project
(ADCS)	Attitude Determination And Control System
(ADN)	Ammonium Dinitramide
(AFRL)	Air Force Research Laboratory
(AMF)	Additive Manufacturing Facility
(AMODS)	Autonomous On-Orbit Diagnostic System
(AOCS)	Attitude And Orbit Control System
(API)	Application Programming Interfaces
(ARC)	Ames Research Center
(ASICS)	Application Specific Integrated Circuits
(ASRF)	Atmospheric Sciences Research Facility
(ATA)	Active Thermal Architecture
(BOL)	Beginning of Life
(C&DH)	Command and Data Handling
(CARA)	Conjunction Assessment Risk Analysis
(CCD)	Charge Couple Devices
(CCSDS)	Consultative Committee For Space Data Systems
(CDMA)	Code Division Multiple Access
(Cfe)	Core Executive
(CFRP)	Carbon Fiber-Reinforced Plastic
(Cfs)	Core Flight System
(CI)	Continuous Integration
(CMOS)	Complementary Metal Oxide Semiconductors
(CNES)	French Space Agency
(COBRA)	Compact On-Board Robotic Articulator
(COTS)	Commercial-Off-The-Shelf
(CRC)	Cyclic Redundancy Check
(CTD)	Composite Technology Development
(CTE)	Coefficient Of Thermal Expansion
(CUBIT)	Cubesat Identification Tag

(Cuebsat)	Cube Satellite
(D3)	D-Orbit Decommissioning Device
(DCB)	Deployable Composite Boom
(DDD)	Displacement Damage Dose
(DLR)	German Aerospace Center
(DOM)	De-Orbit Mechanism
(DRM)	Design Reference Mission
(DSAC)	Deep Space Atomic Clock
(DSN)	Deep Space Network
(DSOC)	Deep Space Optical Communications
(DTE)	Direct-To-Earth
(DTG)	Direct-To-Ground
(EAR)	Export Administration Regulations
(ECC)	Error-Correcting Code
(EDAC)	Error Detection And Correction
(EEE)	Electrical, Electronic And Electro-Mechanical
(ELROI)	Extremely Low Resource Optical Identifier
(EMC)	Electromagnetic Compatibility
(EMI)	Electromagnetic Interference
(EO)	Earth Observation
(EOL)	End-of-Life
(EP)	Electric Propulsion
(EPS)	Electrical Power System
(EPSS)	Enabling Propulsion System For Small Satellites
(ESA)	European Space Agency
(ESA)	Electrically Steered Arrays
(ESSI)	Enhanced Synchronous Serial Interface
(FCC)	Federal Communications Commission
(FEC)	Forward Error Correction
(FEEP)	Field Emission Electric Propulsion
(FETS)	Folding Elastic Thermal Surface
(FIPS)	Federal Information Processing Standard
(FOGs)	Fiber Optic Gyros

FOV	Field of View
(FPGAs)	Field Programmable Gate Arrays
(FPPT)	Fiber-Fed Pulsed Plasma Thruster
(FRAM)	Ferroelectric Random-Access Memory
(FSW)	Flight Software
(GBESA)	Ground-Based Electrically-Steered Array
(GBPA)	Ground Based Phase Array
(GCD)	Game Changing Development
(GEO)	Geo-Synchronous Orbit
(GEVS)	General Environmental Verification Standard
(GFTS)	Graphite Fiber Thermal Straps
(GIT)	Gridded-Ion Thrusters
(GNC)	Guidance Navigation And Control
(GPIM)	Green Propellant Infusion Mission
(GPIO)	General Purpose Input/Output
(GPS)	Global Positioning Satellite
(GPUs)	Graphics Processor Units
(GSE)	Global Satellite Engineering
(GSFC)	Goddard Space Flight Center
(GTO)	Geosynchronous Transfer Orbit
(HAN)	Hydroxyl Ammonium Nitrate
(HCI)	Horizon Crossing Indicators
(HEC)	High Efficiency Cooler
(HEO)	Highly Elliptical Orbit
(HET)	Hall-Effect Thruster
(HUSIR)	Haystack Ultrawideband Satellite Imaging Radar
(I/O)	Input & Output
(I&T)	Integration and Testing
(IADC)	Inter-Agency Space Debris Coordination Committee
(IARU)	International Amateur Radio Union
(IDL)	Interactive Data Language
(IMUs)	Inertial Measurement Units

