NASA/TP–2015–216648/REV1

Small Spacecraft Technology State of the Art

Mission Design Division
Ames Research Center, Moffett Field, California

December 2015

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collection of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.
- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, and organizing and publishing research results.

For more information about the NASA STI Program, see the following:

- Access the NASA STI program home page at ***http://www.sti.nasa.gov***
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at 443-757-5803
- Phone the NASA STI Help Desk at 443-757-5802
- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TP–2015–216648/REV1

Small Spacecraft Technology State of the Art

Mission Design Division
Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

December 2015

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
703-605-6000

This report is also available in electronic form at

Abstract

This report provides an overview of the current state of the art of small spacecraft technology. It was first commissioned by NASA's Small Spaceraft Technology Program (SSTP) in mid-2013 in response to the rapid growth in interest in using small spacecraft for many types of missions in Earth orbit and beyond, and revised in mid-2015. For the sake of this assessment, small spacecraft are defined to be spacecraft with a mass less than 180 kg. This report provides a summary of the state of the art for each of the following small spacecraft technology domains: Complete Spacecraft, Power, Propulsion, Guidance Navigation and Control, Structures, Materials and Mechanisms, Thermal Control, Command and Data Handling, Communications, Integration, Launch and Deployment, Ground Data Systems and Operations, and Passive Deorbit Devices. Due to the high market penetration of cubesats, particular emphasis is placed on the state of the art of cubesat-related technology.

Disclaimer

The document lists or describes many specific products and technologies as examples and references but their inclusion does not imply any endorsement by NASA. Failure to include any specific products or technologies that might be considered relevant under a particular topic was unintentional.

Acknowledgements

This report has been based largely on desktop research and published documents on small spacecraft technology, industry consultation and participation at conferences. Helpful suggestions and contributions were also received from numerous people at NASA Ames Research Center, and in particular the authors wish to acknowledge the reviewers James Bell, Josh Benton, Matt D'Ortenzio, Josh Forgione, Vanessa Kuroda, Dawn McIntosh, Marc Murbach, Matt Nehrenz, Hugo Sanchez, Matt Sorgenfrei, Sarah Thompson, Eddie Uribe and Bruce Yost.

From NASA Glenn Research Center the authors would like to thank the reviewers Matt Deans, Fred Elliot, Josh Freeh, David Jacobson, William Marshall, Felix A. Miranda, Tim Smith and Brandon White.

Finally, the authors would like to thank all of the compaines, universities and organizations who provided information for this report.

NASA Ames Research Center, Mission Design Division
September, 2015

Division Chief:
Chad Frost
Project Manager:
Elwood Agasid

Editor:
Rogan Shimmin
Contributing Authors:
Elwood Agasid, Roland Burton, Roberto Carlino, Gregory Defouw, Andres Dono Perez, Arif Göktuğ Karacalıoğlu, Benjamin Klamm, Abraham Rademacher, James Schalkwyck, Rogan Shimmin, Julia Tilles, Sasha Weston

Contents

Preface

At the time the small spacecraft state of the art report was first published in 2013, there had been 247 cubesats and 105 other small spacecraft (non-cubesats under 50 kg) launched, with 92 cubesats launched in 2013 alone. Since that publication, there have been 201 small spacecraft launched, falling 169 short of estimates due to an unfortunate series of launch failures (Buchen, 2015). Due to this almost doubling of flight heritage, it was decided to release a new edition of this report.

A request for information (RFI) was released in the Federal Business Opportunities (FBO) and NASA Acquisition Internet Site (NAIS). While response to these requests was subdued, research continued using journal and conference papers, web resources and a public solicitation at the annual AIAA/USU Conference on Small Satellites in Logan, Utah on 8-13 August 2015.

Each chapter emphasizes new technologies developed since the previous edition of the report was released. A table provides 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 discuss which technologies missions have been using and why they are used in preference to older technologies.

A central element of the report is to list state of the art technologies by technology readiness level (TRL). The authors have endeavored to independently verify TRL by citing published test results. Where these test results disagree with vendors' own advertised TRL, the authors have engaged the vendors to discuss the discrepancy. It is important to note that this report takes a broader 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.

In some cases multiple companies are developing similar products. In these cases only companies with the leading TRL will be identified in the tables. The TRL will be based purely on the technology fulfilling the TRL definitions, regardless of specific mission requirements. For example, a very important design factor for solar electric propulsion is the duration of operation, and the applicability of passive deorbit devices can vary drastically at different altitudes. For the purposes of this document, simply having functioned in the relevant environment is sufficient to achieve TRL. Furthermore, if a technology has flown on a mission without working, or without providing valid confirmation to the operator, that "flight heritage" will be discounted.

The report structure is consistent with the previous edition, with a few notable exceptions. As small spacecraft have matured since the previous edition of this report, they are now being seriously considered for deep space missions. This has led to intense scrutiny over the radiation protection in small satellites, especially given the low-cost, often commercial off-the-shelf (COTS) paradigm they occupy. Consequently this report has included radiation chamber test data where available for the subsystems susceptible to high energy particles.

Additional chapters were considered for the report. Due to time and available resources, the only addition was passive deorbit devices, but it is important that future editions of this report include the rapidly growing fields of flight software, assembly integration & testing services, and mission modeling & simulation, all of which are now extensively represented at small spacecraft conferences. It is acknowledged that these fields are still in their infancy, but just as the included subsystems have evolved and reliable conventions and standards have emerged since the first edition, the same is expected over the coming years for these new chapters.

During our consultation it was also pointed out that for all the components available, no engineering project is successful without solid engineering management. Given the high percentage of universities now attempting to design, build and launch cubesats, this is an important consideration. A future edition of this report will hopefully include a chapter on best practices and state of the art management.

References

Buchen, E. (2015). Spaceworks small satellite report: Trends and market observations. In *Proceedings of the AIAA/USU Conference on Small Satellites.* Logan, Utah.

Executive Summary

Integrated Spacecraft Platforms

Since the last edition of this report, some vendors have compiled the subsystems represented in the later chapters into complete, integrated spacecraft platforms, available off-the-shelf for rapid integration and delivery. Thus the state of the art performance is commensurate with the subsystem performance listed below. A variety of small spacecraft buses are available from Millenium Space Systems, and Spaceflight Industries in the USA, and Astro- und Feinwerktechnik Adlershof, Berlin Space Technologies GmbH and Surrey Satellite Technology Ltd in Europe. Complete cubesat buses are available from Tyvak Nanosatellite Systems Inc., Blue Canyon Technologies LLC and Pumpkin Inc in the USA, and GomSpace ApS in Europe. There are many other vendors providing engineering services to design a turnkey small spacecraft platform customized to mission requirements.

Power

Each year small spacecraft power subsystems benefit from improvements in solar cell efficiency, battery chemistry, and the trend of miniaturization in the electronics technology. State of the artsolar cells are reaching between 29-33% efficiency and advanced lithium-ion and lithium polymer batteries can have specific energy reaching 250 Whkg^{-1}. Power management and distribution systems are still often designed in house but there are increasing numbers of lightweight, robust, commercially available PMAD systems from a variety of producers. Consumer electronics trends and improvements in solar technology driven by a new focus on terrestrial renewable energy are largely to thank for these advances as the small spacecraft industry market is still too small to drive large-scale R&D.

There are many promising photovoltaic technologies currently in development that will increase the efficiency and/or reduce the cost and weight of solar cells. These include 46% four-junction cells, lightweight flexible solar cells at 20% efficiency, and cells that make use of cheap organic electronics. While there continue to be advances in the thermo-nuclear and fuel cell power-generation areas, more development needs to be done (largely in miniaturization) before some of these promising technologies become available for use on small spacecraft.

Propulsion

Propulsion systems for small spacecraft have consistently increased their maturity and robustness with respect to the previous report. A significant effort in the design, development and testing of miniaturized thrusters have been performed by several institutions. Versions of larger spacecraft systems have been adapted so satisfy the power, mass and volume constraints that are required in small buses. Fundamental components such as regulators, valves, feed systems or tanks have been also re-designed and, currently, several systems have high TRLs. Regarding chemical propulsion systems, low complexity technologies such as cold gas systems have already started to be flown in small spacecraft and even cubesats. Other options such as non-toxic propellant systems or solid motors have been incorporated into existing $50 - 150$ kg class spacecraft or are ready to be flown in the next year. Electric propulsion systems have been evolved by a series of continuous testing campaigns for a wide range of technologies. Electrosprays, Hall-Effect Thrusters, Pulsed Plasma Thrusters and ion engines are now nearly ready to become fully integrated subsystems in small spacecraft missions in the next few years. In regards to solar sails, recent successful demonstrations and tests have indicated a path towards the utilization of this propellant-less technology for both LEO and interplanetary missions.

Guidance, Navigation and Control

The current state of the art for small spacecraft guidance, navigation and control performance is 1.5 m onboard orbital position accuracy (using GPS) and pointing to better than $0.1°$ using reaction wheels, MEMS gyros and a star tracker. Component technology for Earth orbiting missions is mature and all key GNC components are available at TRL 9 from a variety of vendors. Components for deep space small spacecraft missions are relatively immature but are expected to reach high TRL within the next two to three years. Innovation in GNC is focused on miniaturization of existing technology and the development of single vendor integrated attitude determination and control units.

Structures, Materials and Mechanisms

The state of the art for primary structures used for small spacecraft, larger than 12U, continues to be custom in-house designs, or for tailored solutions, offered by the industry, to meet specific mission requirements. There have been recent attempts to establish a standard extensible bus in this class of spacecraft, and with it a standard chassis. However, the benefits of this effort have yet to be realized. In the smaller than 12U class of spacecraft, there has been several unique solutions offered by a growing industry for off-the-shelf spacecraft structures and structural components. These off-the-shelf components complement the standard approach of custom designed frames (typically fabricated using milled aluminum) enabling a larger set of solutions for spacecraft designers. Most of the recent additions to the off-the-shelf market have been in the 3U class of cubesats. However, there are now at least a few relatively mature (TRL 6-7) off-the-shelf 6U chassis being offered. This is a class of spacecraft that has just now begun to show signs of rapid acceleration in adoption for flight missions. There are even 12U solutions being provided by many of these vendors (a sign of the industry's desire to be ready for the next thing). 3D printed primary structures remain on the horizon. But with several flight missions, soon to be launched using these materials, the horizon on this technology for primary structures appears to be closer than ever.

Thermal Control

Thermal control management regulates the functional temperature range required throughout all spacecraft components. As small spacecraft design matures, the techniques that control the defined thermal environment must be able to meet these smaller volume and power constraints. Traditional spacecraft thermal management may need additional testing and fabrication for small spacecraft application.

While insulation (MLI) and surface coating (paint/tape) can still be applied to small spacecraft, technologies such as passive louvers, non metallic thermal straps, sunshades and cryocoolers are being designed for smaller platforms. This increase in spacecraft thermal management ability will facilitate the expansion of small spacecraft design. Several thermal control mechanisms are currently being proposed, tested and fabricated for small spacecraft application: thermal storage units for energy storage; stowed and deployable passive radiators; and miniaturized circulator pumps requiring minimal power input.

Command and Data Handling

Avionics solutions for small spacecraft and in particular, cubesats, are abundant. Ongoing advances in the embedded systems industry have provided highly capable platforms and components that allow for rapid and low cost development of command and data handling (C&DH) systems. Embedded systems have paved the way for the development of highly integrated, low mass and low power processing and control systems. Many of the commercial off-the-shelf (COTS) hardware have successfully flown in the LEO environment over short mission durations. A number of commercial vendors are providing complete integrated avionics system on a PC/104 board or boards, incorporating computer processor, memory, I/O and EPS. A number of vendors source systems and components from a variety of manufacturers, which allow spacecraft developers to pick and choose components that will meet their design requirements. There are open source solutions available to those who are interested in investigating an entry-level means of developing spacecraft avionics.

As the cubesat class of small spacecraft evolve into deep space and extended duration missions, there will be a need to address the impact of the space radiation environment. It will be necessary to develop radiation tolerant system designs to ensure mission reliability and success. Radiation hardened (rad-hard) hardware is available for a majority of the electronic components used in C&DH systems. However rad-hard devices can be significantly more costly when compared to standard COTS components. Developers will undoubtedly utilize a combination of rad-hard components, COTS devices, shielding and mitigation techniques such as watchdog timers and memory scrubbing to reduce radiation environment impacts and improve system reliability in an effort to keep development costs as low as possible.

Communications

Communication systems for cubesats have largely utilized the VHF and UHF bands (primarily using whip antennas), or L- and S-bands (primarily using patch antennas), which have been adequate for lower-data-rate missions operating in LEO. Cubesat missions have also taken advantage of Iridium and Globalstar transponders to relay data to Earth via commercial constellations, and off-the-shelf radios such as Bluetooth- and ZigBee-compatible radios also show promise for cubesat missions.

X-band through Ka-band communication is gaining more traction as cubesat missions become more sophisticated and require higher data throughput, with missions being planned beyond LEO. The higher frequencies offer more bandwidth and are less crowded, and the corresponding antennas can offer similar gain but with a smaller aperture. The drawback, however, is that the higher frequencies are more heavily attenuated by Earth's atmosphere, requiring either more power to drive the signal or a higher number of ground stations. The development of cubesat-compatible deployable dish antennas and other higher-gain antennas are also adding to the solution.

The advent of software-defined radio (SDR) has not totally replaced hardware-defined radio. Though an SDR can operate at various frequencies and various modulation schemes with a simple change in software and generally has a smaller footprint than hardware-defined radio, it generally consumes more power, which is a large drawback on power-constrained cubesats. However, a counter to this drawback is that a single SDR unit can function as multiple radios at multiple wavelengths, and it can be reprogrammed in-flight.

Laser communication (lasercom) for cubesats is a TRL-8 technology that will most-likely be demonstrated in space by 2016. While lasers onboard cubesats have a relatively high TRL status, asymmetric laser communication is a lower TRL concept whereby the laser is hosted by a ground station, and the laser signal is modulated and passively reflected (onboard the cubesat) back to Earth. The development of X-band and Ka-band transmitters, arrayed and deployable high-gain antennas and lasercom systems represent the new frontier of cubesat communication systems.

Integration, Launch and Deployment

More and more small spacecraft are launched every year. Technologies in launch vehicles, integration, and deployment systems are responding to the changing small spacecraft market. The traditional ride-share method where the small spacecraft hitches a ride in the leftover mass, volume, and other performance margins is still the primary way of putting small spacecraft into orbit. But the new technological advancements show that the popularity of classical ride-sharing might slowly decrease in the upcoming years. Dedicated ride-sharing, where an integrator books a complete launch mission and sells the available capacity to multiple spacecraft operators without the need of a primary customer, is becoming more popular in the sector. Using an orbital maneuvering system which acts as an inter-stage on a launch vehicle and then propels itself after separation is another new approach. Furthermore, ISS cargo vehicles are gaining additional capabilities to deliver secondary payloads to orbits higher then ISS altitude once their primary mission is complete. Beside any ride-share approach, more than twenty orbital launch vehicles are under development to carry payloads ranging from 5 kg to 500 kg to orbit. Some of these new systems propose to launch orbital payloads from airborne vehicles, suborbital systems, or even high altitude balloons. A wide variety of integration services and deployment systems are also under development to keep up with the increasing launch and deployment demand of small spacecraft.

Ground Data Systems and Mission Operations

Transmitting telemetry and scientific data back to Earth in the specified quality and quantity, and tracking and commanding the spacecraft to take certain actions depend on reliable telecommunications with ground stations. Although in the past amateur ground stations have been essential for cubesat missions, currently, small spacecraft and ground systems are rapidly shifting to non-amateur communications, as power systems become more effective, attitude control systems more accurate and a higher data rate is needed for science or new technology missions. In the scenario of small spacecraft missions, many companies are developing new state of the art systems for ground stations. Some of them focus more on single products (such as antennas, transceiver, simulation software) that are the cutting edge technology yet to be validated in space missions, others consolidate and extend their services with turnkey solutions, which add more capability and availability to their already developed ground systems. Alternatives to common ground systems are inter-satellite communications, which relay data to the ground through constellations of satellites (such as Iridium or Globalstar). Still, there are a lot of new promising areas and technologies that ground data systems can explore and develop for future Small Spacecraft missions.

Passive Deorbit Systems

The requirement for deorbit capability is implemented to constrain the amount of generated space debris orbiting Earth. If a small spacecraft is unable to be parked in a graveyard orbit or naturally reenter Earth's atmosphere in under 25 year, a deorbit system must be integrated. In the past decade, there have only been a few advancements on passive deorbit technologies, such as drag sails and electromagnetic tethers. NanoSail-D2, DeorbitSail and CanX-7 are all cubesat platforms that have successfully demonstrated the utilization of drag sails for deorbiting in Low Earth Orbit within the 25 year post mission requirement. Terminator Tape is another deorbit option that uses electromagnetic tethers that is currently being flown on Aerocube-V cubesat.

1 Introduction

1.1 Objective

The objective of this report is to assess and give an overview of the state of the art in small spacecraft technology. It was first commissioned by NASA's Small Spacecraft Technology Program (SSTP) in mid-2013 in response to the rapid growth in interest in using small spacecraft for missions beyond LEO, and revised in mid-2015. In addition to reporting on what is currently available, a prognosis is provided describing technologies on the horizon.

Information in this report has been collected primarily through desk research and is not intended to be exhaustive - no such assessment can be comprehensive. New technology is developed continuously, and emerging technologies will mature to become the state of the art. The authors intend to regularly update this report, and current technologies that were inadvertently missed will be identified and included in the next version. The valuable input of readers is solicited at arc-smallsats@mail.nasa.gov - please include "state of the art report" in the subject line.

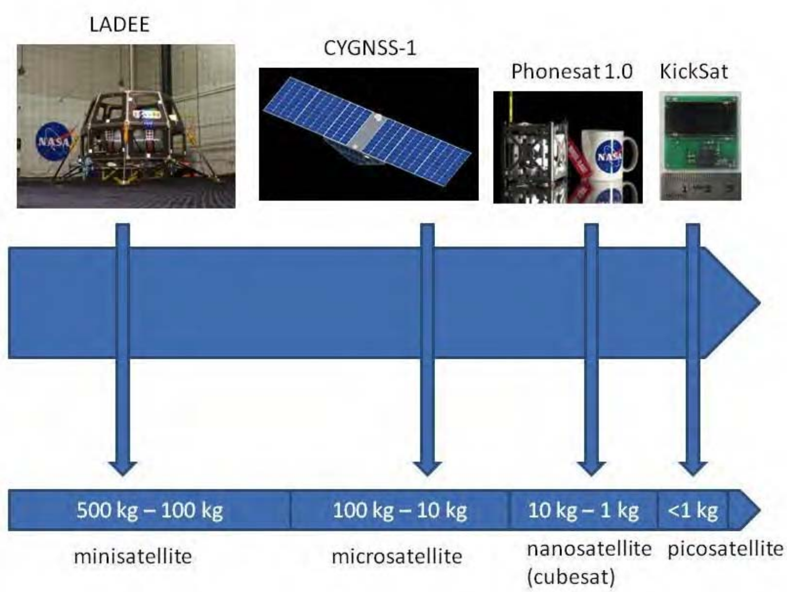
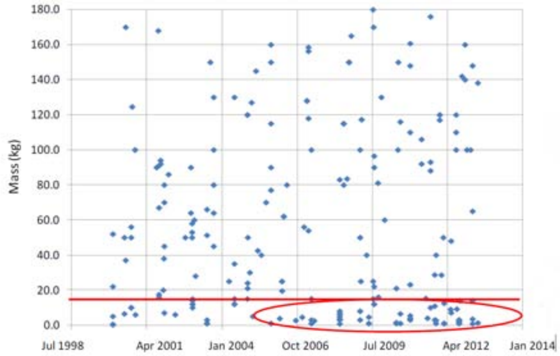


Figure 1.1. Overview of the variety of spacecraft that fall into the small spacecraft category.

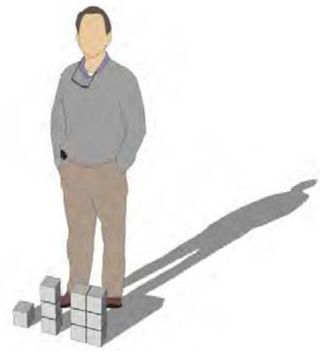
1.2 Scope

A spacecraft is hereafter called a "small spacecraft" when its wet mass is below 180 kg. This definition adopts the terminology set out by NASA's Small Spacecraft Technology Program (SSTP) (National Aeronautics and Space Administration, 2015a). Figure 1.1 gives an example of the variety of spacecraft that fall into the small spacecraft category.

At the upper mass limit there are minisatellites like FASTSAT (Fast, Affordable, Science and Technology Satellite), NASA's first minisatellite mission launched in 2010 with a mass slightly below 180 kg. On the lower mass end, there are projects such as KickSat, which aimed to deploy picosatellites the size of a large postage stamp and with a mass below 10 grams. Spacecraft are



(a) Launch dates vs mass of the small spacecraft studied in this report.



(b) Cubesats with form factors of 1U, 3U, and 6U, respectively. The volume of the 1U base unit is $100 \times 100 \times 100$ mm.

Figure 1.2. Cubesats

generally grouped according to their mass, where small spacecraft include minisatellites with a mass of 100-500 kg, microsatellites with a mass of 10-100 kg, nanosatellites with a mass of 1-10 kg, and picosatellites with a mass below 1 kg.

Cubesats are a standard for small spacecraft that weigh only a few kilograms and are based on a form factor of a $100 \times 100 \times 100$ mm cube. Cubesats can be composed of a single cube (a "1U" cubesat) or several cubes combined forming, for instance, 3U or 6U units (see Figure 1.2). Due to their high market penetration and their increased usage in recent times, particular emphasis is put on the state of the art of cubesat technology in this report (see also Figure 1.2). The technology tables shown in subsequent sections are not meant to be comprehensive. Their goal is to illustrate the current state of the art based on desk research in a limited amount of time.

1.3 Assessment

The state of the art assessment of a technology is performed using NASA's TRL scale (see Figure 1.3). A technology is deemed state of the art whenever its TRL is larger than or equal to 6. A TRL of 6 indicates that the model or prototype is near the desired configuration in terms of performance, weight, and volume, and has been tested and demonstrated in a relevant environment. A relevant environment is either a high fidelity laboratory environment or a simulated operational environment (National Aeronautics and Space Administration, 2015b). A technology is considered not state of the art whenever its TRL is lower than or equal to 5. In this category, the technology is considered to be "on the horizon". This definition of "state of the art" has been chosen because of its inherent simplicity. Clearly, old and possibly obsolete technology has a TRL larger than 6 but cannot be considered as state of the art. The bias in the definition has been recognized and care has been taken in the report to exclude obsolete technology from the study.

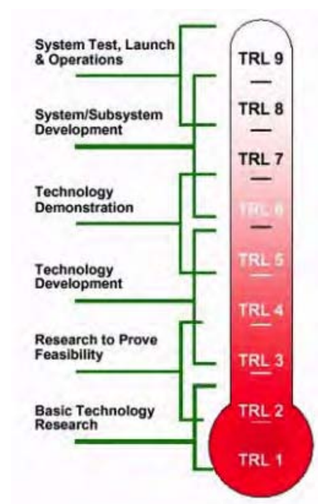


Figure 1.3. NASA Technology Readiness Levels (TRLs) (National Aeronautics and Space Administration, 2015b).

1.4 Overview

This report is structured as follows: in section 2 the state of the art of small spacecraft technology is addressed by focusing on the spacecraft system as a whole. The current best practices of integration are presented. Then, in section 3 to section 11, the state of the art of the spacecraft subsystems are presented in turn:

- Power
- Propulsion
- Guidance, Navigation and Control (GN&C)
- Structures, Materials and Mechanisms
- Thermal Systems
- Command and Data Handling (C&DH)
- Communications
- Integration, Launch and Deployment
- Ground Data System and Operations
- Passive Deorbit Devices

Conclusions on the overall state of the art of small spacecraft are presented in section 13.

References

National Aeronautics and Space Administration. (2015a). *NASA's Small Satellite Missions.* `http://www.nasa.gov/mission_pages/smallsats/`. (Accessed: 2015-10-28)

National Aeronautics and Space Administration. (2015b). *Technology Readiness Level.* `http://www.nasa.gov/content/technology-readiness-level`. (Accessed: 2015-10-28)

2 Integrated Spacecraft Platforms

2.1 Introduction

As the market for small spacecraft and cubesats has expanded since the last edition of this report, a niche has emerged for off-the-shelf assembled spacecraft buses. These buses provide integrated platforms upon which a payload can be hosted and ready to fly in a very short amount of time. As the platform may be purchased for any of a wide variety of missions, the subsystems are sized to be as diverse and capable as possible.

Two trends have emerged in the cubesat bus market: cubesat component developers with a sufficiently diverse portfolio of subsystems offering package deals, or companies traditionally offering engineering services for larger bespoke platforms miniaturizing their subsystems.

2.2 State of the Art

Small spacecraft Millenium Space Systems has been developing the Altair small spacecraft platform under contract from DARPA (Millenium Space Systems, Inc., 2015c). The Altair is a smaller version of their Aquila series (up to 3000 kg) which has extensive flight heritage. So far the Altair has undergone balloon testing (Millenium Space Systems, Inc., 2015a), thermal vacuum and vibration testing (Millenium Space Systems, Inc., 2015b). The first launch is scheduled for 2016 on the F-15 Airborne Launch Assist Space Access (ALASA), also sponsored by DARPA.

Astro- und Feinwerktechnik Adlershof offers the TET-1 platform, which flew on a Soyuz-FG/Fregat launch in 2012 as a secondary payload. TET-1 is larger than Altair, at $670 \times 580 \times 880$ mm but offers the same 50 kg payload mass. The TET-1 attitude control system, reused from the BIRD (Bispectral and Infrared Remote Detection) DLR mission in 2001, provides 2 arcmin pointing and 10 arcsec knowledge (Astro- und Feinwerktechnik Adlershof GmbH, 2015).

Berlin Space Technologies produces a series of small spacecraft named the LEOS-30 TRLX, LEOS-50 TRLX, and LEOS-100. The LEOS platforms are based on designs flown for multiple TUBSAT and LAPAN missions (European Space Agency, 2015a, 2015b). Two LEOS-50 platforms will be delivered later this year as the Kent Ridge mission while a LEOS-100 will be delivered in mid-2016 (Buhl, Danziger, & Segert, 2015; Segert, 2015).

The LEOS-30 is a 20 kg spacecraft, allowing 5-8 kg payload capacity. UHF and S-band communications are provided, and the system is designed for a 2 year operational life.

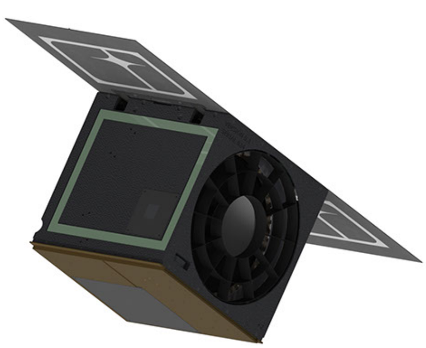


Figure 2.1. The Altair bus. Image courtesy of Millenium Space Systems, Inc. (2015c).

Figure 2.2. The TET-1 bus. Image courtesy of Astro- und Feinwerktechnik Adlershof GmbH (2015).

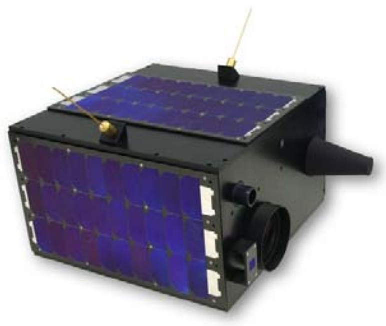


Figure 2.3. The LEOS 50 bus. Image courtesy of Berlin Space Technologies GmbH (2015).

Figure 2.4. The SSTL-150 bus. Image courtesy of Surrey Satellite Technology Ltd. (2015).

The LEOS-50 is a 50 kg spacecraft, allowing 15-25 kg payload capacity. UHF communications are provided for telemetry and control, while a 100 Mbps X-band link is available for data downlink. The ADCS provides 1 arcmin pointing accuracy and 10 arcsec pointing knowledge with a 10°/s slew rate and less than 15 arcsec/s jitter. The vehicle is $600 \times 600 \times 300$ mm, provides an average of 20 W payload power within a payload volume of $400 \times 400 \times 200$ mm and is designed for an operational lifetime of 5 years.

The LEOS-100 is a larger structure reusing the LEOS-50 avionics. Due to the larger mass it provides 1 arcmin pointing accuracy and 2.5 arcsec pointing knowledge with a 5°/s slew rate and less than 5 arcsec/s jitter. The vehicle is $600 \times 600 \times 800$ mm with a mass of 65 kg, and the payload volume is $500 \times 500 \times 500$ mm with an allowance of 30-50 kg. The larger vehicle generates more solar power and can provide 60 W average power to the payload, while the X-band communications have also been upgraded to 400 Mbps. The LEOS-100 also has options for 2 Gbps optical data downlink and cold gas or electrical propulsion.

Surrey Satellite Technology Limited (SSTL) has a long legacy of small spacecraft in orbit. There are 8 of the SSTL-100 in orbit, 10 of the SSTL-150, and a version modified to fit the ESPA ring called the SSTL-150 ESPA. A down-specced variant on the SSTL-150 called SSTL-X50 is in final testing for a forthcoming launch.

Table 2.1. Integrated small spacecraft platforms

Product	Manufacturer	Status	Radiation testing
Altair	Millenium Space Systems	TRL 8	LEO parts heritage
TET-1	Astro- und Feinwerktechnik	TRL 9	13 krad
LEOS 30/50/100	Berlin Space Technologies GmbH	TRL 8	LEO parts heritage
SCOUT	Spaceflight Industries	TRL 8	15 krad
SSTL-100/150/X	Surrey Satellite Technology Limited	TRL 9	5 krad

Table 2.2. Integrated small spacecraft platform specifications

Product	Vehicle size	Payload mass	Payload power	Pointing control	Pointing knowledge
MSS Altair	300 × 300 × 300 mm	50 kg	90 W	0.3 arcmin	10 arcsec
AF Adlershof TET-1	670 × 580 × 880 mm	50 kg		2 arcmin	10 arcsec
BST LEOS-30		20 kg			
BST LEOS-50	600 × 600 × 300 mm	50 kg	20 W	1 arcmin	10 arcsec
BST LEOS-100	600 × 600 × 800 mm	65 kg	60 W	1 arcmin	2.5 arcsec
SSTL-100		20 kg			
SSTL-150	600 × 600 × 300 mm	50 kg	20 W	1 arcmin	10 arcsec
SSTL-150 ESPA	600 × 600 × 800 mm	65 kg	60 W	1 arcmin	2.5 arcsec
SSTL-X50	600 × 600 × 800 mm	75 kg	60 W	1 arcmin	2.5 arcsec
SLI SCOUT	400 × 460 × 840 mm	55 kg	95 W	3 arcmin	18 arcsec

Cubesats Tyvak NanoSatellite Technology Inc. is replacing their Intrepid platform with the new Endeavour platform, available in a variety of form factors from 3U to 12U. Two 3U Endeavour spacecraft are scheduled to fly in 2016 as NASA's Cubesat Proximity Operations Demonstration (CPOD) (Tyvak NanoSatellite Systems Inc., 2015a, 2015b). The 3U variant weighs 5.99 kg with payload, allows 2U payload volume, and offers 15 W payload average power. The ADCS provides 0.06° pointing control and 25 arcsec pointing knowledge, 3° per second slew rate using reaction wheels and torque coils. Endeavour generates up to 70 W power, and provides S-band communications of 10 Mbps in addition to the UHF offering. Endeavour has been radiation tested for over 24 months mission lifetime (10 krad) in collaboration with Vanderbilt University (Puig-Suari, 2015; Tyvak NanoSatellite Systems Inc., 2012). The solar panels and radio flew on JPL's IPEX mission in 2013, and the radio flew again on CalPoly's Exocube mission in 2015.

GomSpace ApS of Denmark produces a series of cubesats under the moniker GOMX. The avionics provide 5° pointing knowledge and 10° pointing control. There are 1U, 2U and 3U variants available, directly affecting the payload volume and mass. The variation in surface area affects available power from the solar panels. All these systems include a UHF/VHF radio link. The GOMX-1 mission flown by Aalborg University launched a 2U configuration on a Dnepr in 2013, hosting an ADSB receiver. The GOMX-2 reflight was destroyed in the CRS-3 launch. GOMX-3 has delivered a 3U configuration to the space station via a Japanese H-IIB rocket in August 2015, but has not been deployed from the station yet (GomSpace ApS, 2015). A 1U variant with an integrated 3 MP optical imaging payload is available off the shelf under the name NanoEye. Two of these units have been delivered for flight but have not undergone radiation testing.

Blue Canyon Technologies LLC has pursued a smaller, modular form factor. The $\frac{1}{2}$U XB1 module can be stacked into larger cubesat form factors. Supporting configurations up to 27U, the XB1 centers around two XACT modules with additional power, thermal management, payload and

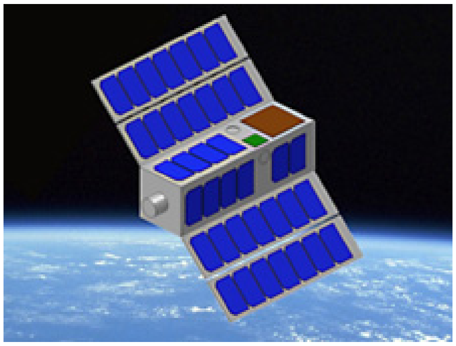


Figure 2.5. The Endeavour bus as used in the CPOD mission. Image courtesy of Tyvak NanoSatellite Systems Inc. (2015a).

Figure 2.6. The GOMX bus from GomSpace. Image courtesy of GomSpace ApS (2015).

Table 2.3. GomSpace GOMX configurations.

Size	Mass (before payload)	Available volume	Available payload power
1U	725 g	0.4U	1.3 W average
2U	1200 g	1.4U	2.48 W average
3U	1500 g	2.3U	3.68 W average

propulsion interfaces supported with BCT flight software. The two XACT units deliver a pointing accuracy of 0.002°, a pointing stability of 1 arcsec/sec, and a slew rate of 10 deg/sec for a typical 3U cubesat. The XB1 Avionics has been through a full qualification test program and a 3U version is flying in 2016 as part of APL's RAVAN mission. A 6U version is flying in late 2016 as part of the PlanetIQ GPSRO Constellation, and the XB1 avionics will fly on the NASA Goddard CERES mission also in 2016 (Stafford, 2015).

Surrey Satellite Technology Ltd. from the UK is focusing on their larger form factors (50+ kg) (Eisele, 2015), but they also offer two cubesat platforms. The Cube-X and Nano-X platforms are available in 3U, 6U, 12U and 24U, resulting in a total launch mass of 5 to 20 kg.

Some manufacturers such as Pumpkin Inc. offer a package deal of components. For example, the

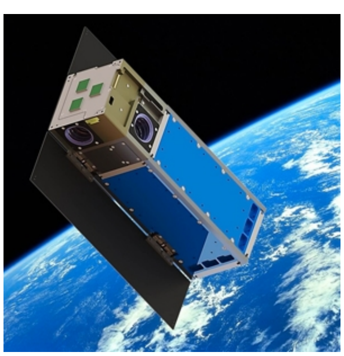


Figure 2.7. The XB1 bus. Image courtesy of Blue Canyon Technologies (2015).

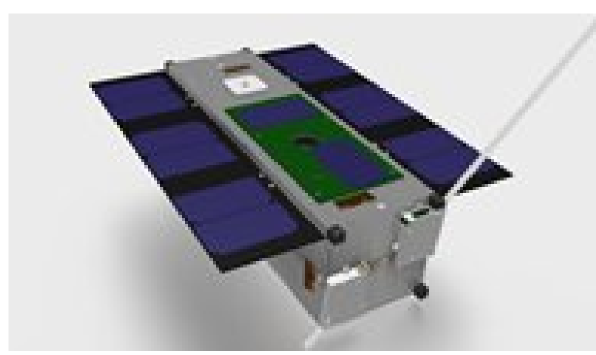


Figure 2.8. The Nano-X bus as used in the STRaND-1 mission. Image courtesy of Surrey Satellite Technology Ltd. (2015).

Figure 2.9. The Complete Cubesat bus. Image courtesy of Innovative Solutions In Space B.V. (2015).

Figure 2.10. The Nukak bus. Image courtesy of Sequoia Space (2015).

Table 2.4. Integrated cubesat platforms

Product	Manufacturer	Status	Radiation testing
Endeavour	Tyvak Nano-Satellite Systems Inc	TRL 8	10 krad
GOMX	GomSpace ApS	TRL 9	10 krad
XB1	Blue Canyon Technologies LLC	TRL 8	
Complete CubeSat Kits	Pumpkin Inc	N/A (no single configuration)	LEO parts heritage
Nukak	Sequoia Space	Unknown	Unknown

MISC 2 Mk II provides a 3U structure allowing $100 \times 100 \times 165$ mm payload volume, with pointing provided by the MAI-100 ADACS from Maryland Aerospace Inc. The MISC 3 also provides a 3U structure allowing $100 \times 100 \times 175$ mm payload volume, with the option of pointing from a MAI-400 ADACS from Maryland Aerospace Inc. or a BCT XACT ADCS from BlueCanyon Technologies (Pumpkin, Inc., 2015).

Other large-scale producers such as Clyde Space from Scotland (Clyde Space Ltd., 2015) and ISIS from the Netherlands (Innovative Solutions In Space B.V., 2015) offer tailored solutions. The individual componentry they offer has flight heritage, but will be addressed individually in the subsequent chapters of this report. As they offer no standard packages they are not discussed further in this chapter.

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. The larger vendors will gain more flight heritage and tweak their platforms to improve performance, while smaller vendors will emerge into the market. For example, SSTL has two new offerings in development called the Next Generation Microsatellite and the FeatherCraft, both still at TRL 3 (Surrey Satellite Technology Ltd., 2015). The Next Generation Microsatellite provides a lower price point compared to the existing platforms, while the FeatherCraft features significantly increased propulsion capability with a Δv of 150 m/s.

One key development likely as the industry matures is 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, but the combination of subsystem mean time between failures (MTBF) into overall system reliability will become a key design criterion as the sample groups become large enough to be statistically significant.

2.4 Conclusion

In the paradigm of larger GEO buses, a number of vendors have pre-designed, fully integrated small spacecraft buses available for purchase. Due to the small market they will of course cooperate with customers to customize the platform. This paradigm is continued in the cubesat form factor, but a new design concept also emerges: due to the cubesat standard interfaces, many standardized components are available, leveraging consumer electronics standards to approach the plug and play philosophy available for terrestrial PCs and computer servers. In particular, since the previous edition of this report cubesat communications and guidance, navigation and control subsystems have matured significantly. At present software is lagging behind hardware in modularity and reusability, and represents the largest hurdle to delivering cubesat missions.

References

Astro- und Feinwerktechnik Adlershof GmbH. (2015). *TET-1 Satellite Bus.* `http://www.astrofein.com/2728/dwnld/admin/33_Prospekt_TET-1.pdf`. (Accessed: 2015-09-14)

Berlin Space Technologies GmbH. (2015). `http://www.berlin-space-tech.com/index.php_id=33.html`. (Accessed: 2015-07-30)

Blue Canyon Technologies. (2015). `http://bluecanyontech.com/space-missions/#spacebuses`. (Accessed: 2015-07-30)

Buhl, M., Danziger, B., & Segert, T. (2015). *Small Satellites Made in Berlin* (Tech. Rep.). Berlin, Germany: Berlin Space Technologies GmbH.

Clyde Space Ltd. (2015). `http://www.clyde-space.com/cubesat_shop`. (Accessed: 2015-07-30)

Eisele, S. (2015). *Personal correspondence.* (2 September 2015)

European Space Agency. (2015a). *LAPAN-A2 - eoPortal Directory - Satellite Missions.* `https://directory.eoportal.org/web/eoportal/satellite-missions/l/lapan-a2`. (Accessed: 2015-10-05)

European Space Agency. (2015b). *TUBSAT - eoPortal Directory - Satellite Missions.* `https://directory.eoportal.org/web/eoportal/satellite-missions/t/tubsat`. (Accessed: 2015-10-05)

GomSpace ApS. (2015). `http://gomspace.com/index.php?p=products-platforms`. (Accessed: 2015-07-30)

Innovative Solutions In Space B.V. (2015). `http://www.cubesatshop.com/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=38&category_id=9&option=com_virtuemart&Itemid=71`. (Accessed: 2015-07-30)

Millenium Space Systems, Inc. (2015a). http://digitalcommons.usu.edu/smallsat/2014/AdvTechI/2/. (Accessed: 2015-09-14)

Millenium Space Systems, Inc. (2015b). http://www.millennium-space.com/platforms.html#altair. (Accessed: 2015-07-30)

Millenium Space Systems, Inc. (2015c). http://www.millennium-space.com/pressreleases/ALTAIR01-20150805.pdf. (Accessed: 2015-09-14)

Puig-Suari, J. (2015). *Tyvak Nanosatellite Systems Response to NASA RFI: NNA15ZRD001L* (Tech. Rep.). Irvine, California: Tyvak NanoSatellite Systems Inc.

Pumpkin, Inc. (2015). http://www.cubesatkit.com/. (Accessed: 2015-07-30)

Segert, T. (2015). *Personal correspondence.* (1 September 2015)

Sequoia Space. (2015). http://www.sequoiaspace.com/en/satellite-missions/. (Accessed: 2015-07-30)

Stafford, G. (2015). *Personal correspondence.* (5 August 2015)

Surrey Satellite Technology Ltd. (2015). http://www.sstl.co.uk/Products/EO---Science-Platforms. (Accessed: 2015-07-30)

Tyvak NanoSatellite Systems Inc. (2012). *Endeavour: The product suite for next generation cubesat mission.* http://mstl.atl.calpoly.edu/~bklofas/Presentations/SummerWorkshop2012/MacGillivray_Endevour.pdf. (Accessed: 2015-09-14)

Tyvak NanoSatellite Systems Inc. (2015a). *CubeSat Proximity Operations Demonstration (CPOD) Overview.* http://www.nasa.gov/sites/default/files/files/A_Williams-A_Tsuda-CPOD_Overview.pdf. (Accessed: 2015-09-14)

Tyvak NanoSatellite Systems Inc. (2015b). http://tyvak.com/endeavour/. (Accessed: 2015-07-30)

3 Power

3.1 Introduction

The electrical power system (EPS) manages electrical power generation, storage and management and commonly makes up one-third of total spacecraft mass. Power generation technologies include photovoltaic cells, solar panels and arrays, and radioisotope or other thermonuclear power generators. Power storage takes place in batteries, which can either be primary batteries charged once before launch, or rechargeable secondary batteries. Power management and distribution (PMAD) systems allow operators to control the flow of power to the spacecraft instruments and subsystems. PMAD systems take a variety of forms and are often custom designed to meet specific mission requirements. Engineers often focus on power generation and storage technologies that have a high specific power or power-to-mass ratio ($\mathrm{W\,h\,kg^{-1}}$) to ensure launch mass is minimized.