(INNOVA)	IN-Orbit And Networked Optical Ground Stations Experimental Verification Advanced Testbed
(ISL)	Intersatellite Link
(ISS)	International Space Station
(ITOS)	Integrated Test And Operations System Improved
(ITJ)	Triple Junction
(ITU)	International Telecommunications Union
(JPL)	Jet Propulsions Laboratory
(Jspoc)	Joint Space Operations Center
(LADEE)	Lunar Atmosphere And Dust Experiment Explorer
(LCRD)	Laser Communications Relay Demonstration Lowell
(LDT)	Discovery Telescope
(LED)	Light-Emitting Diode
(LEO)	Low-Earth Orbit
(Li-ion)	Lithium Ion
(LiPo)	Lithium Polymer
(LLCD)	Lunar Laser Communications Demonstration Low-
(LNA)	Noise Amplifier
(LPT)	Linear Pulse Tube
(LVDS)	Low-Voltage Differential Signaling
(MAPS)	Modular Architecture Propulsion System Mars Cube
(MarCO)	One
(MEO)	Medium Earth Orbit
(Microsat)	Microsatellite
(MEMS)	Microelectromechanical System
(MLI)	Multi-Layer Insulation
(MMH)	Monomethyl Hydrazine
(MOSFETS)	Metal Oxide Semiconductor Field Effect Transistors
(MPFL)	Mechanically Pumped Fluid Loop
(MRAM)	Magnetoresistive Random-Access Memory
(MSFC)	Marshall Space Flight Center
(MSPA)	Multiple Spacecraft Per Aperture
(MTBF)	Mean Time Between Failures

(MULASSIS)	Multi-Layered Shielding Simulation Software
(Nanosat)	Nanosatellite
(NASA)	National Aeronautics And Space Administration
(NEA)	Near-Earth Asteroid
(NEN)	Near Earth Network
(NICT)	National Institute Of Information And Communications Technology
(NIMO)	Networks Integration Management Office
(NODIS)	Nasa Online Directives Information System
(NPR)	Nasa Procedural Requirements
(NSTAR)	Naval Academy Satellite Team For Autonomous Robotics
(NTE)	Nanosatellite Tracking Experiment
(NTIA)	National Telecommunications And Information Administration
(OGS)	Optical Ground Stations
(OPV)	Organic Photovoltaic
(PBM)	Plasma Brake Module
(PCB)	Printed Circuit Board
(PCDU)	Power Conditioning And Distribution Unit
(PET)	Polyethylene Terephthalate
(PGF)	Pyrolytic Graphite Film
(PGS)	Pyrolytic Graphite Sheet
(PLEO)	Polar Low-Earth Orbit
(PMAD)	Power Management And Distribution
(PMDs)	Propellant Management Devices
(PMI)	Progress Towards Mission Infusion
(PPM)	Pulse Position Modulation
(PPP)	Public-Private Partnership
(PPS)	Precise Positioning System
(PPT)	Pulsed Plasma Thrusters
(PTD)	Pathfinder Technology Demonstration
(PTFE)	Polytetrafluoroethylene
(PZT)	Lead-Zirconium-Titanium Oxide
(RECS)	Robotic Experimental Construction Satellite
(RAM)	Random Access Memory

(ROC)	Roll Out Composite
(Rsat-P)	Repair Satellite-Prototype
(RTEMS)	Real-Time Executive For Multiprocessor Systems
(RTGs)	Radioisotope Thermoelectric Generators
(RTOS)	Real-Time Operating Systems
(SA)	Single Access
(SADA)	Solar Array Drive Actuator
(SBIR)	Small Business Innovation Research
(SCAPE)	Self-Contained Atmospheric Protective Ensemble
(SCI)	Serial Communication Interfaces
(SEE)	Single Event Effects
(Sees)	Single Events
(SEL)	Single Event Latch-Up
(SEP)	Solar Electric Propulsion
(SEU)	Single Event Upsets
(SFL)	Space Flight Laboratory
(SLS)	Selective Laser Sintering
(SMA)	S-Band Multiple Access
(Smallsat)	Small Satellite
(SME)	Subject Matter Expert
(SMP)	Symmetric Multiprocessing
(SN)	Space Network
(SNSPD)	Superconducting Nanowire Single Photon Detector
(SOC)	Science Operation Center
(Soc)	System On A Chip
(SPENVIS)	Sphere Space Environment Information System
(SPEs)	Solar Particle Events
(SSN)	Space Surveillance Network
(SSO)	Sun Synchronous Orbit
(SSTP)	Small Spacecraft Technology Program
(STELOC)	Stable Tubular Extendable Lock-Out Composite
(STMD)	Space Technology Mission Directorate
(SWaP)	Size, Weight, and Power