3.2 State of the art

3.2.1 Power Generation

Solar Cells The majority of small spacecraft missions exploit the photoelectric effect to generate electrical current during their mission. Photovoltaic cells, or solar cells, are made out of thin wafers of semiconductors that produce electric current when exposed to light. Solar intensity varies as the inverse square of the distance from the Sun and the projected surface area of the panels exposed to the Sun varies as a cosine of the angle between the panel and the Sun. Most cells manufactured today for terrestrial applications are single junction cells, using a single material that is responsive to a particular portion of solar radiation spectrum, where the photon's energy is higher than the band gap of the cell material. While single junction cells are cheap to manufacture, they are associated with a relatively low efficiency, usually less than 20%. To increase the efficiency of solar cells, multiple layers of materials with different band gaps are combined in multi-junction cells, which can use a wider spectrum of solar radiation. The theoretical efficiency limit for an infinite-junction cell is 86.6% in concentrated sunlight (Green, 2003, p. 65). However, in the aerospace industry, triple junction cells are commonly used due to their high efficiency-to-cost ratio compared to other cells. While solar cells are utilized on most small spacecraft missions, limitations include diminished efficacy as a function of distance from the Sun, inability to function during eclipse periods, high surface area and mass, degradation over time and high cost. Figure 3.1 illustrates the available technologies plotted by energy efficiency. This section will discuss individual solar cells and fully integrated solar panels and arrays separately that are applicable on small spacecraft. Table 3.1 describes small spacecraft solar panel efficiency for different available manufacturers.

AzurSpace's single-junction Silicon Solar Space Cell S32 has unremarkable energy efficiency at only 16.9% and the mass per surface area ratio is less than half of anything else listed at only $32\,\mathrm{mg\,cm^{-2}}$. Additionally, AzurSpace is offering a number of other cells ranging in efficiency from 28-30%. The solar cells are equipped with an integrated bypass diode (AZUR SPACE, 2015).

SpectroLab offers several solar cells in the 26-30% efficiency range. The most efficient cells are 29.3% and are available in $26.62\,\mathrm{cm^2}$, $59.65\,\mathrm{cm^2}$ and customizable. All of SpectroLabs triple-junction cells have had their on-orbit performance validated to ±1.5% of ground test results (Spectrolab, 2015).

Emcore produces two triple-junction solar cells with 28.5% and 29.5% efficiency that are available in standard and custom sizes. These second and third generation cells have rich flight heritage and the ZTJ cells were flown on NASA's CYGNUS mission. (EMCORE, 2012, 2015)

One of the highest-efficiency cells on the market today is manufactured from SolAero at 33%

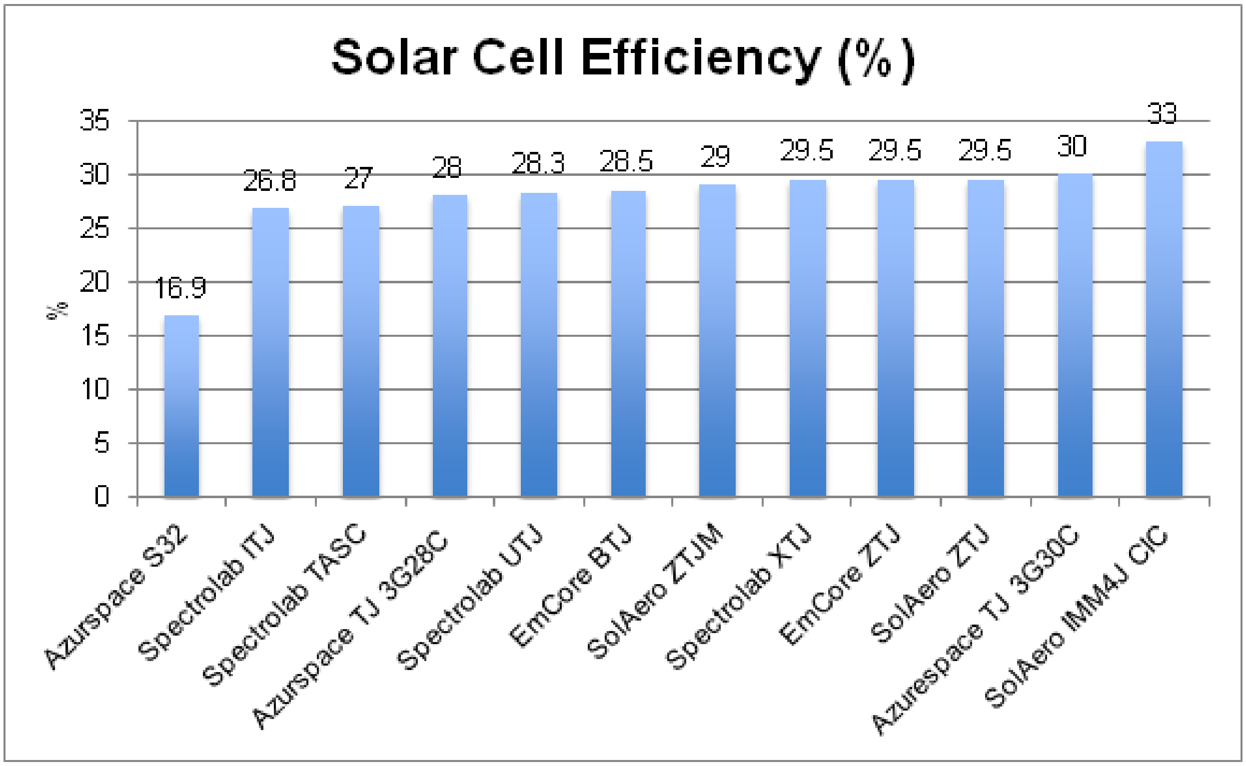


Figure 3.1. Solar Cell Efficiency

efficiency. The cell mass is only 49 mg cm^{-2}, which is around 40% less than traditional multi-junction solar cells. However, its high cost and low TRL (space qualification is still in process) make it less appealing for small spacecraft designers today. SolAero also manufactures 29% and 29.5% efficiency solar cells both of which are fully space qualified for small spacecraft missions (SolAero Technologies, 2015b).

Figure 3.2. SolAero's COBRA and COBRA-1U. Image courtesy of (SolAero Technologies, 2015a).

Solar Panels & Arrays SolAero's COBRA and COBRA-1U are designed for small spacecraft applications and use SolAero's advanced triple junction 29.5% efficiency cells mentioned above. The COBRA's stowed power density for launch is upwards of 30 kW m^{-3} and claims to be the "lowest mass ($>$7 g W^{-1}) available in a self-contained, plug-and-play design suitable for all orbital environments" (SolAero Technologies, 2015a). The cubesat-specific COBRA-1U can be used on cubesats 1U-3U in size or larger, see Figure 3.2.

DHV Technology fabricates 100 × 100 mm 1U solar panels that weigh 39 g and produce 2.24 W that can be seen in Figure 3.3. Assemblies with coverglass can reach up to 30% efficiency if required. DHV also produces 3U (132 g) and 3U-deployable panels producing 8.48 W. In addition to customizable panels, DHV manufactures a 50 × 50 mm "qubesat" panel which weighs 23 g and produces 272 mW (DHV, 2015).

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

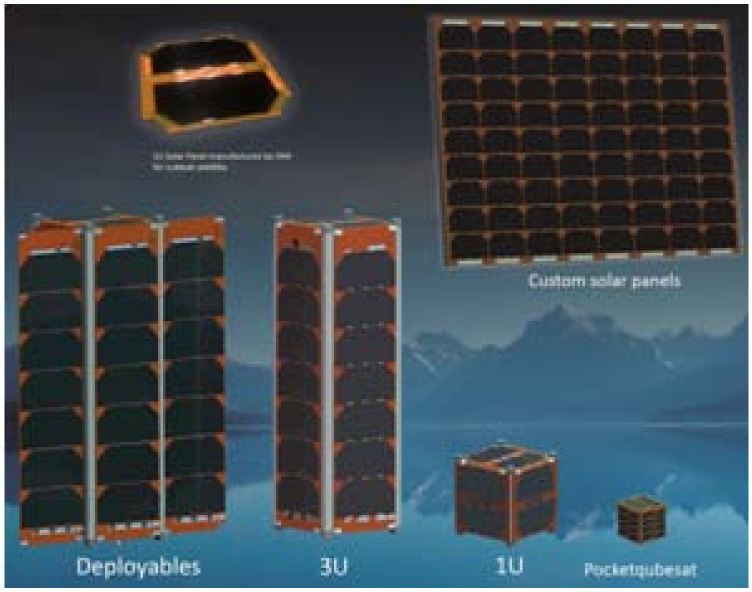


Figure 3.3. DHV's range of small satellite solar panels. Image courtesy of DHV (2015).

and 7.1 W and include a magnetotorquer. The cubesat panel weighs 26-29 g without an integrated magnetorquer or 56-65 g with one and produces 2.3-2.4 W (GomSpace, 2013).

Clyde Space produces 0.5U-12U solar panels, as well as deployable solar panels for 1U and 3U cubesats where alternative solar cells previously mentioned are used. Both the mounted and deployable panels have flown on small spacecraft (Clyde Space, 2015b).

SpectroLab's space solar panels have flown on multiple spacecraft in LEO and GEO. They are available in small sizes (30 cm^2) and use SpectroLab's Improved Triple Junction (ITJ), Ultra Triple Junction (UTJ) or NeXt Triple Junction (XTJ) cells (SpectroLab, 2010).

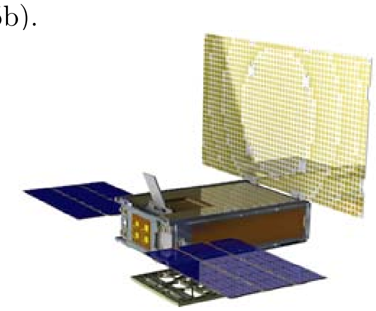


Figure 3.4. MMA's HAWK solar array on the Mars Cube One (MarCO) cubesat. Image courtesy of MMA (2015b).

MMA Design's HaWK (High Watts per Kilogram) solar array is designed for 3U-12U platform spacecraft and is deployable and gimbaled with peak power of 36 W and voltage of 14.2 V (MMA, 2015b). 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% cells and weighs approximately 600 g (MMA, 2015a). Both of these technologies are currently around TRL 7 with the HaWK scheduled to launch on the NASA's BioSentinel mission and JPL's MarCO mission in 2016 and the eHAWK currently undergoing environmental testing, see Figure 3.4.

3.2.2 Power Storage

Solar power generation is not always available for spaceflight operations; the orbit, mission duration, distance from the Sun or required peak instrument power may need stored on-board energy. Primary and secondary batteries are used for power storage and classified according to their different electrochemistries. As primary type batteries are not rechargeable, they are used only for real short mission durations (around 1 day, up to 1 week). Silver-zinc are typically used as they are easier

Table 3.1. Solar Panel Efficiency

Product	Manufacturer	Efficiency	Solar Cells Used	Status
Solar Panel (0.5-12U); Deployable Solar Panel (1U, 3U)	Clyde Space	28.3%	SpectroLab UTJ	TRL 9
Solar Panel (0.5-12U); Deployable Solar Panel (1U, 3U)	Clyde Space	29.5%	SpectroLab XTJ	TRL 9
Solar Panel (0.5-12U); Deployable Solar Panel (1U, 3U)	Clyde Space	30.0%	AzurSpace 3G30A	TRL 9
Solar Panel (5x5cm, 1U, 3U, custom)	DHV	30.0%	Unkn.	TRL 8
NanoPower (CubeSat and custom)	GomSpace	30.0%	AzurSpace 3G30A	TRL 9
HAWK	MMA	28.3%	SolAero ZTJ	TRL 7
eHAWK	MMA	28.3%	SolAero ZTJ	TRL 7
COBRA	SolAero	29.5%	SolAero ZTJ	Unkn.
COBRA-1U	SolAero	29.5%	SolAero ZTJ	Unkn.
Space Solar Panel	Spectrolab	26.8%	SolAero ITJ	TRL 9
Space Solar Panel	Spectrolab	28.3%	SolAero UTJ	TRL 9
Space Solar Panel	Spectrolab	29.5%	SolAero XTJ	TRL 9

to handle and discharge at a higher rate, however there is also a variety of lithium-based primary batteries that have a higher energy density including: lithium sulphur dioxide ($LiSO_2$), lithium carbon monofluoride ($LiCF_x$) and lithium thionyl chloride ($LiSOCl_2$) (Nelson, 199).

Secondary type batteries include nickel-cadmium (NiCd), nickel-hydrogen (NiH_2), lithium-ion (Li-ion) and lithium polymer (Li-po) and 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 provider such as a solar array and are able to provide power on demand and recharge. Each battery type are associated with certain applications that depend on performance parameters, including energy density, cycle life and reliability (Nelson, 199). A comparison of energy densities can be seen in Figure 3.5 and Figure 3.6 and a list of battery energy density per manufacturer is in Table 3.2.

This section will discuss the individual chemical cells as well as pre-assembled batteries of mul-

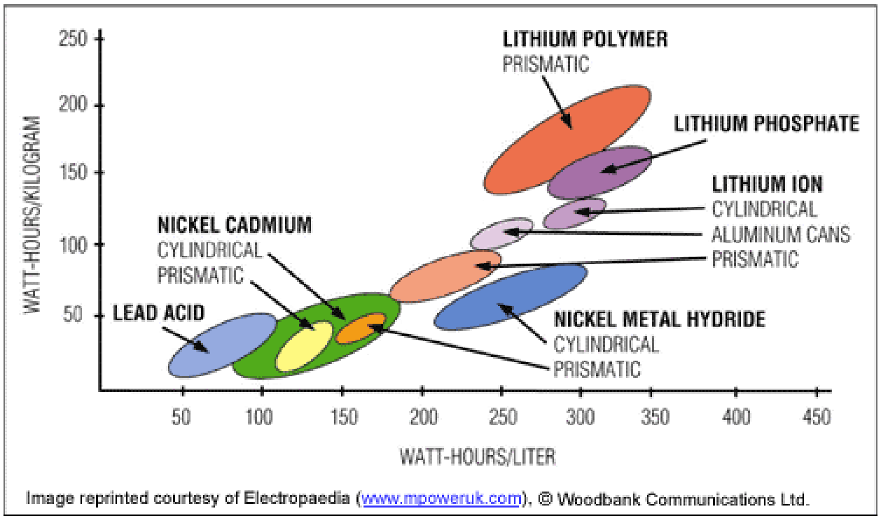


Figure 3.5. The energy densities of various battery types. Image courtesy of Wagner (2006).

tiple 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 energy density. There are, however, a number of other factors worth considering, some of which will be discussed below (Jung & Manzo, 2010). Due to the extreme short mission duration with primary cells, the current state of the art energy storage systems use lithium ion (Li-ion) or lithium polymer (Li-po) secondary cells, and this subsequent section will focus only on those electrochemical composition.

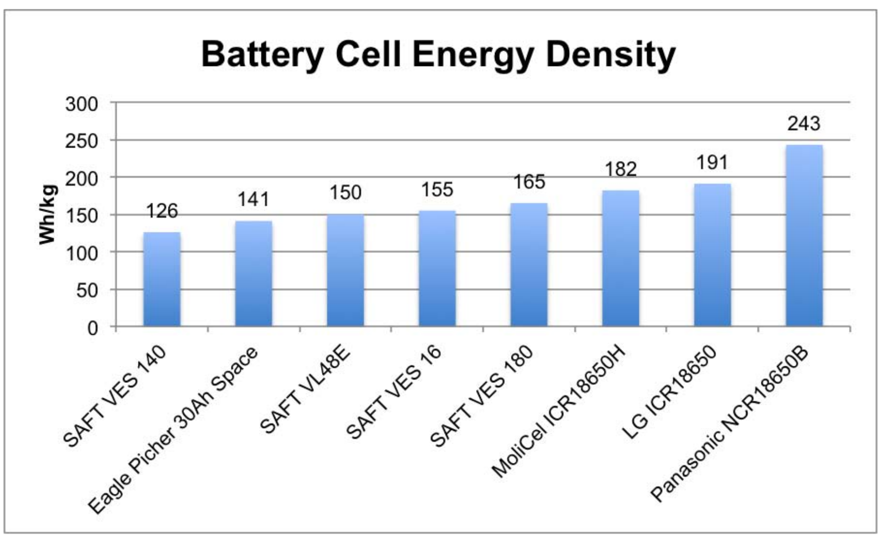


Figure 3.6. Battery Cell Energy Density

Secondary Li-ion and Li-po batteries Typically, Li-ion cells delivery an average voltage of 3.6 V while the highest specific energy obtained is well in excess of $150\,\mathrm{W\,h\,kg^{-1}}$ (Jung & Manzo, 2010).

Eagle Picher produces a number of cells for military and aerospace applications including two advanced Li-ion cells and a Rechargeable Space Battery. Both cells have a high energy density and

Figure 3.7. ABSL Commercial-off-the-shelf Li-ion Battery. Image courtesy of ABSL (2007).

Figure 3.8. Vectronic's VLB-4, -8, -16 Li-ion Battery Pack. Image courtesy of Vectronic Aerospace (2014).

a TRL of 9. Their integrated Space Battery has an energy density of 153.5 $\mathrm{W\,h\,kg^{-1}}$ and produces a nominal voltage of 28.8 V but has a slightly lower TRL of 7.

SAFT is another battery manufacturer with a long history of supplying the aerospace industry. Their Li-ion range include energy includes cells ranging from 126-165 $\mathrm{W\,h\,kg^{-1}}$ (SAFT, 2013).

ABSL's Li-ion 18650 cells have an energy density range of 90-243 $\mathrm{W\,h\,kg^{-1}}$. ABSL's top of the line military and space grade cells have proven long-term reliability and charging, safety & protection circuit built into the battery cells (ABSL, 2007), see Figure 3.7.

The VLB-16 Li-ion battery pack offered from Vectronic Aerospace is specifically designed for use on small spacecraft and uses small spacecraft-qualified SAFT cells. This battery pack integrates current, voltage and temperature measurement functions and includes dynamic balancing that can be determined through a digital control interface (Vectronic Aerospace, 2014), see Figure 3.8.

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 (GomSpace, 2015b).

LG's ICR18650 B3 Li-ion cells have an energy 191 W h/kg and have flown on NASA's PhoneSat spacecraft housed in a 2S2P battery holder from BatterySpace (LG Chem, 2007).

Panasonic produces the 18650B (3400 mA h) Li-ion cells have a high energy density of 243 $\mathrm{W\,h\,kg^{-1}}$ that has a flight heritage on small spacecraft missions including NASA's GeneSat, SporeSat, O/OREOS and PharmaSat (Panasonic, 2012).

Molicel manufacturers the ICR18650H Li-ion cell with a high energy density of 182 $\mathrm{W\,h\,kg^{-1}}$ which require pack control circuitry (Molicel, 2015).

Figure 3.9. Canon BP-930 Li-ion battery pack. Image courtesy of (Canon, 2011).

BatterySpace.com sells a Li-Ion 18650 Battery Holder (2S2P) that was flown successfully on NASA's EDSN mission in conjunction with LG ICR18650 B3 Li-ion cells.

Canon's BP-930s battery pack, see Figure 3.9, is an affordable, flight-proven option for power storage (Canon, 2011). The pack contains four 18650 Li-cells and has flown successfully on NASA's TechEdSat missions.

Clyde Space has designed two Li-polymer batteries specifically for small spacecraft and cubesats. With an energy density of up to 150 $\mathrm{W\,h\,kg^{-1}}$ and voltage of 8.2-32 V, battery temperature, voltage, current and telemetry can be monitored via integrated digital interface. They also have an integrated heater which maintains battery temperatures above 0°C. The use of Li-polymer cells allows the Clyde Space flat-packed batteries to be mass and volume efficient. According to the manufacturer, Clyde Space batteries are used on more cubesat missions than any other provider's.

Table 3.2. Battery energy Density

Product	Manufacturer	Energy Density	Cells Used	Status
COTS 18650 Li ion battery	ABSL	$90\,\mathrm{W\,h\,kg^{-1}}$ - $243\,\mathrm{W\,h\,kg^{-1}}$	Sony, MoliCell, LG, Sanyo, Samsung	TRL 8
BP-930s	Canon	$132\,\mathrm{W\,h\,kg^{-1}}$	four 18650 Li ion cells	TRL 9
Li-Polymer, 8.2V, 1.25 A h - 20 A h	Clyde Space	$150\,\mathrm{W\,h\,kg^{-1}}$	Clyde Space Li Polymer	TRL 9
Li-Polymer, 32V, 6.25 A h	Clyde Space	$150\,\mathrm{W\,h\,kg^{-1}}$	Clyde Space Li Polymer	TRL 8
Rechargeable Space Battery (NPD-002271)	EaglePicher	$153.5\,\mathrm{W\,h\,kg^{-1}}$	EaglePicher Li ion	TRL 7
NanoPower BP4	GomSpace	$160\,\mathrm{W\,h\,kg^{-1}}$	GomSpace NanoPower Li ion	TRL 9
NanoPower BPX	GomSpace	$157\,\mathrm{W\,h\,kg^{-1}}$ - $171\,\mathrm{W\,h\,kg^{-1}}$	GomSpace NanoPower Li ion	TRL 9
Li-Ion Battery Block VLB-X	Vectronic	Unkn.	SAFT Li-ion	Unkn.

3.2.3 Power Management and Distribution

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 Electrical Power Systems (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 non-nominal current and voltage conditions. As electronics vendors settle on standard voltages, PMAD will become more standardized. Well-known producers of PMAD systems that focus on the small spacecraft market include Pumpkin, GomSpace, Stras Space and 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 manufactures and it should be noted that this list is not exhaustive.

ÅAC Microtec provides three Distributed Power and Control Units equipped with different user interfaces (I2C, USB, SpaceWire), see Figure 3.10. They are designed for easy integration of

Figure 3.10. ÅAC Microtec Flight model DPCU-2112. Image courtesy of AAC Microtec (2011).

Figure 3.11. Clyde Space Small Satellite PMAD system. Image courtesy of (Clyde Space, 2015a).

payloads, sensors and sub-systems on advanced small satellites (AAC Microtec, 2011).

Blue Canyon Tech's BCT CubeSat Electrical Power System includes functionality for solar array input power, on-board or external batteries, charge control, power regulation and distribution, and data acquisition (Blue Canyon Tech, 2015).

Clyde Space produces a PMAD and an EPS targeted specifically at small satellites, see Figure 3.11. The PMAD includes a range of topologies and architectures including DET and PPT, COTS, hybrid, and rad-hard components and has at TRL of 9. Their third-generation EPS for 1U-12U cubesats has a TRL of 8 while the second generation EPS is a veteran of many small spacecraft missions (Clyde Space, 2015a).

Crystalspace manufactures a P1U power supply that is optimized for 1U and 2U cubesats. The battery output travels though duplicated converters that can provide 3.3 V, 5 V and 12 V Crystal Space (2015).

Design Net Engineering makes a PMAD system and an Energy Storage Module (ESM). The PMAD system is designed to have highly configurable energy storage, battery chemistry and number of panels. The ESM converts battery power into a locally managed brick of energy that can accept charge from any number of power sources and provide power to spacecraft subsystems.

GomSpace's NanoPower P31us PMAD system is designed for small spacecraft requiring power between one and 30 W, see Figure 3.12 (GomSpace, 2015a).

Modular Devices, Inc. makes a 7.5-20 W Hybrid DC-DC power converter specifically designed for cubesat applications in a radiation environment, TID >100 kRad (Si) (Modular Devices Inc.,

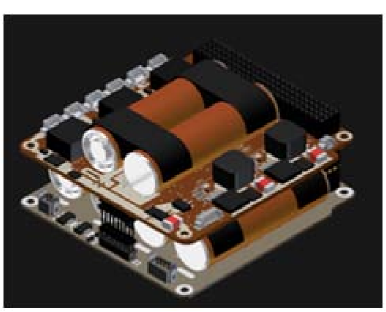


Figure 3.12. GomSpace NanoPower P31us.. Image courtesy of GomSpace (2015a).

Figure 3.13. Surrey LEO PCDUm. Image courtesy of (Surrey Satellite Technology ltd., 2015).

2015).

Stras Space's Drop-In Power Converter is designed for enclosed spaces and easy mounting. It has a wide input voltage range of 3.3 V-40 V and operates with a typical efficiency of 90% (Stras Space, 2015).

Surrey Satellite Technology sells a full PMAD system in the form of their LEO 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. It has flown on over 30 missions (Surrey Satellite Technology ltd., 2015). See Figure 3.13

Vectronic's Power Control and Distribution Unit is one of a range of space power systems designed for small spacecraft. The PCDU monitors output from battery and solar power sources, and switches individual subsystems in response to a telecommand or atomically in the event of an overload or short-cut condition. There are currently eight Vectronic PCAD units on orbit.

Table 3.3. Power Management and Distribution Systems

Product	Manufacturer	Technology Type	Status
DPCU-2100, -2200, -2300	ÅAC Microtec	PMAD	Unkn.
BCT CubeSat Electrical Power System	Blue Canyon Tech	EPS	Unkn.
Small Satellite PCDU	Clyde Space	PMAD	TRL 9
Nanosatellite EPS	Clyde Space	EPS	TRL 8
P1U "Vasik"	Crystalspace	EPS	TRL 8
DNE Energy Storage Module	Design Net Engineering	ESM	Unkn.
NanoPower P31us	GomSpace	PMAD	Unkn.
Series 3699 DC-DC Converter	Modular Devices Inc.	Power Converter	Unkn.
Drop-In Power Converter	Stras Space	Power Converter	TRL 9
LEO PCDU	Surrey	PMAD	TRL 9
Vectronic PCDU	Vectronic	PMAD	Unkn.

3.3 On the horizon

3.3.1 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.

Multi-junction Solar Cells A four-junction solar cell, developed by Fraunhofer Society, is currently reaching 46% efficiency under laboratory conditions and concentrated sunlight, although it is unclear whether the power-to-weight ratio remains the same as current triple-junction cells

(Fraunhofer Society, 2014). Additionally, Boeing Spectrolabs has been experimenting with 5- and 6-junction cells with a theoretical efficiency as high as 70% (King, 2009).

Figure 3.14. A series-connected string of production-sized cells on 1 mil polymer partially rolled onto a tube. Image courtesy of Casey (2014).

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, cheap to manufacture. In 2014, FirstSolar announced a flexible solar cell design with an efficiency of 20.4%, closing the gap on single-junction solar cells (Casey, 2014), shown in Figure 3.14. A flexible solar cell designed specifically for space applications is available from United Solar and has an efficiency of 8% on 1 mil polymer giving them a specific power of 750-1100 $\mathrm{W\,kg^{-1}}$ (Beernink et al., 2007).

Additionally, MIT researchers have developed a solar cell material that can be printed onto paper and folded multiple times without loss of function. While still in its infancy, this technology has the ability to massively reduce the cost of solar cell production while increasing the durability of cells (Barr et al., 2011; Chandler, 2011).

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. Currently they are limited by an efficiency of less than 4% (Scharber & Sariciftci, 2013).

Fuel Cells Hydrogen fuel cells are appealing due to their small, light and reliable qualities and have 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 $\mathrm{W\,h\,kg^{-1}}$ and has a theoretical limit of over 2580 $\mathrm{W\,h\,kg^{-1}}$ (Luo et al., 2008). This makes them more appealing for interplanetary missions and during eclipse periods, however unlike chemical cells, they cannot be recharged on orbit. 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 (Ethier, Paritsky, Moser, Slostad, & Hoyt, 2013).

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 and predictable power production, and are more appealing than relying on batteries and solar panels when surpassing Mars orbit (>3 AU). A full size 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 (National Aeronautics and Space Administration, 2015). Although a radioisotope power system has not yet been integrated on a small spacecraft, they can still be considered when small spacecraft missions traverse interplanetary space. Additional testing and fabrication may be required for smaller platforms.

TPV A thermo-photovoltaic (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.

In a paper given at the Photovoltaic Specialists Conference in 2011, entitled "soda-can sized thermophotovoltaic battery replacement", a TPV with a conversion efficiency of 10% was described that would have a specific energy of approximately 1000 $\mathrm{W\,h\,kg^{-1}}$. This is approximately 6.5 times higher than the specific energy for a Li-ion battery making it a very exciting alternative power source, see Figure 3.15. The authors have not produced a physical prototype (Fraas et al., 2011). Thermophotovoltaics are technically challenging as they require radioisotope fuel to have a temperature of more than 1273 K for high infrared emission, while also maintaining temperature suitable for photovoltaic cells (less than 323 K) for efficient electrical conversion.

Figure 3.15. Small portable TPV battery with adjacent fuel cylinder. Image courtesy of Fraas et al. (2011).

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

3.4 Conclusion

Driven largely by weight and size limitations, small spacecraft are using advanced power generation and storage technology such as >29% 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 commercial-off-the-shelf products not specifically designed for spaceflight. This dramatically reduces cost and increases flexibility of mission design. 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 utilize 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.

References

AAC Microtec. (2011). *Bp-930 material safety data sheet* (Tech. Rep.). Author. http://www.aacmicrotec.com/images/Products/Components/RIA/AAC_DPCU_www.pdf. (Accessed: 11 November 2015)

ABSL. (2007). *Absl?s cots li-ion cell suite development* (Tech. Rep.). Author. https://batteryworkshop.msfc.nasa.gov/presentations/14_ABSL_COTS_Li-Ion_Cell_Suite_Dev_TMax.pdf. (Accessed: 4 November 2015)

AZUR SPACE. (2015). *AZUR SPACE Space Solar Cells.* http://www.azurspace.com/index.php/en/products/products-space/space-solar-cells. (Accessed: 12 October 2015)

Barr, M. C., Rowehl, J. A., Lunt, R. R., Xu, J., Wang, A., Boyce, C. M., ... Gleason, K. K. (2011). Direct monolithic integration of organic photovoltaic circuits on unmodified paper. *Advanced Materials*, *23*. doi: 10.1002/adma.201101263

Beernink, K., Guha, S., Yang, J., Banerjee, A., Lord, K., DeMaggio, G., ... Wolf, D. (2007). Lightweight, flexible solar cells on stainless steel foil and polymer for space and stratospheric applications. In *19th Space Photovoltaic Research and Technology Conference.* http://www.researchgate.net/publication/237442007_LIGHTWEIGHT_FLEXIBLE_SOLAR_CELLS_ON_STAINLESS_STEEL_FOIL_AND_POLYMER_FOR_SPACE_AND_STRATOSPHERIC_APPLICATIONS. (Accessed: 26 October 2015)

Blue Canyon Tech. (2015). *Bp-930 material safety data sheet* (Tech. Rep.). Author. http://bluecanyontech.com/wp-content/uploads/2015/05/EPS-Data-Sheet_1.0.pdf. (Accessed: 16 October 2015)

Canon. (2011). *Bp-930 material safety data sheet* (Tech. Rep.). Canon Asia. http://support-asia.canon-asia.com/fuseaction/support/safetyinformation/pdf/digitalcamera/BP-930-(Rev27May11)-SO.pdf. (Accessed: 11 November 2015)

Casey, T. (2014). First solar knocks it out of the park with new solar cell efficiency record. *Clean Technica*. http://cleantechnica.com/2014/02/27/first-solar-knocks-park-new-solar-cell-efficiency-record/. (Accessed: 26 October 2015)

Chandler, D. L. (2011). While you're up, print me a solar cell. *MIT News*. http://news.mit.edu/2011/printable-solar-cells-0711. (Accessed: 26 October 2015)

Clyde Space. (2015a). *Clyde Space Third-Generation (3G) EPS Range.* http://www.clyde-space.com/3g_eps_range. (Accessed: 3 December 2015)

Clyde Space. (2015b). *CubeSat Lab.* http://www.clyde-space.com/cubesat_shop. (Accessed: 20 September 2015)

Crystal Space. (2015). *Crystalspace P1U ?Vasik? Power Supply.* http://crystalspace.eu/products/crystalspace-p1u-vasik-power-supply/. (Accessed: 3 December 2015)

DHV. (2015). *Solar panels for aerospace applications* (Tech. Rep.). DHV Technology. http://dhvtechnology.com/wp-content/uploads/2013/04/DHV-Tech-Solar-Panel-TDS-2015-v2-june-2015web-version.pdf. (Accessed: 23 September 2015)

EMCORE. (2012). *Ztj photovoltaic cell* (Tech. Rep.). Author. http://www.emcore.com/wp-content/uploads/ZTJ-Cell.pdf. (Accessed: 1 October 2015)

EMCORE. (2015). *BTJ Space Solar Cell.* http://www.emcore.com/btj-space-solar-cell/. (Accessed: 1 October 2015)

Ethier, V., Paritsky, L., Moser, T., Slostad, J., & Hoyt, R. (2013). *Development of a cubesat water-electrolysis propulsion system.* http://digitalcommons.usu.edu/smallsat/2013/all2013/30/. (Accessed: 26 October 2015)

Fraas, L., Avery, J., Minkin, L., & Huang, H. (2011). Soda-can sized thermophotovoltaic battery replacement. In *37th IEEE Photovoltaic Specialists Conference (PVSC).* Seattle, WA. doi:

10.1109/PVSC.2011.6186356

Fraunhofer Society. (2014). *New world record for solar cell efficiency at 46 percent French-German cooperation confirms competitive advantage of European photovoltaic industry.* https://www.ise.fraunhofer.de/en/press-and-media/press-releases/press-releases-2014/new-world-record-for-solar-cell-efficiency-at-46-percent. (Accessed: 26 October 2015)

GomSpace. (2013). *Nanopower p110 series solar panels datasheet* (Tech. Rep.). Author. http://nativesat.com/wp-content/uploads/2014/07/P110-Series-Solar-Panels.pdf. (Accessed: 21 September 2015)

GomSpace. (2015a). *GomSpace NanoPower Modules.* http://gomspace.com/index.php?p=products-p31us. (Accessed: 1 November 2015)

GomSpace. (2015b). *NanoPower Modules.* http://gomspace.com/index.php?p=products-bpx. (Accessed: 6 December 2015)

Green, M. A. (2003). *Third generation photovoltaics: Advanced solar energy conversion* (Vol. 12). Springer. doi: 10.1007/b137807

Jung, D. S., & Manzo, M. A. (2010). *NASA Aerospace Flight Battery Program* (NESC-RP-08-75 ed.) (No. NASA/TM-2010-216728/Volume I). http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100027573.pdf. (Accessed: 26 October 2015)

King, R. (2009). Raising the Efficiency Ceiling in Multijunction Solar Cells. In *Stanford Photonics Research Center Symposium.* Stanford, CA. http://www.spectrolab.com/DataSheets/PV/pv_tech/msce.pdf. (Accessed: 2015-11-06)

LG Chem. (2007). *Product specification rechargeable lithium ion battery model : Icr18650 b3 2600mah* (Tech. Rep.). LG. http://lib.store.yahoo.net/lib/theshorelinemarket/LG-18650-2600.pdf. (Accessed: 4 December 2015)

Luo, N., Miley, G. H., Shrestha, P. J., Gimlin, R., Burton, R., Rusek, J., & Holcomb, F. (2008). Hydrogen-peroxide-based fuel cells for space power systems. *JOURNAL OF PROPULSION AND POWER*, *24*(3). doi: 10.2514/1.31522

MMA. (2015a). *E-HAWK (PAT.) NANOSAT SOLAR ARRAYS.* http://www.mmadesignllc.com/products/hawk-and-e-hawk-nanosat-solar-arrays. (Accessed: 20 September 2015)

MMA. (2015b). *HAWK (PAT.) CUBESAT SOLAR ARRAYS.* http://www.mmadesignllc.com/products/hawk-and-e-hawk-nanosat-solar-arrays. (Accessed: 13 September 2015)

Modular Devices Inc. (2015). *Series 3699 7.5 ? 20 watt hybrid for cubesats and miniaturized satellites* (Tech. Rep.). Author http://www.mdipower.com/content/SelectionTree/pdf/3699-Series.pdf. (Accessed: 4 November 2015)

Molicel. (2015). *Panasonic lithium ion ncr18650b* (Tech. Rep.). Author. http://www.meircell.co.il/files/Moli%20ICR18650H.pdf. (Accessed: 2 November 2015)

National Aeronautics and Space Administration. (2015). *Radioisotope Power Systems (RPS) Program.* https://tec.grc.nasa.gov/rps/. (Accessed: 26 October 2015)

Nelson, R. A. (199). *Spacecraft battery technology.* http://www.aticourses.com/sampler/Spacecraft_Battery_Technology.pdf. (accessed: 18 November 2015)

Panasonic. (2012). *Panasonic lithium ion ncr18650b* (Tech. Rep.). Author. http://industrial.panasonic.com/lecs/www-data/pdf2/ACA4000/ACA4000CE417.pdf. (Accessed: 2 December 2015)

SAFT. (2013). *Market Solutions: Space.* http://www.saftbatteries.com/market-solutions/space. (Accessed: 20 September 2015)

Scharber, M., & Sariciftci, N. (2013). *Efficiency of bulk-heterojunction organic solar cells* (Vol. 38). doi: 10.1016/j.progpolymsci.2013.05.001

SolAero Technologies. (2015a). *Integrated Solar Products.* http://solaerotech.com/products/

integrated-solar-products/. (Accessed: 3 October 2015)

SolAero Technologies. (2015b). *Space Solar Cells / Coverglass Interconnected Cells (CIC).* http://solaerotech.com/products/space-solar-cells-coverglass-interconnected-cells-cic/. (Accessed: 3 October 2015)

SpectroLab. (2010). *Spectrolab space solar panels* (Tech. Rep.). Author. http://www.spectrolab.com/DataSheets/Panel/panels.pdf. (Accessed: 3 September 2015)

Spectrolab. (2015). *Spectrolab Space Products: Cells.* http://www.spectrolab.com/solarcells.htm. (Accessed: 7 October 2015)

Stras Space. (2015). *Stras space drop in power converter* (Tech. Rep.). Author. http://www.stras-space.com/strasspace-products. (Accessed: 14 November 2015)

Surrey Satellite Technology ltd. (2015). *Leo pcdu* (Tech. Rep.). Author http://www.sstl.co.uk/getattachment/fb984708-a8d0-4cc5-9253-49541bf85151/Power-Control-Distribution-Unit-PCDU. (Accessed: 12 November 2015)

Vectronic Aerospace. (2014). *Li-Ion Battery Block VLB-4/ -8 /-16.* http://www.vectronic-aerospace.com/space.php?p=battery. (Accessed: 4 November 2015)

Wagner, R. (2006). *Battery fuel gauges: Accurately measuring charge level* (Tech. Rep. No. 3958). Maxim Integrated. https://www.maximintegrated.com/en/app-notes/index.mvp/id/3958. (Accessed: 26 October 2015)

4 Propulsion

4.1 Introduction

There are currently a wide range of technologies for propulsion systems, however the miniaturization of these systems for small spacecraft is a particular challenge. The purpose of this chapter is to identify and analyze the current status of the main propulsion technologies for small spacecraft and to present an overview of the available systems. Performance tests and technology demonstrations were considered in order to assess the maturity and robustness of each system. Some of the current systems are adaptable to a large variety of smaller buses.

While cold gas or pulsed plasma systems are targeted for small delta-v, Δv application, modules that can provide more demanding maneuvers need still development. Small spacecraft buses other than cubesats have more flexibility to accommodate systems with several thruster units to provide more attitude control and also large single axis maneuvers. Missions have demonstrated these technologies successfully and performance data gathered has paved the way for future modifications of the existing hardware in order to re-adapt the designs to satisfy demanding constraints. Table 4.1 shows a summary of the current state of the art for different propulsion methods.

Electric and chemical systems have experienced a significant maturation process with respect to the previous report. Thrust stand measurements in vacuum and lifetime tests have been performed for an extensive variety of devices and a serious effort has been made by several companies, agencies and institutions to satisfy small spacecraft requirements. Fundamental components such as Power Processing Units (PPUs) and particular mass, power and volume constraints have been adjusted to smaller buses.

Hazardous propellants introduce handling and safety challenges and increase the total cost of the mission, while several non-toxic propellants also provide less safety and handling requirements and also higher specific impulse and density, which is beneficial for Δv budgets. Electric propulsion devices have been miniaturized to successfully adapt to small buses and low thrust options for cubesats, such as electrosprays or Pulsed Plasma Thrusters (PPT), enable easy integration due to their low degree of complexity. For more ambitious mission concepts that require higher Δv technologies such as Hall Effect and ion system, are still being developed. Finally, in regards to propellant-less systems, the recent launch of LightSail has advanced the state of the art of solar sails for small spacecraft.

The TRL for small spacecraft propulsion is usually lower compared to other subsystems. This section considers systems that have been flown or are actively being developed in the last few years to account for the most recent advances in the technology. The chapter is divided in three main categories: chemical, electric and propellant-less systems, which are divided into smaller subsections depending on the type of thrust generation. Whenever pertinent, this report considers complete propulsion systems composed of thrusters, feed systems, propellant storage and Power Processing Units but not including electrical power supply. In addition, for some subsections, single thruster heads are also introduced.

4.2 State of the Art

4.2.1 Chemical Propulsion Systems

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

Table 4.1. Propulsion system types for small spacecraft

Product	Manufacturer	Specific Impulse	Status
Hydrazine	0.5-4 N	150-250 s	TRL 6
Cold Gas	10 mN-10 N	65-70 s	GN2/ Butane TRL 9
Non-toxic Propulsion	0.1-27 N	220-250 s	HAN TRL 8, ADN TRL 6
Pulsed Plasma and Vacuum Arc Thrusters	1 -1300 μN	500-3000 s	Teflon TRL 8, Titanium TRL 7
Electrospray propulsion	10-120 μN	500-5000 s	TRL 6
Hall Effect Thrusters	10-50 mN	1000-2000 s	Xenon TRL 8, iodine TRL 4
Ion engines	1-10 mN	1000-3500 s	Xenon TRL 8, Iodine TRL 4
Solar Sails	0.25-0.6 mN	N/A	TRL 6 (85 m^2) TRL 7 (35 m^2)

Hydrazine propellant There are a significant number of mature hydrazine propulsion systems used in large spacecraft that present a generally reliable option as the characteristics in terms of mass and volume of these compact systems allow them to be a suitable fit for some small spacecraft buses. Thrusters that perform small correction maneuvers and attitude control in large spacecraft may be large enough to perform high thrust maneuvers for small spacecraft and can act as main propulsion system. Hydrazine propulsion systems typically incorporate a double stage flow control valve that regulates the propellant supply and a catalyst bed heater with thermal insulation. Typically, they 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. Typically, hydrazine achievable specific impulses are in the 150-250 s range. Because hydrazine systems are so widely used for large satellites, robust ecosystem components exist, and hydrazine propulsion systems are custom-designed for specific applications using available components. This section considers both commercial off-the-shelf (COTS) hydrazine thrusters and integrated complete propulsion systems.

Airbus Defense and Space has developed a 1 N class hydrazine thruster that has extensive flight heritage, including use on the small spacecraft, ALSAT-2. Aerojet Rocketdyne has leveraged existing designs with flight heritage from large spacecraft that may be applicable to small buses, such as MR-103 thruster used on New Horizons for attitude control applications (Stratton, 2004). Other Aerojet Rocketdyne thrusters potentially applicable to small spacecraft include the MR-111 and the MR-106 (Aerojet Rocketdyne, 2015).

The Cubesat High-Impulse Adaptable Modular Propulsion System (CHAMPS) project leverages the miniaturization effort performed for previous small hydrazine thrusters to develop cubesat monopropellant propulsion systems. These modules satisfy a wide range of maneuvers from station-keeping and orbit transfers to momentum management. There are various configurations, such as the MPS-120, that support up to four 1 N hydrazine thrusters configured to provide pitch, yaw, and roll control as well as single axis thrusting vector. Additional versions of the MPS series are under development that utilize various thruster technologies such as cold gas (MPS-110), non-toxic AF-

M315E propellant (MPS-130) or electric propulsion devices (MPS-160) (Aerojet Rocketdyne, 2015). The MPS-120 was selected and funded by NASA to go through extensive testing. The 3D printed titanium isolation and tank systems were demonstrated in mid-2014 and one engine performed a hot fire test in late 2014 (Carpenter, Schmuland, Overly, & Masse, 2014). Aerojet Rocketdyne is also developing integrated modular propulsion systems for larger small spacecraft. The MPS-220 consist of two 22 N primary engines and eight 1 N auxiliary thruster that use hydrazine as propellant (Aerojet Rocketdyne, 2015).