(TAFTS)	Two Arm Flexible Thermal Strap
(TDRSS)	Tracking And Data Relay Satellite System
(TID)	Total Ionizing Dose
(TLE)	Two Line Element
(TMA)	Technology Maturity Assessment
(TMR)	Triple Modular Redundancy
(TOGS)	Transportable Optical Ground Station
(TPV)	Thermophotovoltaic
(TRAC)	Triangle Rollable And Collapsible
(TRL)	Technology Readiness Level
(TSU)	Thermal Storage Unit
(TT&C)	Telemetry, Tracking, And Commanding
(ULP)	Ultra-Low Power
(USB)	Universal Serial Bus
(UTJ)	Ultra Triple Junction
(VESPA)	Vega Secondary Payload Adapter
(VUV)	Vacuum Ultraviolet
(WFF)	Wallops Flight Facility
(XTJ)	NeXt Triple Junction

Appendix E. Technology Readiness Levels

<table>
<tr><th>TRL</th><th>Definition</th><th>Hardware Description</th><th>Software Description</th><th>Success criteria</th></tr>
<tr><td rowspan="2">1</td><td>Basic principles observed and reported.</td><td>Scientific knowledge generated underpinning hardware technology concepts/applications.</td><td>Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.</td><td>Peer reviewed documentation of research underlying the proposed concept/application.</td></tr>
<tr><td colspan="4">Examples:
a. Initial Paper published providing representative examples of phenomenon as well as supporting equations for a concept.
b. Conference presentations on concepts and basic observations presented within the scientific community.</td></tr>
<tr><td rowspan="2">2</td><td>Technology concept and/or application formulated.</td><td>Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.</td><td>Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations, and concepts defined. Basic principles coded. Experiments performed with synthetic data.</td><td>Documented description of the application/concept that addresses feasibility and benefit.</td></tr>
<tr><td colspan="4">Examples:
a. Carbon nanotube composites were created for lightweight, high-strength structural materials for space structures.
b. Mini-CO_2 Scrubber: Applies advanced processes to remove carbon dioxide and potentially other undesirable gases from spacecraft cabin air.</td></tr>
</table>

3	Analytical and experimental proof-of-concept of critical function and/or characteristics.	Research and development are initiated, including analytical and laboratory studies to validate predictions regarding the technology.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
	Examples: a. High efficiency Gallium Arsenide solar panels for space application is conceived for use over a wide temperature range. The concept critically relies on improved welding technology for the cell assembly. Samples of solar cell assemblies are manufactured and submitted to a preliminary thermal environment test at ambient pressure for demonstrating the concept viability. b. A fiber optic laser gyroscope is envisioned using optical fibers for the light propagation and Sagnac Effect. The overall concept is modeled including the laser source, the optical fiber loop, and the phase shift measurement. The laser injection in the optical fiber and the detection principles are supported by dedicated experiments. c. In Situ Resource Utilization: Demonstrated the application of a cryofreezer for CO_2 acquisition and microwave processor for water extraction from soils.			
4	Component and/or breadboard validation in a laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality in a laboratory environment.	Key, functionality critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of potentially relevant environment.

<table>
<tr><td></td><td colspan="4">Examples:
a. Fiber optic laser gyroscope: A breadboard model is built including the proposed laser diode, optical fiber and detection system. The angular velocity measurement performance is demonstrated in the laboratory for one axis rotation.
b. Bi-liquid chemical propulsion engine: A breadboard of the engine is built and thrust performance is demonstrated at ambient pressure. Calculations are done to estimate the theoretical performance in the expected environment (e.g., pressure, temperature).
c. A new fuzzy logic approach to avionics is validated in a lab environment by testing the algorithms in a partially computer-based, partially bench-top component (with fiber optic gyros) demonstration in a controls lab using simulated vehicle inputs.
d. Variable Specific Impulse Magnetosphere Rocket (VASIMR): 100 kW magnetoplasma engine operated 10 hours cumulative (up to 3 minutes continuous) in a laboratory vacuum chamber.</td></tr>
<tr><td>5</td><td>Component and/or brassboard validated in a relevant environment.</td><td>A medium-fidelity component and/or brassboard, with realistic support elements, is built and operated for validation in a relevant environment so as to demonstrate overall performance in critical areas.</td><td>End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Implementations.</td><td>Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements. Performance predictions are made for subsequent development phases.</td></tr>
</table>