Moog ISP has extensive experience in the design and testing of propulsion systems and components for large spacecraft. These may also apply for smaller platforms as some of their flight-proven thrusters are light-weight and have moderate power requirements. The Monarch-5 thruster flew in NASA JPL's Soil Moisture Active Passive (SMAP) spacecraft in 2015 and provided 4.5 N of steady state thrust. Other thrusters potentially applicable into small spacecraft buses include the MONARC-1 and the MONARC-22 series (Moog ISP, 2014).

Non-Toxic Propellant Non-toxic propellants are designated green as they have a reduced toxicity due to the lower danger of component chemicals and reduced vapor pressure as compared to hydrazine. This results in less safety requirements for handling these propellants, potentially including the lack of required SCAPE suit (self contained atmospheric protective ensemble) and reduces operational oversight by safety and emergency personnel. Fueling for these may also be considered a parallel operation or have a less significant required exclusionary zone, allowing for the acceleration of launch readiness operations. Non-toxic propellants are less likely to exothermicallly decompose at room temperature even in the presence of a catalyst. Therefore they require less inhibits resulting in less valve seats to power, including a less stringent temperature requirement with less system heater power. Non-toxic propellants also provide higher performance than the current state of the art fuel and have higher density-specific impulse achieving improved mass fractions. As a majority of these non-toxic propellants are in development, systems using these propellants present technical challenges including increased power consumption and the selection of materials due to higher combustion temperatures. The primary ionic liquid propellants with flight heritage or upcoming spaceflight plans are LMP-103S and AF-M215E. Table 4.2 lists the current state of the art in green propellants.

Figure 4.1. ECAPS HPGP thruster. Image courtesy of ECAPS SSC ECAPS (2015).

The Ecological Advanced Propulsion Systems, Inc. (ECAPS) High Performance Green Propulsion (HPGP) system, shown in Figure 4.1, uses ammonium dinitramide-based LMP-103S as propellant. Its density is slightly higher than hydrazine ($1.24\,\mathrm{g\,cm^{-3}}$ vs $1.02\,\mathrm{g\,cm^{-3}}$). The PRISMA mission incorporated successfully the 1 N version of this system in 2010. Furthermore, Skybox Imaging conducted a trade study of various propulsion alternatives for application in spacecraft constellations and selected this system (Dyer, Dinardi, & Anflo, 2013). HPGP systems are being implemented in SkySat missions such as SkySat-3, and SkySat block-I. HPGP systems are currently developed for three different thrust magnitudes: 1 N, 5 N and 22 N, with higher thrust systems in development (Persson, 2015) (Dinardi, Beckel, & Dyer, 2013). VACCO partnered with ECAPS to design a self-contained unit that can deliver up to 1808 N s of total impulse and can be adapted for different sizes, 0.5U to 1U. The VACCO/ECAPS Micro Propulsion System (MiPS) is designed to meet the specific cubesat standards and has four 100 mN ADN-propellant thrusters. Each engine is throttlable in order to have vector control. This unit has also an alternative hybrid version that incorporates one 100 mN ADN thruster and four 10 mN cold gas thrusters for attitude control, providing up to 1036 N s of total impulse for main Δv applications and 69 N s for RCS (VACCO Industries, 2015).

Another non-toxic propellant in development is the U.S. Air Force developed AF-M315E, a hydroxylammonium nitrate (HAN) based monopropellant. Aerojet Rocketdyne is currently developing propulsion systems utilizing this propellant. The AF-M315E has a density of 1.47 g cm^{-3} (about 45% more than hydrazine) and a specific impulse of 230 - 250 s can be achieved by using this propellant. While some components have heritage from previous hydrazine systems, others that are compatible with AF-M315E propellant, such as valves and filters, are at TRL 6 (Spores, Masse, Kimbrel, & McLean, 2014). The propulsion system will be flown as a technology demonstration on the NASA Green Propellant Infusion Mission (GPIM), scheduled to launch in 2016. This small spacecraft is designed to test the performance of this propulsion technology in space by using five 1 N class thrusters (GR-1) for small attitude control maneuvers (McLean et al., 2015). Aerojet completed a hot-fire test of the GR-1 version in 2014 and further tests in 2015. 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 will only carry 1-N class GR-1 units when launched in 2016 (Masse et al., 2015). The TRL is currently 6 for the GR-1 (Figure 4.2), and 5 for the larger GR-22 (Figure 4.3).

The AF-M315E propellant is used by a 0.5 N thruster that is being developed by Busek. This device was placed on an inverted-pendulum type thrust stand for a test campaign. Three performance profiles were demonstrated: steady state, long and short duration pulses. For operating the thruster, there is a catalyst pre-heat requirement of 12 W for about eight minutes. In addition, the thruster is combined with a piezo-actuated micro-valve that is suitable for long-term propellant compatibility. While integrated system testing of the thruster and microvalve have occurred, further development is required before raising the TRL of the integrated system. The integrated testing demonstrated minimum impulse bits of 36 mN. A full duty cycle test of the whole system is included in future activities (Tsay, Frongillo, Lafko, & Zwahlen, 2014).

Tethers Unlimited, Inc. is developing a water electrolysis propulsion system called HYDROS, illustrated in Figure 4.4 that fits into 1U volume and uses water as propellant. On-orbit, water is electrolyzed into oxygen and hydrogen and these propellants are combusted as in a traditional bi-propellant thruster. This system is designed to be integrated into any cubesat configuration due

Figure 4.2. GR1 thruster. Image courtesy of Aerojet Rocketdyne Masse et al. (2015).

Figure 4.3. GR22 thruster. Image courtesy of Aerojet RocketdyneMasse et al. (2015).

Table 4.2. Green Propellant Propulsion Systems

Product	Manufacturer	Thrust	Specific Impulse	Status
GR-1	Aerojet Rocketdyne	0.26-1.42 N	231 s	TRL 6
GR-22	Aerojet Rocketdyne	5.7-26.9 N	248 s	TRL 5
1 N HPGP	ECAPS	0.25-1.00 N	204-235 s	TRL 8
HYDROS	Tethers Unlimited Inc.	0.2-0.6 N	258 s	TRL 5
BGT-X5	Busek	0.5 N	220 s	TRL 5

to a modular nozzle and its injector design. A ground test campaign between Tethers Unlimited and the Air Force Institute of Technology (AFIT) measured thrust and specific impulse for the $\frac{1}{2}$U version (James, Moser, Conley, Slostad, & Hoyt, 2015).

Cold and Warm Gas Cold gas systems are relatively simple systems that provide limited spacecraft propulsive capability and are one of the most mature technologies for small spacecraft. Thrust is produced by the expulsion of an inert, non-toxic propellant which can be stored in high pressure gas or saturated liquid forms. Warm gas systems have been used in several missions for pressurization and use the same basic principle yielding more specific impulse performance than cold gas.

Figure 4.4. HYDROS engineering unit. Image courtesy of Tethers Unlimited, Inc.James et al. (2015).

Warm and cold gases are suitable for small buses due to their very low grade of complexity and are inexpensive and robust. They can be used when small total impulse is required. Primary advantages include small impulse bit for attitude control applications and the association of small volume and low weight. Recently, new designs have improved the relatively high power requirement of these systems and there are currently thrusters that can be implemented into small buses such as 3 U cubesats. Table 4.3 shows current state of the art for cold and warm gas propulsion systems that are small spacecraft applicable.

A cold gas thruster developed by Marotta (Figure 4.5) flew on the NASA ST-5 mission 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 (Schappell, Scarduffa, Smith, & Solway, 2005).

Surrey Satellite Technology Ltd. (SSTL) has a butane propulsion system included in several small spacecraft missions for a wide range of applications in Low Earth Orbit (LEO) 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 4.6. It uses electrical power to heat the thruster and improve the specific impulse performance with respect to the cold gas mode. It has been through more than five years of design life and it uses a RS-422 interface (Gibbon, 2010).

In June 2014, the Institute for Aerospace Studies in Toronto (UTIAS) launched two small spacecraft of 15 kg each to demonstrate formation flying. The Canadian Nanosatellite Advanced

Propulsion System (CNAPS), shown in Figure 4.7, consisted of four thrusters fueled with liquid sulfur hexafluoride. This non-toxic propellant was selected since it has high vapor pressure and density which is important for making a self-pressurizing system. This propulsion module is a novel version of the previous NanoPS that flew in the CanX-2 mission in 2008 (Bonin et al., 2015).

Another recently flight-demonstrated propulsion system was flown in the POPSAT-HIP1 cubesat mission and was developed by Microspace Rapid Pte Ltd in Singapore. It consisted of a total of eight micro-nozzles that provided three rotation axes control and single-axis thrust for translational applications. The total Δv has been estimated from laboratory data to be between 2.25 and $3.05\,\mathrm{m\,s^{-1}}$. Each thruster has 1 mN of nominal thrust by using argon propellant. An electromagnetic microvalve with a very short opening time of 1 ms operates each thruster (Manzoni & Brama, 2015).

NanoSpace has developed a complete Microelectromechanical systems (MEMS) cold gas propulsion system for cubesats (Figure 4.8) that provides accurate thrust control by using four thrusters with butane propellant. 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 220 g and average power consumption is 2 W during operation (Kvell et al., 2014). This system is based on a flight-proven technology flown on the PRISMA mission, launched in 2010. Here, two thruster pods with four thrusters each were tested using Nitrogen as the propellant and each thruster provided up to 8 mN (Rangsten et al., 2012). Additionally, the MEMS cold gas system was included into the bus of the TW-1 cubesat, launched in September 2015 (Rui C. Barbosa, NASASpaceflight.com, n.d.).

The CubeSat Proximity Operations Demonstration (CPOD) is a mission led by Tyvak Nano-Satellite Systems. 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 25 mN (VACCO Industries, 2015). It uses self-pressurizing R134a 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 on more than 70000 firings (Bowen, Villa, & Williams, 2015)

Solid motors Solid rocket technology is typically utilized 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 mN range. These are restartable, have steering capabilities and are suitable for small spacecraft applications, unlike larger spacecraft systems that provided too much acceleration. Table 4.4 shows current state of the art in solid motors for small

Figure 4.5. Marotta cold gas thruster. Image courtesy of Marotta.

Figure 4.6. SSTL butane propulsion system. Image courtesy of SSTL Gibbon (2010).

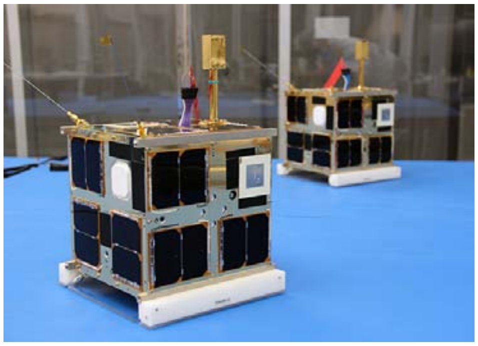


Figure 4.7. CNAPS spacecraft with UTIAS propulsion modules. Image courtesy of UTIAS website.

Figure 4.8. NanoSpace MEMS cold gas system. Image courtesy of NanoSpace.

Table 4.3. Cold and Warm Gas Propulsion Systems

Product	Manufacturer	Thrust	Specific Impulse	Propellant	Status
Micro-Thruster	Marotta	0.05-2.36 N	65 s	Nitrogen	TRL 9
Butane Propulsion System	SSTL	0.5 N	80 s	Butane	TRL 9
MEMS	NanoSpace	0.01–1 mN	50-75 s	Butane	TRL 8
POPSAT-HIP1	Micro Space	0.083-1.1 mN	32-43 s	Argon	TRL 8
CNAPS	UTIAS/SFL	12.5-40 mN	40 s	Sulfur hexafluoride	TRL 9
CPOD	VACCO	25 mN	40 s	R134a	TRL 6

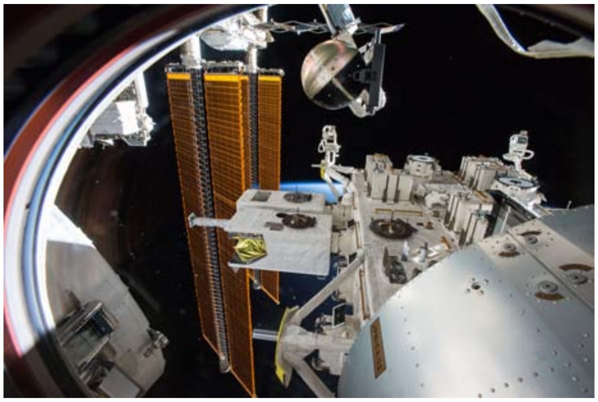


Figure 4.9. SpinSat Mission deploying from International Space Station (SpinSat top center). Image courtesy of National Aeronautics and Space Administratio.

Figure 4.10. Module of DSSP thrusters. Image courtesy of DSSP Nicholas et al. (2013).

spacecraft. These thrust vector control systems can be coupled with existing solid rocket motors to provide controllable high Δv in relatively short time. A flight campaign tested the ability of these systems 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 sec developed by Industrial Solid Propulsion (Zondervan et al., 2014).

SPINSAT, a 57 kg spacecraft launched in 2014, incorporated a set of solid motors (Figure 4.9 and Figure 4.10) which were part of the attitude control system and were developed by Digital Solid State Propulsion LLC (DSSP). The system was based on a set of Electrically Controlled Solid Propellant (ESP) thrusters that consisted of two coaxial electrodes separated by a thin layer of electric solid propellant. This material is highly energetic but non-pyrotechnic and allow for better burn control. They are only ignited if an electric current is applied, the lack of moving parts and duration control make the system suitable for small spacecraft.

In total, 72 thrusters formed the propulsion system of the spacecraft. Six of them were included in each of the twelve plugs strategically located around the bus. Performance characterization is done by firing the thrusters in pairs and measuring the changes in the spin rate by both on-board and on-ground assets (Nicholas et al., 2013).

Table 4.4. Solid Rocket Motors

Product	Manufacturer	Total Mass	Average Thrust	Specific Impulse	Status
ISP 30 sec motor	Industrial Solid Propulsion	0.95 kg	37 N	187 s	TRL 7
STAR 4G	Orbital ATK	1.5 kg	258 N	277 s	TRL 6
CAPS-3	DSSP	2.33 kg	0.3 N	Up to 900 s	TRL 8

4.2.2 Electric Propulsion Systems

Electric propulsion has experienced significant improvement in terms of available systems and maturity of components. For many small spacecraft concepts, high specific impulses are necessary to comply with Δv budgets. Depending on thruster technology, specific impulse for electric propulsion can range between 700-3000 s. However, thrust is low meaning long maneuver times. Some thrusters are more suitable for small correction maneuvers and attitude control applications due to low impulse bits while others are designed to achieve high accelerations for interplanetary spiral trajectories. A wide spectrum in propellants is offered with electric propulsion. Iodine is proposed for some technologies due to its very high density that allow high Δv maneuvers for transfer trajectories. For smaller Δv applications, solid state materials such as polytetrafluoroethylene (PTFE) are used in most Pulsed Plasma Thrusters (PPTs) while electrosprays use various forms of ionic liquid.

Resistojets Resistojets are the simplest form of electric propulsion. Thrust is produced by heating the propellant by electrical means so that the resulting gas can be expanded and expelled at large velocities out of the nozzle.**??** lists current state of the art Resistojets designs that are small spacecraft applicable.

Surrey Satellite Technology Ltd. (SSTL) has developed a resistojet propulsion system that has flown in several missions. It can work with different types of propellant such as xenon, butane or nitrogen. Thrust can be up to 100 mN and the specific impulse varies with the selected propellant ranging from 48 s for xenon to 99 s for nitrogen. The system uses power from 30 to 50 W and does not require a PPU since it works directly from the bus voltage input.

CU Aerospace and VACCO have built a Propulsion Unit for Cubesats (PUC). It consist of a full integrated system that includes controller, PPU, valves, sensors and a Micro-Cavity Discharge (MCD) thruster. High density and self pressurizing liquids are used as propellants by using the MCD heating technology together with an optimized low mass flow nozzle (Carroll et al., 2015).

CU Aerospace and VACCO Industries have also developed a Cubesat High Impulse Propulsion System (CHIPS). This module incorporates a main micro-resistojet plus four equally distributed cold gas thrusters acting as a 3-axis attitude control system. By leveraging VACCO's compact friction-less valve technology and utilizing an inert and non-toxic R-134a propellant, this system achieves a high total impulse to volume ratio. It occupies a 1 U+ space in order to target 2U and 6U spacecraft buses. A fully integrated system with flow and power control has been demonstrated at the Electric Propulsion Laboratory at the University of Urbana-Champaign, Illinois. Tests included thrust and specific impulse measurements that estimated 82 s for the warm fire mode and 47 s for the cold fire mode. It can provide up to 563 N s of total impulse and a throttleable thrust of 30 mN in warm fire mode, which is used for primary propulsion. The cold gas mode is used for the three axis attitude control and provides 323 N s of total impulse and 19 mN of thrust. The TRL of the integrated system is 5 and a second phase is currently in development (Hejmanowski, Woodruff, Burton, Carroll, & Cardin, 2015).

Busek Co Inc. has leveraged previous flight and design efforts to miniaturize fundamental components such as valves and PPUs for a micro-resistojet. This system uses non-toxic ammonia propellant and delivers a total impulse of 404 N s for main Δv applications and 23 N s for ACS (Busek Co. Inc., 2015).

Electrosprays Electrospray propulsion systems use the principle of electrostatic extraction and acceleration of ions from a propellant consisting of a negligible vapor pressure conductive salt. One of the biggest advantages of this technology with respect to other traditional electric propulsion systems is that no gas-phase ionization is required. The propellant does not need to be pressurized for storage since it flows via capillary action due to the ion evaporation process. The emission can be controlled by modulation of the voltage input in a closed loop feedback with current measurements. In addition, in some cases, both species of negative and positive ions can be utilized, avoiding the need for a neutralizer which simplifies the design and operation of the system. Expelled ions achieve very high velocities which translates into high specific impulse. Typically, the most widely used propellant in electrosprays is the ionic liquid 1-Ethyl-3-Methyl-Imidazolium Tetrafluoroborate (EMI-BF4). NASA's Advanced In-Space Propulsion (AISP) project has created a portfolio that includes the development of Microfluidic Electrospray Propulsion (MEP). Table 4.5 displays the current state of the art for small spacecraft applicable electrospray thrusters.

Electrospray technology has been advanced significantly at the The Massachusetts Institute of Technology (MIT) Space Propulsion Laboratory (SPL) and some companies have started to commercialize systems based on this effort. Figure 4.12 is the Electrospray thruster developed at MIT. Voltage versus current curves and time of flight spectroscopy among other tests have helped to understand the ionic and electrical characteristics of the thruster. MIT has demonstrated a total of 315 hours of continuous electrospray operation and a magnetically levitated thrust balance was used to measure thrust at μN levels (Mier-Hicks & Lozano, 2015). Each thruster has a total of 480 emitters, a passive propellant management system that includes a $1.2\,\text{cm}^3$ tank and an acceleration chamber. At the system level, MIT has developed the Scalable ion Electrospray Propulsion System (S-iEPS), shown in Figure 4.11, that features a total of eight thrusters that fire along a single axis. This module is able to provide $74\,\mu$N and more than 1160 s of specific impulse at a power draw of less than 1.5 W. It is light weight, about 95 g including PPU, and fits in a 0.2 U volume (Krejci et al., 2015).

Fully integrated electrospray systems, designed mainly for cubesat applications, are being developed by Accion Systems. IMPACT and MAX-1 are two different complete electrospray modules that have been through thrust measurements and lifetime and efficiency tests. IMPACT offers thrust in one direction and also 2-axis attitude control, has a wet mass of 0.5 kg and provides a total impulse of 45 Ns per axis. MAX-1 provides single-axis thrust, has a wet mass of 0.3 kg and a total impulse of 86 Ns (Accion Systems Inc., 2015).

Busek Inc. is developing a fully integrated electrospray propulsion system in the mN range. This module includes a propellant-less cathode neutralizer and a low pressure customizable tank that were leveraged from the module incorporated into the NASA ST-7/ ESA LISA Pathfinder

Table 4.5. Electrospray Propulsion Systems

Product	Manufacturer	Thrust	Power	Specific Impulse	Status
S-iEPS	MIT	$74\,\mu$N	1.5 W	1160 s	TRL 6
IMPACT	Accion Systems Inc.	$60\,\mu$N per axis	0.75 W per axis	1200 s	TRL 5
MAX-1	Accion Systems Inc.	$120\,\mu$N	1.6 W	2000 s	TRL 5
1 mN Electrospray	Busek	0.7 mN	15 W	800 s	TRL 5
100μ	Busek	0.1 mN	5 W	2300 s	TRL 5

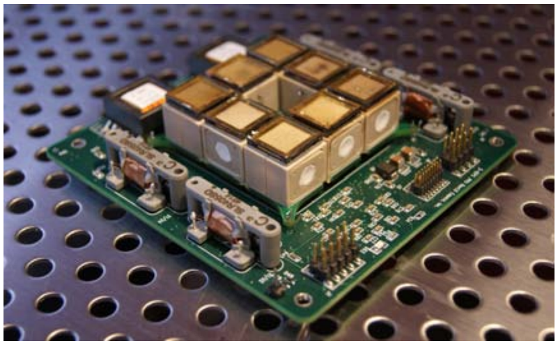


Figure 4.11. S-iEPS propulsion system. Image courtesy of MIT SPL.

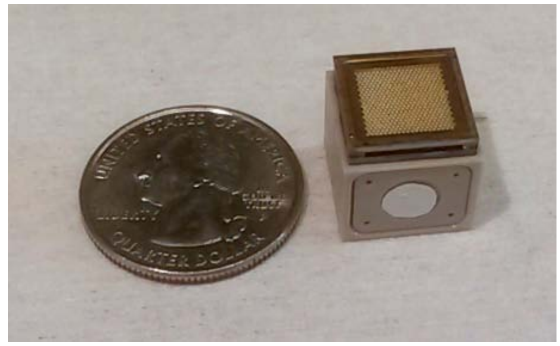


Figure 4.12. Electrospray thruster. Image courtesy of MIT SPL.

spacecraft. The system uses 15 W of power and provides 675 N s with 50 mL of propellant and has a mass of 1.15 kg. Tests in relevant conditions are being performed to raise the TRL from 5 to 6 (Busek Co. Inc., 2015). The system features a 100 μN class thruster that provides a specific impulse of 2300 s and consumes 5 W. It can deliver 85 m s^{-1} to a 4 kg cubesat by having a wet mass of 320 g and 10 mL of an ionic liquid propellant that has been fully characterized during the ST-7 flight program (Busek Co. Inc., 2015).

The Micro Devices Laboratory (MDL) at the Jet Propulsion Laboratory (JPL) has developed a highly integrated and scalable indium MEP system (Figure 4.13) that has a dry mass of less than 10 g and provides thrust in the 20-100 μN range. Indium metal is stored in solid form and heated afterwards to be used as propellant. Over 10 hours of continuous operation tested an initial prototype assembly (JPL, 2013).

Ion Engines In ion thrusters, propellant is ionized by using various plasma generation techniques. Radio Frequency (RF) engines achieve thrust by producing ions with electrode-less inductive discharges that are typically achieved by using a helical coil at frequencies in the range of 1 MHz. The particles are then accelerated at very high exhaust velocities by electrostatic grids. These devices have a high efficiency when compared to other electric propulsion systems. In addition, the absence of electrodes avoids potential threats to thruster lifetime which is only limited by grid erosion. Table 4.6 displays the current state of the art ion engines for small spacecraft.

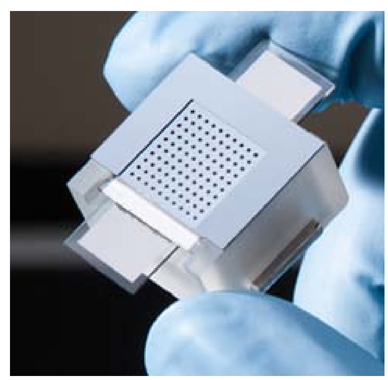


Figure 4.13. Indium MEP . Image courtesy of Jet Propulsion Laboratory.

Busek is developing a RF ion thruster that can operate with both xenon and iodine propellants, achieving similar performances (Tsay, Frongillo, & Hohman, 2015). The BIT-3 engine has 3 cm diameter grids and is capable of providing variable specific impulse and thrust. At 60 W of operating power, it can achieve an efficiency of 35%. Recent test performance results on the iodine version have shown that thrust-to-power ratios are similar to the ones achieved with xenon as propellant. Complementary technology associated with the thruster such as propellant tanks and feed system have been demonstrated as well for this propellant. The compatibility with iodine is made possible since the plasma-generation chambers in RF engines are generally built with ceramic materials that are resistant to corrosion. A lower TRL, smaller thruster version of just 1 cm grids, the BIT-1, is also under development by Busek (Tsay et al., 2015).

Recently, the Japanese Proximate Object Close flyby with Optical Navigation (PROCYON) mission has shown successful operation of a propulsion system in Space. The Ion thruster and Cold-gas thruster Unified Propulsion System (I-COUPS) was designed at the University of Tokyo and is an integrated system comprised of two sets of ion and cold gas thrusters. Both technologies share the same gas feed system that provides xenon to be used as propellant. This combines high thrust and large Δv capabilities. Cold gas thrusters are used for reaction wheel de-saturation and small correction burns, while ion engines are kept for deep space maneuvers. In total, the mass of the propulsion system is less than 10 kg, including propellant. The ion engines in the I-COUPS unit are an evolution of the Miniature Ion Propulsion System (MIPS), which was previously launched on board the Hodoyoshi-3/4 mission in October 2014. This spacecraft was placed on a Sun Synchronous Orbit and had 65 kg of mass. The MIPS had a wet mass of 8.1 kg with 1 kg of propellant mass. Ion thruster operation was proven by providing continuous acceleration (Takegahara et al., 2015).

Airbus is developing a family of RF ion thrusters over the last few years and has designed the RIT-μX (Figure 4.14) for small spacecraft buses and for high precision maneuvers. Various thrust configurations were proposed and tested. In 2013, a system in the 50-500 μN range was demonstrated and thrust resolution, linearity, response and noise met LISA Pathfinder mission requirements, which increased the TRL to 5. The nominal power to operate is less than 50 W and the specific impulse is between 300 and 3000 s, depending on the configuration. The maximum demonstrated specific impulse was 3500 s. It uses xenon as propellant and it has a dry mass of 440 g (Leiter et al., 2015).

Figure 4.14. RIT μX propulsion unit. Image courtesy of Airbus.

Pulsed Plasma and Vacuum Arc Thrusters In Pulsed Plasma Thrusters (PPTs), thrust is produced by triggering a high voltage discharge between two electrodes that result in an electric arc that typically ablates a solid state material. A self-generated magnetic field is produced and then accelerates and expels particles from the thruster head. Typically the propellant is pushed forward by a spring as it is being consumed. This technology has significant heritage from larger spacecraft versions and due to its simplicity, miniaturization was more achievable compared to other electric propulsion systems. Major problems such as electrode shortcuts or non-uniform propellant ablation are under active research. These systems are suitable for attitude control and fine pointing applications since the trigger pulse of the discharge can be adjusted, small impulse bits can be

Table 4.6. Ion Propulsion Systems and thrusters

Product	Manufacturer	Thrust	Power	Specific Impulse	Propellant	Status
BIT-3	Busek	1.4 mN	60 W	3500 s	Xenon-Iodine	TRL 5
BIT-1	Busek	0.1 mN	10 W	2250 s	Xenon	TRL 5
I-COUPS	University of Tokyo	0.3 mN	N/A	1000 s	Xenon	TRL 8
RIT μX	Airbus	50-500μN	50 W	300-3000 s	Xenon	TRL 5

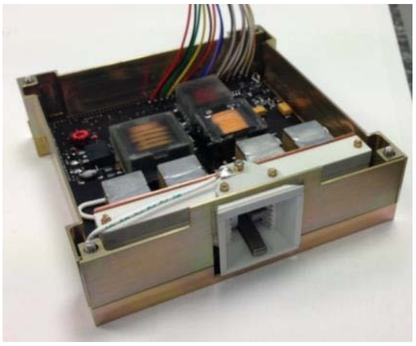


Figure 4.15. PPTCUP propulsion system. Image courtesy of Mars Space and Clyde Space Ciaralli et al. (2015).

Figure 4.16. BmP-220 propulsion unit. Image courtesy of Busek Co Inc..

achieved that allow for high precision. Typically the propulsion system consists of just a PPU that controls the required discharge to operate the thrusters by storing energy in a capacitor bank, which accounts for a significant portion of the system mass. Various materials have been tested for PPT utilization, however, PTFE is the industry standard. Table 4.7 accounts for current small spacecraft applicable state of the art PPT thrusters.

Mars Space Ltd. and Clyde Space Ltd. have developed a compact propulsion module (Figure 4.15) specifically designed to provide maneuvering capabilities to cubesats. At the University of Southampton, thermal cycling, vibration, Electro Magnetic Compatibility (EMC) and lifetime tests were performed. Vibration test results showed that the module sustains the mechanical vibrations during launch and Electro-Magnetic (EM) noise levels during discharge were mostly compliant with guidelines. The system has a total mass of 270 g and is characterized by an average specific impulse of 655 s and a total impulse of 48.2 N s. It has a single thruster that uses PTFE propellant and is side-fed to maximize discharge length, with an electrode design that minimizes carbonization (Ciaralli et al., 2015).

Busek has extensive experience in the development of pulsed plasma propulsion. Their Micro Pulsed Plasma Altitude Control System (MPCAS) flew on the FalconSat-3 mission in 2007. This module consisted of eight thrusters and provided attitude control with precise impulse bits of 80 μN s at moderate power of less than 10 W (France, Anthony, & Hart, 2011) by using PTFE propellant. The system had heritage from previous investigations conducted at the Air Force Research Laboratory (AFRL) (Bayley, Shoptaugh, Percoski, & Lawrence, 2010) and has been evolving since this first approach. The BmP-220 is the latest version of the Busek PPT family, consumes less than 7.5 W, weighs less than 0.5 kg and all required components fit in a $10 \times 10 \times 7$ cm volume, see Figure 4.16. It can provide up to 220 N s of total impulse with 40 g of propellant. An innovative solid state switching technology enables the implementation of several emitters in a single unit. The specific impulse is 536 s and the minimum impulse bit is 0.02 mN s. The system TRL is estimated to be 5 (Busek Co. Inc., 2015).

Vacuum arc thrusters are another type of plasma-based propulsion device that produces thrust by propellant ionization. This technology consist of two metallic electrodes separated by a dielectric insulator. One of them is used as solid metallic propellant and it is consumed as the thruster operates. Advantages of using a metallic solid propellant over the more traditional option of PTFE are a lower energy consumption per ionized mass, high pulse stability and higher repetition rates due to the thermal properties of metals.

The Micro-Cathode Arc Thruster (μCAT) developed by The George Washington University

Table 4.7. Pulsed Plasma and Vacuum Arc Propulsion Systems

Product	Manufacturer	Thrust	Power	Specific Impulse	Propellant	Status
PPTCUP	Mars Space and Clyde Space	40 μN	2 W	655 s	PTFE	TRL 6
NanoSat PPT	Mars Space and Clyde Space	90 μN	5 W	640 s	PTFE	TRL 5
μCAT	GWU and USNA	1 to 50 μN	2 to 14 W	2500-3000 s	Titanium	TRL 7
BmP-220	Busek	20 μN-s Impulse bit	1.5 W	536 s	PTFE	TRL 5
MPACS	Busek	80 μN-s Impulse bit	10 W	827 s	PTFE	TRL 8

(GWU), uses vacuum discharges to ablate the cathode material. It consists of a 5 mm thruster head that contains concentrically aligned and cylindrically shaped anode, cathode and insulator. By sending a pulse created by the PPU to the electrode interface, a high voltage arc is produced across it (Keidar et al., 2015). The μCAT offers a quasi-perfect ionization degree of the plasma particles in the exhaust plume, giving a near zero back flux. This propulsion technology generates thrust by consuming cathode material made of titanium with a high voltage vacuum arc, producing highly ionized plasma jets with high exhaust velocities. In addition, the incorporation of an external magnetic coil improves significantly the capabilities of the thruster (Keidar et al., 2013).

An autonomous and modular micro electric propulsion system based on this technology has been designed and built at NASA Ames Research Center in partnership with GWU. This module fits into a 0.2 U volume and consists of one Printed Circuit Boards (PCB) that command and operate up to four vacuum arc thrusters. Two PPUs, implemented in the main PCB, create the necessary discharges to operate the thruster that have an average thrust in the μN range which is controlled by selecting different thrusting frequencies. This system was tested and measured in relevant conditions of vacuum at NASA Glenn Research Center with a high accuracy torsional thrust stand.

Furthermore, a partnership between GWU and The United States Naval Academy resulted in the integration of a μ-CAT propulsion system into the Ballistically Reinforced Communication Satellite (BRICSAT). This mission was launched in May of 2015 and consisted of four PPUs to operate four thrusters in total. Preliminary retrieved data has shown that the system successfully accomplished the objective of detumbling the spacecraft. After two days, the propulsion system was able to reduce the initial tumbling from $30\,^{\circ}\,s^{-1}$ to nearly $1.5\,^{\circ}\,s^{-1}$, increasing the TRL of this system from 6 to 7 (Hurley et al., 2015).

Hall Effect Thrusters Hall Effect propulsion is a mature technology for large spacecraft systems. Miniaturization of some of the components, such as neutralizers, is complicated to achieve and power consumption is relatively high compared to other electric propulsion technologies. However, an improvement has been made to integrate complete Hall Effect propulsion systems that can potentially support large transfers for interplanetary missions. See Table 4.8 for current state of the art technology in Hall Effect Thrusters for small spacecraft.

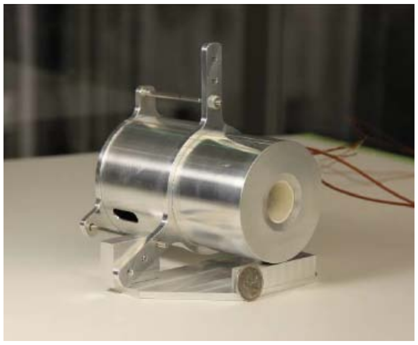


Figure 4.17. Cylindrical Hall Effect Thruster . Image courtesy of UTIAS SFL.

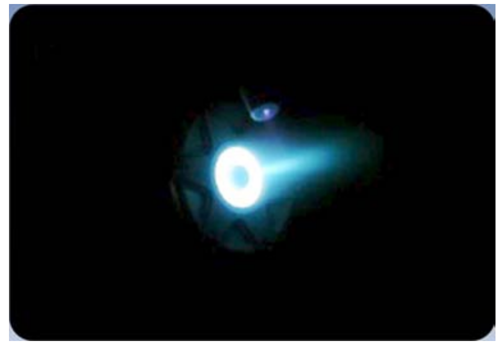


Figure 4.18. BHT-200 during operation . Image courtesy of Busek Co Inc..

Busek has developed a complete Hall Effect thruster propulsion system for small spacecraft. The BHT-200, shown in Figure 4.18, is suitable for small spacecraft buses of relatively high mass and power supply since it needs 100-300 W to operate. This system has flight heritage from the 2006 TacSat-2 mission, and was part of the payload in the FalconSat-5 mission in 2010. In addition, it will be flown in the FalconSat-6 mission, scheduled for 2016. This model can operate with multiple propellants (Busek Co. Inc., 2015). The utilization of iodine will advance the technology due to its increased density over xenon and its lower operating pressure, which reduces cost and risk implications. More details can be found in subsection 4.3.

The HT100, developed by Sitael Aerospace, has been extensively tested through campaigns that include characterization under thermal-vacuum conditions and structural analysis under heavy loads. Erosion has been observed in an endurance test that lasted for 1650 hours where no thermal problems or important performance reduction was observed. The nominal operation power at 175 W gives a thrust range of 5-15 mN. The thruster mass is 440 g, it utilizes xenon as propellant and it can achieve a peak total efficiency of up to 35% and a maximum specific impulse of 1350 s. The HT100 has been selected for an in-orbit validation program by the European and Italian space agencies. A larger version, the HT400, operates at a nominal power of 400 W and it is at TRL 5 (Misuri, Ducci, Albertoni, Andrenucci, & Pedrini, 2015).

The Space Flight Laboratory (SFL) at the University of Toronto is developing a low power cylindrical Hall thruster (Figure 4.17) that operates below 200 W and has a diameter of 26 mm for the ionization chamber. The cylindrical geometry of the ionization chamber was chosen in order to overcome the challenges of the annular chamber of traditional Hall thrusters. With this configuration, better efficiencies can be achieved while maintaining a sufficient thrust magnitude between 2.5-12 mN. Annular ionization chambers are mechanically simpler and produce high thrust to power ratios that are beneficial for small spacecraft applications. However, the efficiency still gets reduced when this chamber gets redesigned to optimize low power operation.

Excluding cathode, the weight of the first prototype was 1.6 kg. This device went under magnetic characterization and performance tests in vacuum. It uses xenon as a baseline propellant due to its improved performance over other gases such as argon. Further testing and design modifications will be done in order to raise the TRL from 5 to 6 in early 2016 (Pigeon et al., 2015).

4.2.3 Propellant-less Systems

Systems that do not carry propellant for thrust generation are an ideal candidate for small spacecraft. They avoid complexity and reduce mass limitations. They can achieve high accelerations that can

Table 4.8. Hall Effect Propulsion Systems and thrusters

Product	Manufacturer	Thrust	Power	Specific Impulse	Status
BHT-200	Busek	13 mN	200 W	1390 s	Xenon TRL 8 , Iodine TRL 4
HT100	SITAEL	5-15 mN	175 W	up to 1350 s	Xenon TRL 6
CHT	UTIAS SFL	6.2 mN	200 W	1139 s	Xenon TRL 5

potentially propel an object for interplanetary travel.

Solar sails are the most popular method of propellant-less propulsion. They take advantage of solar radiation pressure by reflecting photons on a large sail made of a highly reflective material. Several missions have been conducted to demonstrate this technology for large buses such as the Japanese IKAROS, launched in 2010. Regarding small spacecraft, NASA has been conducting extensive research that resulted in the launch in 2010 of NanoSail-D2, a technology demonstration mission managed and designed by NASA Ames Research Center and NASA Marshall Space Flight Center. The sail had a deployed surface area of $10\,\mathrm{m}^2$, was made of a thin highly reflective material called CP-1 and weighted 4.2 kg (Alhorn et al., 2011).

One of the most recent solar sail mission for small spacecraft was performed by The Planetary Society in 2015. The 3U LightSail-A spacecraft completed its technology demonstration test in Space by fully deploying a solar sail in LEO. The dimensions were 5.6 m on a side and $32\,\mathrm{m}^2$ of total area once it was deployed. In 2016, a follow up mission, LightSail-B will complete the project by leveraging the experience acquired in the first flight and perform additional maneuvers. This spacecraft will fly in a Falcon heavy rocket to an approximately 720 km LEO orbit, where an orbital change in altitude or inclination will be performed (Ridenoure et al., 2015).

4.3 On the Horizon

As propulsion technology matures, more small spacecraft missions will incorporate propulsion systems on boardallowing for more complex mission architectures. This section will cover near-term spacecraft with propulsion as well as promising technologies that will become an important propulsion asset for future missions.

Technologies in development The Cubesat Ampibolar Thruster (CAT) is a novel device developed by the University of Michigan that utilizes a magnetic helicon discharge to ionize the propellant. The thruster (Figure 4.19) does not require a separate electron source and no resultant magnetic dipole is produced. High plasma density is created through a high efficiency helicon RF source and a large accelerating electric field is achieved. A large variety of propellants in solid or liquefied state can be used thanks to the electrode-less design of the thruster. Iodine has been presented as the most promising propellant due to its low cost and high storage density. This system can

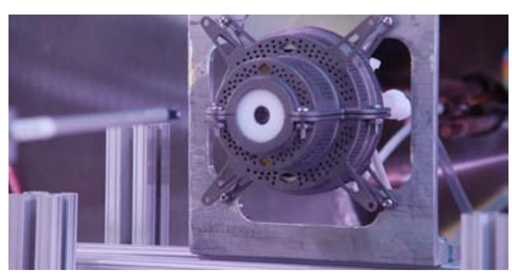


Figure 4.19. Cubesat Ambipolar Thruster (CAT) . Image courtesy of Phase Four LLC.

achieve an estimated specific impulse of 1010 s when using iodine. Currently, the PPU is still in development phase and some of the components for iodine utilization are at TRL 3(Spangelo & Longmier, 2015). Initial tests were performed by using both xenon and argon as propellant. For xenon, CAT was designed to operate on 10-50 W in order to address some of the power limitations that small spacecraft face. In this configuration, the TRL is 4 and thrust and specific impulse are in the 0.5-4 mN range and the 400-800 s range respectively (Sheehan, Collard, Ebersohn, & Longmier, 2015). The company Phase Four LLC is developing an integrated flight unit of the CAT (Doug Messier, Parabolic Arc, 2015).

There are several other propulsion technologies currently being developed: Ventions LLC is working on an integrated 3 U cubesat propulsion system using non-toxic propellant; hybrid non-toxic/cold gas propulsion system for 6 U and 12 U spacecraft by Planetary Resources Development Corporation; and a non-toxic solid rocket for cubesats that allows for second ignition and utilizes an aluminized version of an Electric Solid Propellant (ESP) from Digital Solid State Propulsion (DSSP). ESPs provide more safety for handling compared to traditional solid energetic propellants and are electrically ignited (NASA SBIR, 2014).

Orbital Technologies Corporation (ORBITEC) is developing the Miniature Nontoxic Oxide-Propane (MINNOP) propulsion system. It consists of a bipropellant system for small spacecraft that can provide a significant increment in specific impulse performance with respect to hydrazine systems when used in bi-propellant mode and small levels of minimum impulse bit when used in cold gas mode. Current efforts are pointed towards the demonstration of the bipropellant thrust chamber and ignition within suitable weight constraints in order to fit into a 1 U form factor (NASA SBIR, 2014).

Another high-performance propellant is a nitrous oxide fuel blended mono-propellant known as NOFBX developed by Firestar technologies. This self pressurizing non-toxic propellant can offer more than 320 s of specific impulse and it provides 3.5 to 3.9 times higher specific energy density than hydrazine (Mungas et al., 2011).

The Inductively Coupled Electromagnetic (ICE) thruster is a novel technology that is being developed by MSNW LLC. This system uses a small integrated RF oscillator to generate plasma. The total volume of the thruster and the PPU is expected to be less than 0.125 U. One of the main advantages is that this system can virtually use any liquid propellant. Anticipated operating power is between 10-50 W. The current goal is to achieve TRL 4 (NASA Press release, n.d.).

An experimental characterization of a low power helicon thruster has been performed at the Stanford University's Plasma Physics Laboratory. Tests were conducted by operating on water and argon propellants. Thrust was observed at various performance levels, achieving magnitudes of 2-5 μN. Future work in on-going and include optimization for greater performance and thrust stand measurements (Biggs et al., 2015).

NanoAvionics JSC is developing a non-toxic mono-propellant propulsion system. It uses ADN as propellant and gives 252 s of specific impulse. Current efforts are focused on the miniaturization of a catalyst bed heater system and development of fuel feeding equipment. This module will be ready for flight in the LituanicaSAT-2 3 U cubesat as part of the European QB50 initiative and is currently TRL 4.