	Examples: a. A 6.0-meter deployable space telescope comprised of multiple petals is proposed for near infrared astronomy operating at 30K. Optical performance of individual petals in a cold environment is a critical function and is driven by material selection. A series of 1m mirrors (corresponding to a single petal) were fabricated from different materials and tested at 30K to evaluate performance and to select the final material for the telescope. Performance was extrapolated to the full-sized mirror. b. For a launch vehicle, TRL 5 is the level demonstrating the availability of the technology at subscale level (e.g., the fuel management is a critical function for a re-ignitable upper stage). The demonstration of the management of the propellant is achieved on the ground at a subscale level. c. ISS Additive Manufacturing Facility: Characterization tests compare parts and material properties of polymer specimens printed on ISS to copies printed on the ground.

<table>
<tr><td rowspan="2">6</td><td>System/sub-system model or prototype demonstration in a relevant environment.</td><td>A high-fidelity prototype of the system/subsystems that adequately addresses all critical scaling issues is built and tested in a relevant environment to demonstrate performance under critical environmental conditions.</td><td>Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.</td><td>Documented test performance demonstrating agreement with analytical predictions.</td></tr>
<tr><td colspan="4">Examples:
a. A remote sensing camera includes a large 3-meter telescope, a detection assembly, a cooling cabin for the detector cooling, and an electronics control unit. All elements have been demonstrated at TRL 6 except for the mirror assembly and its optical performance in orbit, which is driven by the distance between the primary and secondary mirrors needing to be stable within a fraction of a micrometer. The corresponding critical part includes the two mirrors and their supporting structure. A full-scale prototype consisting of the two mirrors and the supporting structure is built and tested in the relevant environment (e.g., including thermo-elastic distortions and launch vibrations) for demonstrating the required stability can effectively be met with the proposed design.
b. Vacuum Pressure Integrated Suit Test (VPIST): Demonstrated the integrated performance of the Orion suit loop when integrated with human-suited test subjects in a vacuum chamber.</td></tr>
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<table>
<tr><td rowspan="2">7</td><td>System prototype demonstration in an operational environment.</td><td>A high-fidelity prototype or engineering unit that adequately addresses all critical scaling issues is built and functions in the actual operational environment and platform (ground, airborne, or space).</td><td>Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.</td><td>Documented test performance demonstrating agreement with analytical predictions.</td></tr>
<tr><td colspan="4">Examples:
a. Mars Pathfinder Rover flight and operation on Mars as a technology demonstration for future micro-rovers based on that system design.
b. First flight test of a new launch vehicle, which is a performance demonstration in the operational environment. Design changes could follow as a result of the flight test.
c. In-space demonstration missions for technology (e.g., autonomous robotics and deep space atomic clock). Successful flight demonstration could result in use of the technology in a future operational mission
d. Robotic External Leak Locator (RELL): Originally flown as a technology demonstrator, the test article was subsequently put to use to help operators locate the likely spot where ammonia was leaking from the International Space Station (ISS) External Active Thermal Control System Loop B.</td></tr>
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<table>
<tr><td rowspan="2">8</td><td>Actual system completed and “flight qualified” through test and demonstration.</td><td>The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space). If necessary*, life testing has been completed.</td><td>All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation completed.</td><td>Documented test performance verifying analytical predictions.</td></tr>
<tr><td colspan="4">Note:
*“If necessary” refers to the need to life test either for worn out mechanisms, for temperature stability over time, and for performance over time in extreme environments. An evaluation on a case-by-case basis should be made to determine the system/systems that warrant life testing and the tests begun early in the technology development process to enable completion by TRL 8. It is preferable to have the technology life test initiated and completed at the earliest possible stage in development. Some components may require life testing on or after TRL 5.

Examples:
a. The level is reached when the final product is qualified for the operational environment through test and analysis. Examples are when Cassini and Galileo were qualified, but not yet flown.
b. Interim Cryo Propulsion Stage (ICPS): A Delta Cryogenic Second Stage modified to meet Space Launch System requirements for Exploration Mission-1 (EM-1). Qualified and accepted by NASA for flight on EM-1.</td></tr>
</table>

9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All documentation has been completed. Sustaining software support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.
	Examples: a. Flown spacecraft (e.g., Cassini, Hubble Space telescope). b. Technologies flown in an operational environment. c. Nanoracks CubeSat Deployer: Commercially developed and operated small satellite deployer on-board the ISS.			

Note: In cases of conflict between NASA directives concerning TRL definitions, NPR 7123.1 will take precedence.