The Mechanical and Aerospace Engineering Department at Utah State University has built and tested a non-toxic 22 N thruster for small spacecraft. This unit uses innovative propellants: compressed gaseous oxygen and ABS plastic. Additive manufacturing is used to build various system components such as the nozzle or the fuel grain. The system is restartable and can be throttled from 1 N to 22 N while maintaining performance and robustness. The achieved laboratory specific impulse was above 230 s (Whitmore, Merkley, Spurrier, & Walker, 2015).

Princeton Plasma Physics Laboratory, with The Aerospace Corporation, have tested the performance of a small Cylindrical Hall Thruster with permanent magnets. The measured thrust was in the 3-6.5 mN range with a specific impulse of 1000-1900 s. Efficiency studies were also conducted at a discharge voltage of 300 V achieving a maximum thruster efficiency over 20%. This version demonstrated even superior performance in comparison to another version that utilizes electromagnets coils (Spektor et al., 2011).

Future small spacecraft missions with propulsion Due to the significant improvement in propulsion technologies, mission concepts that were previously limited to large spacecraft are now possible with small buses. Interplanetary missions are becoming less costly, and therefore several institutions are assuming more risks to perform science missions with higher payoffs. As an example, NASA's Exploration Mission (EM-1) is going to be used to provide secondary payload opportunity for up to eleven 6 U cubesat. The mission trajectory would provide access to deep space or a Moon orbit.

The iodine satellite (iSAT) mission, a partnership project between NASA Marshall Space Flight Center, Busek Co. Inc. and NASA Glenn Research Center, consists of a 12 U cubesat in a high performance integrated bus configuration that will perform propulsive inclination and altitude plane changes. This spacecraft will include a Busek's BHT-200-I propulsion system with iodine propellant that offers a similar performance than the xenon version when operating at the same power level. It is expected to be delivered for launch in the second quarter of 2017 (Dankanich, Polzin, Calvert, & Kamhawi, 2014) and an 80 hour endurance test of the engineering model has been performed at NASA Glenn Research Center. The objective was to characterize the performance of the thruster over the throttling range, to demonstrate feed system components and to study the plume and thermal models during operation (Polzin et al., 2015).

NASA Ames and Glenn Research Centers are working on the Pathfinder Technology Demonstration (PTD) project which consists of a series of 6 U cubesats that will be launched to test the performance of new subsystem technologies on orbit. For the first flight version, various state of the art electrospray systems, previously discussed in subsubsection 4.2.2, are being considered.

JPL is developing the InSight mission which is going to be launched in March 2016 that will incorporate two identical cubesats as part of the Mars Cube One (MarCO) technology demonstration. These spacecraft will need to perform up to five Trajectory Correction Maneuvers (TCMs) during the mission to Mars. These cubesats include an integrated propulsion system, developed by VACCO Industries, that contains four thrusters for attitude control and other four for the TCMs. The module uses cold gas R-236FA as propellant, produces 755 N s of total impulse and weighs 3.49 kg(Klesh & Krajewski, 2015).

A team at Purdue University and NASA Goddard Space Flight Center is developing the Film Evaporation MEMS Tunable Array (FEMTA). This technology consists of a group of nozzles made of high aspect ratio slots. Each nozzle produces thrust by applying local heat to a propellant capillary interface and the main advantages are the absence of any mechanisms and a low power consumption, in the order of mW. Up to three generations of these devices have been built and improved over time. Vanadium and platinum heaters were used for the most updated version and thrust, propellant and mass flow rate response have been characterized. Thrust levels from 15 to 600 μN were observed at less than 100 mW of input power while specific impulse ranged from 5 to 40 s. Repeatable thrust pulses were consistent in magnitude and could be controlled. This system is a promising option for attitude control and small maneuver applications in cubesats (Cofer, O'Neill, Heister, Alexeenko, & Cardiff, 2015).

Two separate 3 U cubesats are part of the Interplanetary NanoSpacecraft Pathfinder In a Relevant Environment (INSPIRE) mission. These spacecraft will be placed in an Earth escape trajectory in order to test the performance of the communication, navigation and operations segments in deep space. A cold gas system developed by the University of Texas, Austin, has been included that utilizes the additive manufacturing techniques that were previously used for the MiPS cold gas module. The MiPS flew in the MEPSI-3 mission from the Aerospace Corporation (Hinkley, 2008), (Cardin, Coste, Williamson, & Gloyer, 2003). Further research was conducted by UT Austin to redefine the 3D printing process to adapt the system to the Bevo-2 and ARMADILLO mission concepts. The additive manufacturing process allows the fabrication of complex features in small volumes and a saturated liquid propellant is released through a converging-diverging nozzle in order to produce thrust. Tests have measured specific impulse in the range of 65-89 s and thrust in the range of 110-150 mN across different temperatures (Arestie, Hudson, & Lightsey, 2012). A version of this propulsion unit will be used for attitude control maneuvers and nominal flight operations for the INSPIRE mission (Klesh et al., 2013).

NEA Scout and Lunar Flashlight are two NASA JPL missions that are going to be launched as part of EM-1, scheduled for 2018. Both of the interplanetary 6 U cubesats will deploy an identical sail of $80\,\mathrm{m}^2$ of area with $0.0601\,\mathrm{mm\,s}^{-2}$ of characteristic acceleration. NEA Scout solar sail will be used as a main propulsion system whereas Lunar Flashlight sail will be used mainly for station keeping and to reflect light into selected lunar craters once in orbit. The duty cycle for NEA Scout is 90% while for Lunar Flashlight is 85% (Carlisle et al., 2015).

4.4 Conclusion

A significant variety of propulsion technologies are currently available for small spacecraft. While cold gas and pulsed plasma thrusters present an ideal option for attitude control applications, they have limitations for more ambitious maneuvers such as large orbital transfers. Other alternatives such as hydrazine, non-toxic propellants and solid motors provide a high capability and are suitable for medium size buses and missions that require higher Δv budgets. Some spacecraft have already flown with these systems or are being scheduled to fly in the next year. For the near future, the focus is placed on non-toxic propellants that avoid safety and operational complications and provide sufficient density and specific impulse. The application of this technology in cubesats is still in development as some of the components need to be scaled down to comply with volume, power and mass constraints.

Electrosprays, Hall Effect thrusters and ion engines are in an active phase of development and active testing and technology demonstrations are expected for different bus sizes. These propulsion technologies will allow spacecraft to achieve very high Δv and ,therefore, to perform interplanetary transfers with low thrust.

Several other technologies, as well as new versions of existing systems with improved capabilities, are being proposed and a wide range of mature options in the following years are forecasted. As the industry progresses and more launches are scheduled, more propulsion systems will be included on board small spacecraft , increasing the average TRL for this subsystem.

References

Accion Systems Inc. (2015). *MAX-1 Scalable electric propulsion system for small satellites.* http://static1.squarespace.com/static/5446faa2e4b025843cfc6731/t/549c68cee4b0b2b297f4fa09/1419536590919/MAX-1+brochure.pdf. (Acccessed: 2015-11-02)

Aerojet Rocketdyne. (2015). *Aerojet Rocketdyne official website.* https://www.rocket.com/propulsion-systems/. (Acccessed: 2015-11-02)

Alhorn, D. C., Casas, J. P., Agasid, E. F., Adams, C. L., Laue, G., Kitts, C., & O'Brien, S. (2011). Nanosail-D: The Small Satellite That Could! In *25th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2011.

Arestie, S., Hudson, B., & Lightsey, G. (2012). Development of a Modular Cold Gas Propulsion System for Small Satellite Applications. *The Journal of Small Satellites*, *1*(2), 63-74.

Bayley, D. J., Shoptaugh, B. J., Percoski, W. D., & Lawrence, T. J. (2010). *The FalconOPS Program: Space Operations at the United States Air Force Academy* (Tech. Rep.). United States Air Force Academy, Colorado: United States Air Force Academy.

Biggs, D., Avery, S., Raymond, L., Liang, W., Gascon, N., Fabris, A. L., ... Cappelli, M. (2015). A Compact Helicon Thruster for CubeSat Applications. In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan.

Bonin, G., Roth, N., Armitage, S., Newman, J., risi, B., & Zee, R. E. (2015). CanX-4 and CanX-5 Precision Formation Flight: Mission Accomplished! In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2015.

Bowen, J., Villa, M., & Williams, A. (2015). CubeSat based Rendezvous, Proximity Operations, and Docking in the CPOD Mission. In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2015.

Busek Co. Inc. (2015). *BmP-220 Micro-Pulsed Plasma Thruster.* `http://www.busek.com/index_htm_files/70008502F.pdf`. (Acccessed: 2015-11-02)

Cardin, J. M., Coste, K., Williamson, D., & Gloyer, P. (2003). A Cold Gas Micro-Propulsion System for CubeSats. In *17th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2003.

Carlisle, G., Landau, D., Grebow, D., Lantoine, G., Nandi, S., Gustafson, E., ... Stuart, J. (2015). Concurrent Mission Design of NEA Scout & Lunar Flashlight, Solar Sail CubeSat Missions. In *Proceedings from AIAA Space Operations and Support Technical Committee Improving Space Operations Workshops.*

Carpenter, C., Schmuland, D., Overly, J., & Masse, R. (2014). Test Results for the MPS-120 and MPS-130 CubeSat Propulsion Systems. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Carroll, D. L., Cardin, J. M., Burton, R. L., Benavides, G. F., Hejmanowski, N., Woodruff, C., ... Bhandari, R. (2015). Propulsion Unit for CubeSats (PUC). In *62nd JANNAF Propulsion Meeting.* Nashville, TN, 1-5 June 2015.

Ciaralli, S., Coletti, M., & Gabriel, S. B. (2015). Qualification of a Pulsed Plasma Thruster for CubeSat Propulsion (PPTCUP). In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan.

Cofer, A., O'Neill, W., Heister, S., Alexeenko, A., & Cardiff, E. (2015). Film-Evaporation MEMS Tunable Array for Low-Mass SmallSat Propulsion: Design Improvements and Thrust Characterization. In *51st AIAA/SAE/ASEE Joint Propulsion Conference.* Orlando, Florida.

Dankanich, J. W., Polzin, K. A., Calvert, D., & Kamhawi, H. (2014). The iodine Satellite (iSAT) Hall Thruster Demonstration Mission Concept and Development. In *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference.* 28-30 Jul. 2014; Cleveland, OH; United States.

Dinardi, A., Beckel, S., & Dyer, J. (2013). Implementation and Continued Development of High Performance Green Propulsion in the United States. In *AIAA 2013-5441.*

Doug Messier, Parabolic Arc. (2015). *Phase Four Receives 1 Million DARPA Contract for CubeSat Thruster.* `http://www.parabolicarc.com/2015/11/25/phase/`. (Acccessed: 2015-11-30)

Dyer, J., Dinardi, A., & Anflo, K. (2013). First Implementation of High Performance Green Propulsion in a Constellation of Small Satellites. In *27th Annual Small Satellite Conference.*

Logan, Utah, 2013.

France, M. E., Anthony, J. F., & Hart, S. (2011). USAFA Astronautics Capstone Program—Proving Ground For Future Operationally Responsive Space Leaders. In *AIAA Reinventing Space Conference, AIAA-RS-2011-1002.*

Gibbon, D. (2010). A Review of the use of butane as a low cost propellant. In *Space Propulsion Conference.* San Sebastian, Spain, May 2010.

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

Hinkley, D. (2008). A Novel Cold Gas Propulsion System for Nanosatellites and Picosatellites. In *22nd Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2008.

Hurley, S., Teel, G., Lukas, J., Haque, S., Keidar, M., Dinelli, C., & Kang, J. (2015). Thruster Subsystem for the United States Naval Academy's (USNA) Ballistically Reinforced Communication Satellite (BRICSat-P). In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan, July 2015.

James, K., Moser, T., Conley, A., Slostad, J., & Hoyt, R. (2015). Performance Characterization of the HYDROS Water Electrolysis Thruster. In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2015.

JPL. (2013). *Microfluidic Electrospray Propulsion May Allow Microspacecraft to Fly to Mars or the Asteroid Belt.* http://microdevices.jpl.nasa.gov/news/news-microfluidic-electrospray-propulsion.php. (Acccessed: 2015-11-10)

Keidar, M., Haque, S., Zhuang, T., Shashurin, A., Chiu, D., Teel, G., ... Uribe, E. (2013). Micro-Cathode Arc Thruster for PhoneSat Propulsion. In *27th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2013.

Keidar, M., Zhuang, T., Shashurin, A., Teel, G., Chiu, D., Lukas, J., ... Brieda, L. (2015). Electric propulsion for small satellites. *Plasma Physics and Controlled Fusion 57 (2015) 014005 (10pp).*

Klesh, A., Baker, J., Castillo-Rogez, J., Halatek, L., Murphy, N., Raymond, C., ... Lightsey, G. (2013). INSPIRE: Interplanetary NanoSpacecraft Pathfinder In Relevant Environment. In *AIAA SPACE 2013 Conference and Exposition.* San Diego, California, September 2013.

Klesh, A., & Krajewski, J. (2015). MarCO: CubeSats to Mars in 2016. In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2015.

Krejci, D., Mier-Hicks, F., Fucetola, C., Lozano, P., Schouten, A. H., & Martel, F. (2015). Design and Characterization of a Scalable ion Electrospray Propulsion System. In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan.

Kvell, U., Puusepp, M., Kaminski, F., Past, J.-E., Palmer, K., Gronland, T.-A., & Noorma, M. (2014). Nanosatellite orbit control using MEMS cold gas thrusters. In *Proceedings of the Estonian Academy of Sciences, 63, 2S, 279–285.*

Leiter, H., Altmann, C., Kukies, R., J.Kuhmann, Post, J.-P., Berger, M., & Rath, M. (2015). Evolution of the AIRBUS DS GmbH Radio Frequency Ion Thruster Family. In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan.

Manzoni, G., & Brama, Y. L. (2015). Cubesat Micropropulsion Characterization in Low Earth Orbit. In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2015.

Masse, R. K., Spores, R. A., Kimbrel, S., allen, M., Kimbrel, S., & McLean, C. (2015). Enabling High Performance Green Propulsion for SmallSats. In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2015.

McLean, C., Deininger, W., Marotta, B., Spores, R., Masse, R., Smith, T., ... Bacha, C. (2015).

Green Propellant Infusion Mission Program Overview,Status, and Flight Operations. In *51st AIAA/ASME/SAE/ASEE Joint Propulsion Conference.* Orlando, Florida, July 27-29, 2015.

Mier-Hicks, F., & Lozano, P. C. (2015). Thrust Measurements of Ion Electrospray Thrusters using a CubeSat Compatible Magnetically Levitated Thrust Balance. In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan, July 2015.

Misuri, T., Ducci, C., Albertoni, R., Andrenucci, M., & Pedrini, D. (2015). SITAEL Low Power Hall Effect Thrusters for Small Satellites. In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan.

Moog ISP. (2014). *Moog Monopropellant thrusters brochure.* `http://www.moog.com/literature/Space_Defense/ISP/Monopropellant_Thrusters_Rev_0613.pdf`. (Acccessed: 2015-11-05)

Mungas, G., Vozoff, M., Rishikof, B., Strak, D., London, A., Fryer, J., & Buchanan, L. (2011). NOFBX Monopropulsion Overview. In *14th Annual FAA Commercial Space Transportation Conference.*

NASA Press release. (n.d.). *Technology Development Project Selections .* `https://www.nasa.gov/content/technology-development-project-selections/#.Vmsn7L83L-s`. (Acccessed: 2015-11-22)

NASA SBIR. (2014). *SBIR.* `sbir.nasa.gov/`. (Acccessed: 2015-11-15)

Nicholas, A., Finne, T., Galysh, I., Mai, A., & Yen, J. (2013). CubeSat Solid Rocket Motor Propulsion Systems providing delta-Vs greater than 500 m/s. In *27th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2013.

Persson, M. (2015). Commercial Breakthrough for ECAPS HPGP replacing Hydrazine. In *Rymdforum.* Gothenburg, Sweden, 10 March 2015.

Pigeon, C. E., Orr, N. G., Larouche, B. P., Tarantini, V., Bonin, G., & Zee, R. E. (2015). A Low Power Cylindrical Hall Thruster for Next Generation Microsatellites. In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Polzin, K. A., Peeples, S., Seixal, J., Mauro, S., Lewis, B., Jerman, G., … Lee, L. (2015). Propulsion System Development for the Iodine Satellite (iSAT) Demonstration Mission. In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan.

Rangsten, P., Bejhed, J., Johansson, H., Bendixen, M., Jonsson, K., & Gronland, T.-A. (2012). Advanced MEMS components in closed-loop micro propulsion applications. In *26th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Ridenoure, R., Munakata, R., Diaz, A., Wong, S., Plante, B., Stetson, D., … Foley, J. (2015). LightSail Program Status: One Down, One to Go. In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Rui C. Barbosa, NASASpaceflight.com. (n.d.). *China debuts Long March 11 lofting Tianwang-1 trio.* `http://www.nasaspaceflight.com/2015/09/china-debuts-long-march-11-lofting-tianwang-1-trio/`. (Acccessed: 2015-12-01)

Schappell, D. T., Scarduffa, E., Smith, P., & Solway, N. (2005). Advances in Marotta Electric and Satellite Propulsion Fluid Control Activities. In *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference.* July 10-13, 2005, Tucson, AZ.

Sheehan, J. P., Collard, T. A., Ebersohn, F. H., & Longmier, B. W. (2015). Initial Operation of the CubeSat Ambipolar Thruster. In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan.

Spangelo, S., & Longmier, B. (2015). Optimization of cubeSat System-level Design and propulsion Systems for Earth-Escape Missions. *Journal of Spacecraft and Rockets*, *52*(4), 1009–1019.

Spektor, R., Diamant, K. D., Beiting, E., Swenson, K. A., Goddard, D., Raitses, Y., & Fisch, N. J. (2011). Characterization of a Cylindrical Hall Thruster with Permanent Magnets. In *32nd*

International Electric Propulsion Conference and 6th Nano-satellite Symposium. Wiesbaden, Germany.

Spores, R., Masse, R., Kimbrel, S., & McLean, C. (2014). GPIM AF-M315E Propulsion System. In *50th Joint Propulsion Conference.* Cleveland, Ohio, 28 July 2014.

SSC ECAPS. (2015). *HPGP, the next level of propulsion.* `http://www.sscspace.com/ecaps`. (Acccessed: 2015-09-09)

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

Takegahara, H., Kuninaka, H., Funaki, I., Ando, A., Komurasaki, K., Koizumi, H., ... Kakami, A. (2015). Overview of Electric Propulsion Research Activities in Japan. In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan, July 2015.

Tsay, M., Frongillo, J., & Hohman, K. (2015). Iodine-Fueled Mini RF Ion Thruster for CubeSat Applications. In *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium.* Hyogo-Kobe, Japan, July 2015.

Tsay, M., Frongillo, J., Lafko, D., & Zwahlen, J. (2014). Development Status and 1U CubeSat Application of Busek's 0.5N Green Monopropellant Thruster. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan,Utah, August 2014.

VACCO Industries. (2015). *Cubesat Propulsion Systems from VACCO.* `http://www.cubesat-propulsion.com/`. (Acccessed: 2015-09-14)

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

Zondervan, K. L., Fuller, J., Rowen, D., Hardy, B., Kobel, C., Chen, S.-H., ... Kremer, A. (2014). CubeSat Solid Rocket Motor Propulsion Systems providing delta-Vs greater than 500 m/s. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah, August 2014.

5 Guidance, Navigation and 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, an onboard position determination capability can be provided by a GPS receiver. Alternatively, ground based radar tracking systems can be used. If onboard knowledge is required then these radar observations can be uploaded and paired with a suitable propagator. Commonly, the USAF published two line element (TLE) sets(Shepherd, Lt Col Glen and Air Force Space Command, 2006) are paired with the SGP4 propagator (Vallado, Crawford, Hujsak, & Kelso, 2006). In deep space, position determination is performed using the Deep Space Network (DSN) and an onboard radio transponder (Thornton & Border, 2003).

ADCS includes sensors used to determine attitude and attitude rate, such as star trackers and gyros, and actuators designed to change a spacecraft's attitude, such as reaction wheels and thrusters. There are many attitude control and determination architectures and algorithms suitable for use in small spacecraft (Wertz, 2012).

The continuing trend in small spacecraft GNC is the miniaturization of existing technologies. While 3-axis stabilized, GPS equipped 100 kg class spacecraft have been flown for over a decade, it has only been in the past few years that such technologies have become available for 10 kg class spacecraft. Table 5.1 summarizes the current state of the art performance for GNC subsystems in small spacecraft.

Table 5.1. The state of the art for GNC subsystems

Subsystem	Performance	Status
Reaction Wheels	0.1 N m peak torque, 1.5 N m s storage	TRL 9
Magnetorquers	5 A m^2 peak dipole	TRL 9
Star Trackers	25 arcsec pointing knowledge	TRL 9
Sun Sensors	0.1 °accuracy	TRL 9
Earth Sensors	0.25 °accuracy	TRL 9
Gyroscopes	$1\,°\,h^{-1}$ bias stability, $0.1\,°\,h^{-\frac{1}{2}}$ random walk	TRL 9
GPS Receivers	1.5 m position accuracy	TRL 9
Integrated Units	0.007 °pointing capability	TRL 6

5.2 State of the art

5.2.1 Integrated Units

Integrated units combine multiple different attitude and navigation components into a single part with the aim to provide a simple, single component solution to a spacecraft's GNC requirements. Typical components included are reaction wheels, magnetometers, magnetorquers and star trackers. The units often include built-in attitude determination and momentum management algorithms.

Table 5.2 describes some of the integrated units currently available, though none have flown yet. Both units described in the table are $\frac{1}{2}$U units, and the unit from Blue Canyon Technologies is illustrated in Figure 5.1.

Figure 5.1. BCT XACT Integrated ADCS Unit. Image courtesy of Blue Canyon Technologies.

Figure 5.2. Sinclair Interplanetary RW-0.03 Reaction Wheel. Image courtesy of Sinclair Interplanetary.

Table 5.2. Integrated GNC units

Product	Manufacturer	Mass (kg)	Components	Pointing Capability	Status
MAI-400	Maryland Aerospace	0.694	3 reaction wheels, 3-axis magnetometer, 2 HCIs, 3 torque rods	?°	TRL 6
BCT XACT	Blue Canyon Technologies	0.85	3 reaction wheels, 3-axis magnetometer, star tracker, 3 torque rods	0.007°	TRL 6

5.2.2 Reaction Wheels

Miniaturized reaction wheels provide small spacecraft with a precision pointing capability. Reaction wheels can provide arbitrary torques limited only by the wheel's peak torque and momentum capacity. Table 5.3 lists a selection of high heritage miniature reaction wheels, and Figure 5.2 illustrates one of the wheels offered by Sinclair Interplanetary. For full three-axis control, a spacecraft requires three wheels. However, a four wheel configuration is often used to provide fault tolerance (Jin, Ko, & Ryoo, 2008). Due to parasitic external torques, reaction wheels need to be periodically desaturated using an actuator that provides an external torque, such as thrusters or magnetorquers (Wisniewski & Kulczycki, 2005).

5.2.3 Magnetorquers

Magnetorquers are an established technology used in small spacecraft and can provide control torques perpendicular to the local external magnetic field. Table 5.4 lists a selection of high heritage magnetorquers and Figure 5.3 illustrates some of ZARM Technik's product offerings. Magnetorquers are often used in combination with wheels to remove excess momentum. As control torques can only be provided in the plane perpendicular to the local magnetic field, full 3-axis stabilization is

Table 5.3. Reaction Wheels

Product	Manufacturer	Mass (kg)	Peak Torque (N m)	Momentum Capacity (N m s)	Radiation Tolerance (krad)	Status
10SP-M	Surrey Satellite Technology	0.96	0.011	0.42	5	TRL 9
100SP-O	Surrey Satellite Technology	2.6	0.11	1.5	5	TRL 9
RW-0.03	Sinclair Interplanetary	0.185	0.002	0.04	20	TRL 9

not possible at any given time. However, orbit periodic control is possible using only magnetorquers as the spacecraft moves through the magnetic field (Wisniewski & Stoustrup, 2004) .

Table 5.4. Magnetorquers

Product	Manufacturer	Mass	Peak Dipole	Radiation Tolerance	Status
MTR-5	Surrey Satellite Technology	0.5 kg	5 A m^2	5 krad	TRL 9
MT0.1-1	ZARM	0.003 kg	0.1 A m^2		TRL 9
MT1-1	ZARM	0.060 kg	1 A m^2		TRL 9
TQ-15-28-0-1-1	Spaceflight Industries	0.727 kg	15 A m^2		TRL 9

5.2.4 Thrusters

Thrusters used for attitude control are described in 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 the spacecraft's attitude by comparing a digital image captured with a CCD or CMOS sensor to an onboard star catalog (Spratling & Mortari, 2009). Table 5.5 lists some models suitable for use on a small spacecraft, one of which is illustrated in Figure 5.4.

Figure 5.3. ZARM Technik Magnetorquers for Micro-Satellites. Image courtesy of ZARM.

Figure 5.4. SSTL Procyon Star Tracker. Image courtesy of Surrey Satellite Technology Ltd.

Table 5.5. Star Trackers

Product	Manufacturer	Mass (incl. baffle)	Accuracy	Radiation Tolerance	Status
Rigel-L	Surrey Satellite Technology	2.2 kg	25 arcsec	5 krad	TRL 9
Procyon	Surrey Satellite Technology	1.7 kg	50 arcsec		TRL 9
ST-16	Sinclair Interplanetary	0.12 kg	74 arcsec	9 krad	TRL 9

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 (Psiaki, Martel, & Pal, 1990) and also orbital position (Psiaki, Huang, & Fox, 1993). Table 5.6 provides a summary of some 3-axis magnetometers available for small spacecraft, one of which is illustrated in Figure 5.5.

Table 5.6. Magnetometers

Product	Manufacturer	Mass	Resolution	Orthogonality	Radiation Tolerance	Status
Magnetometer	New Space Systems	0.2 kg	6.5 nT	$<1°$	10 krad	TRL 9
MicroMag3	PNI Corp	0.2 kg	15 nT	$<1°$		TRL 9
Magnetometer	Surrey Satellite Technology	0.19 kg	10 nT	$<1°$	5 krad (Si)	TRL 9

Figure 5.5. NSS Magnetometer. Image courtesy of NewSpace Systems.

Figure 5.6. Adcole Coarse Sun Sensor Detector (Cosine Type). Image courtesy of Adcole Corporation.

5.2.7 Sun Sensors

Sun sensors are used to provide an estimate of the location of the Sun in the spacecraft body frame, which in turn can be used as an input in attitude estimation. Coarse sensors only provide a non-directional cosine reading (Allgeier, Mahin, & Fitz-Coy, 2009), and a spacecraft would require a minimum of six. Fine sun sensors provide a full 2-axis estimate of Sun location (Chang, Yun, & Lee, 2007) and a minimum of four are required. A selection of sun sensors are described in Table 5.7 one of which is illustrated in Figure 5.6.

Table 5.7. Sun Sensors

Product	Manufacturer	Mass (kg)	Accuracy	Radiation Tolerance	Status
Fine (digital) Sun Sensor	New Space Systems	0.035	0.1°	10 krad	TRL 9
Analog Sun Detector	Adcole	0.068	0.75°		TRL 9
CSS-01	Space Micro	0.0141	5°		TRL 9

5.2.8 Earth Sensors

Earth sensors can be simple infrared horizon crossing indicators (HCI) or can utilize more advanced thermopile sensors to detect the temperature differences between the poles and the equator. Examples of such technologies are described in Table 5.8 and illustrated in Figure 5.7.

Table 5.8. Earth Sensors

Product	Manufacturer	Mass (kg)	Accuracy	Status
Static Earth Sensor	Maryland Aerospace	0.033	0.25°	TRL 9
Mini Digital HCI	Servo	0.050	0.75°	TRL 9

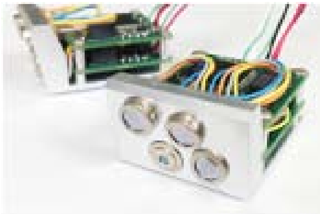


Figure 5.7. MAI-SES. Image courtesy of Maryland Aerospace Inc.

Figure 5.8. LN-200S Fiber Optic Gyro and IMU. Image courtesy of Northrop Grumman Corporation.

5.2.9 Gyros

Gyroscopes provide a measurement of angular velocity. The main gyro types used in small spacecraft are fiber optic gyros (FOGs) and MEMS gyros, with FOGs offering better performance at a mass and cost penalty (Greenheck, Bishop, Jonardi, & Christian, 2014). Table 5.9 lists a sample of gyros available for small spacecraft, one of which is illustrated in Figure 5.8.

Table 5.9. Gyros

Product	Manufacturer	Type	Mass (kg)	Bias Stability	Random Walk	Radiation Tolerance	Status
MIRAS-01	Surrey Satellite Technology	3-axis MEMS	2.8	$10\,^\circ\,\mathrm{h}^{-1}$	$0.6\,^\circ\,\mathrm{h}^{-\frac{1}{2}}$	5 krad	TRL 9
LN-200S	Northrop Grumman	3-axis FOG	0.75	$1\,^\circ\,\mathrm{h}^{-1}$	$0.1\,^\circ\,\mathrm{h}^{-\frac{1}{2}}$	10 krad	TRL 9
ADIS16405	Analog Devices	3-axis MEMS	0.016	$25\,^\circ\,\mathrm{h}^{-1}$	$2.0\,^\circ\,\mathrm{h}^{-\frac{1}{2}}$		TRL 9

5.2.10 GPS

For Low Earth Orbiting 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. The NovaTel OEM615 board, replacing the ubiquitous OEMV1, is illustrated in Figure 5.9. GPS accuracy is limited by propagation variance through the exosphere and the underlying precision of the civilian use C/A code (Montenbruck et al., 2012). GPS units are controlled under the Export Administration Regulations (EAR) and must be licensed to remove COCOM limits (Office of the Federal Register, 2015).

Figure 5.9. NovaTel OEM615 Dual-Frequency GNSS Receiver. Image courtesy of NovAtel Inc.

Figure 5.10. General Dynamics SDST. Image courtesy of General Dynamics.

Table 5.10. GPS Receivers

Product	Manufacturer	Mass	Accuracy	Radiation Tolerance	Status
SGR-05U	Surrey Satellite Technology	0.040 kg	10 m	5 krad	TRL 9
SGR-10	Surrey Satellite Technology	0.95 kg	10 m	10 krad	TRL 9
OEM615	Novatel	0.021 kg	1.5 m		TRL 9

5.2.11 Deep Space Navigation

In deep space, navigation is performed using radio transponders in conjunction with the Deep Space Network (DSN). At the time of writing the only small spacecraft suitable deep space transponder to have flown previously is the JPL designed and General Dynamics manufactured Small Deep Space Transponder (SDST). However, JPL has designed a deep space transponder suitable for use in a cubesat, IRIS. Table 5.11 details these two radios, and the SDST is illustrated in Figure 5.10. IRIS is derived from the Low Mass Radio Science Transponder (LMRST) and is scheduled to fly on INSPIRE (Aguirre, 2015).

Table 5.11. Deep Space Transponders

Product	Manufacturer	Mass	Bands	Status
SDST	General Dynamics	3.2 kg	X, Ka	TRL 9
IRIS V2	JPL	0.5 kg	X, Ka, S, UHF	TRL 6

5.3 On the Horizon

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, increases in longevity, or higher accuracy. This is especially true for GNC components designed for deep space missions, where small spacecraft focused missions have only very recently been proposed.

5.4 Conclusion

Small spacecraft GNC is a mature area, with many previously flown and high TRL components offered by several different vendors. Soon-to-be-flown integrated units will offer a simple, single vendor single component solution for ADCS which will simplify GNC subsystem design.

References

Aguirre, F. (2015, March). X-Band electronics for the INSPIRE Cubesat deep space radio. In *Aerospace Conference, 2015 IEEE* (p. 1-10). doi: 10.1109/AERO.2015.7119295

Allgeier, S. E., Mahin, M., & Fitz-Coy, N. G. (2009). Design and analysis of a coarse sun sensor for pico-satellites. In *Proceedings of the AIAA Infotech at Aerospace Conference and Exhibit and AIAA Unmanned... Unlimited Conference* (pp. 2009–1837).

Chang, Y.-K., Yun, M.-Y., & Lee, B.-H. (2007). A new modeling and validation of two-axis miniature fine sun sensor. *Sensors and Actuators A: Physical*, *134*(2), 357–365.

Greenheck, D., Bishop, R., Jonardi, E., & Christian, J. (2014). Design and Testing of a Low-Cost MEMS IMU Cluster for SmallSat Applications. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Jin, J., Ko, S., & Ryoo, C.-K. (2008). Fault tolerant control for satellites with four reaction wheels. *Control Engineering Practice*, *16*(10), 1250–1258.

Montenbruck, O., Swatschina, P., Markgraf, M., Santandrea, S., Naudet, J., & Tilmans, E. (2012). Precision spacecraft navigation using a low-cost GPS receiver. *GPS solutions*, *16*(4), 519–529.

Office of the Federal Register. (2015). Foreign availability determination procedures and criteria. *Code of Federal Regulations*, *Title 15 Part 768.7*.

Psiaki, M. L., Huang, L., & Fox, S. M. (1993). Ground tests of magnetometer-based autonomous navigation (MAGNAV) for low-earth-orbiting spacecraft. *Journal of Guidance, Control, and Dynamics*, *16*(1), 206–214.

Psiaki, M. L., Martel, F., & Pal, P. K. (1990). Three-axis attitude determination via Kalman filtering of magnetometer data. *Journal of Guidance, Control, and Dynamics*, *13*(3), 506–514.

Shepherd, Lt Col Glen and Air Force Space Command. (2006). Space Surveillance Network. In *Shared Space Situational Awareness Conference, Colorado Springs, CO.*

Spratling, B. B., & Mortari, D. (2009). A survey on star identification algorithms. *Algorithms*, *2*(1), 93–107.

Thornton, C. L., & Border, J. S. (2003). *Radiometric tracking techniques for deep-space navigation.* John Wiley & Sons.

Vallado, D. A., Crawford, P., Hujsak, R., & Kelso, T. (2006). Revisiting spacetrack report# 3. *AIAA*, *6753*, 2006.

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

Wisniewski, R., & Kulczycki, P. (2005). Slew maneuver control for spacecraft equipped with star camera and reaction wheels. *Control Engineering Practice*, *13*(3), 349-356.

Wisniewski, R., & Stoustrup, J. (2004). Periodic H2 synthesis for spacecraft attitude control with magnetorquers. *Journal of Guidance, Control, and Dynamics*, *27*(5), 874-881.

6 Structures, Materials and Mechanisms

6.1 Introduction

Since the last edition of this report there has been further expansion of offerings for off-the-shelf structures and likewise an expansion of custom machined, composite, and even printed structures used, or proposed for use, on small spacecraft missions. This chapter will refer to small spacecraft structures with a focus on 1U - 12U platforms and specifically those components designed to transmit loads through the spacecraft to the interface of the launch and deployment system and provide attachment points for payloads and associated components. These structures are typically classified as the primary structure. For contrast, secondary structures are all other structures, like solar panels, thermal blankets etc., that only need to support themselves. When a primary structure fails it is almost always catastrophic, while a failure of a secondary structure typically does not affect the integrity of the spacecraft but can have a significant impact on the overall mission. These structural categories serve as a good reference but the lines between them can be hard to distinguish for small spacecraft since they 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 often essential that the structural components be as volume efficient as possible. To achieve this volume efficiency, the primary structural components must not only carry mechanical loads, but may also serve as the primary component for thermal management, provide primary means for radiation shielding, serve as a pressure containment vessel, and even behave as a strain actuation component– features that are often assigned to secondary structural components in larger spacecraft.

Important to any discussion of small spacecraft structure is the material of the structure itself. Typically a spacecraft's structure is made up of both metallic and non-metallic materials. Metals are commonly homogeneous and isotropic, meaning they have the same properties at every point and in every direction. Non-metals, such as composites, are normally neither homogeneous nor isotropic. Material choice is driven by the operational environment of the spacecraft and must ensure adequate margin for launch and operational loads, thermal balance and thermal stress management, and by the sensitivities of the instrumentation and payload to outgassing and thermal displacements.

The design of the structure is not only affected by the different subsystems and launch environments, but also the application and operations of the spacecraft, such as the configuration differences for a spin versus a 3-axis stabilized system. Instrumentation also places requirements on the structure and can require mechanisms, such as deployable boom to create some distance between a magnetometer and the spacecraft to mitigate its effect on the measurement.

Also included in this chapter is an overview of radiation effects and some mitigation strategies as it impacts structural design considerations for small spacecraft.

6.2 State of the art

Two general approaches are common for primary structures in the small spacecraft market: off-the-shelf structures and custom machined or printed components. Maybe unsurprisingly, most off-the-shelf offerings are for the cubesat market. Often the off-the-shelf 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 the off-the-shelf structure offered.

6.2.1 Primary Structure

There are now several companies that provide cubesat primary structures (often called frames or chassis). Most are machined from 6061-T6 or 7071 aluminum and are designed with several mounting locations for components in an attempt to offer configuration flexibility for spacecraft designers. This section will highlight several approaches taken by various vendors in the cubesat market. Of the offerings included in the survey, 1U to 3U formats are most prevalent, but there are a few frames that are designed for 6U and even 12U spacecraft. To date, however, the author is not aware of any mission that has flown, or even gone beyond the proposal phase for a 12U spacecraft. Also of note, the exact format of the 12U cubesat seems to be evolving. This trend is similar to the development of the 6U and is typical until a dispenser is qualified, which tends to set the standard for the exact dimensional constraints of the spacecraft within.

Monocoque Construction

Pumpkin, Inc. CubeSat Kit The structural approach taken by Pumpkin for their 1U - 3U spacecraft is of a monocoque approach, where loads are carried by the external skin in an attempt to maximize internal volume. Pumpkin, Inc. provides several off-the-shelf cubesat structures intended as components of their CubeSat Kit solutions in 0.5U, 1U, 1.5U, 2U and 3U sizes (Pumpkin, Inc., 2015c). All structures strictly adhere to the cubesat standard (1U $= 10 \times 10 \times 10\,\mathrm{cm}$), and consist of riveted sheet-metal construction, offered as skeletonized Figure 6.1) and solid-wall configurations.

Figure 6.1. 1U Skeletonized CubeSat Kit. Image courtesy of Pumpkin, Inc. (2015a).

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. A modular 3U structure from NanoAvionics is shown in Figure 6.2. These components are intended to be modular, made from 7075 aluminum, and like many off-the-shelf cubesat structures, compliant with the PC/104 form factor (NanoAvionics, 2015).

Radius CubeSat Structures Radius Space has also chosen a highly modular approach to develop a family of cubeSat structures that range from the 1U to 12U sizes. Figure 6.3 shows this modular approach for 1U to 3U sizes. PCB integration is typically accomplished through a stacked configuration, although Radius Space asserts the structures allow for different PCB orientations for all but the 1U frame.

Card Slot System

Complex Systems & Small Satellites (C3S) C3S has developed a 3U cubesat structure that utilizes a card slot system, as shown in Figure 6.4, which is intended to provide several stated benefits over the more common PC/104 stack solution. These benefits include access to individual cards during integration and testing (PC/104 solutions require de-integration of an entire stack to isolate a single card), improved stack-up tolerance, and better thermal management of individual

Figure 6.2. Nano Avionics Small Satellite Structures. Image courtesy of NanoAvionics (2015).

Figure 6.3. The Radius Space Modular Structures. Image courtesy of Radius Space (2015).

cards compared to a traditional PC/104 stack, where all cards are connected series and are thermally interdependent (Complex Systems & Small Satellites, 2015).

6.2.2 Mechanisms

There are several companies offering mechanisms for the small spacecraft and smaller markets. Although not exhaustive, this section will highlight a few devices for release actuation, component pointing, and boom extension, that represent the state of the art for the cubesat market. Deployable mechanisms used for deorbit devices, please refer to section 12.

CDT: 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 6.5, employs an innovative interlocking 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 CTE.

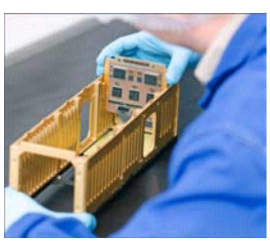


Figure 6.4. C3S 3U CubeSat Structure. Image courtesy of Complex Systems & Small Satellites (2015).

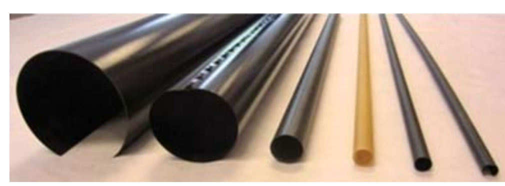


Figure 6.5. CTD's Deployable Composite Booms. Image courtesy of Composite Technology Development (2015).

Tethers Unlimited: 3 DOF Gimbal Mechanism Tethers Unlimited offers a 3 DOF gimbal mechanism called the Compact On-Board Robotic Articulator (COBRA). This mechanism provides accurate pointing for sensors and thrusters. The COBRA packages down to $100 \times 100 \times 33.25$ mm and weighs 155 grams (Tethers Unlimited, Inc., 2015). An image of the COBRA is shown in Figure 6.6.

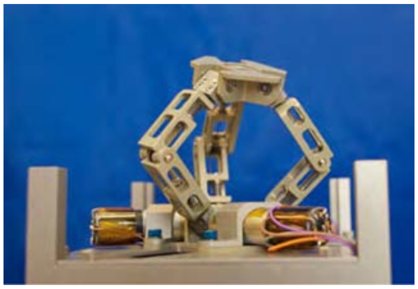


Figure 6.6. Tethers Unlimited Compact On-Board Robotic Articulator. Image courtesy of Tethers Unlimited, Inc. (2015).

Figure 6.7. Honeybee Robotics CubeSat SADA with iPhone for scale. Image courtesy of Honeybee Robotics (2015a).

Honeybee: Solar Panel Drive Actuator Honeybee in cooperation with MMA has developed a Solar Array Drive Actuator (SADA), shown in Figure 6.7, that accommodates $\pm$ 180° single axis rotation for solar array pointing. Honeybee also offers the unit in a slip-ring configuration for continuous rotation. Table 6.1 highlights a few key specifications for this actuator (Honeybee Robotics, 2015b).

Table 6.1. Honeybee SADA

Mass (slip Ring Option)	180 g
Backlash	$< 3°$
Operating Temperature Range	-30 to $+85$ °C
Size	$100 \times 100 \times 6.5$ mm
Radiation Tolerance	10 krad
Wire Wrap	7 channels per wing @ 1.4 A per channel
Slip Ring	10 channels per wing @ 0.5 A per channel

TiNi Aerospace: Frangibolt Release Actuator TiNi Aerospace has several release mechanisms available for the spacecraft market, but perhaps the most relevant to the cubesat market is the Frangibolt Actuator (particularly the FD04 model), due to its 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 fastener in tension (TiNi Aerospace, 2015). The Frangibolt is intended to be reusable by re-compressing the actuator using a custom tool and replacing the notched fastener. Figure 6.8 shows a model of the FD04 Frangibolt actuator and Table 6.2 describes a few key specifications.

Figure 6.8. TiNi Areospace Frangibolt Actuator. Image courtesy of TiNi Aerospace (2015).

6.3 On the Horizon

6U and 12U off-the-shelf structures Off-the-shelf 6U and 12U structural components are products that could be considered "on the horizon," though several companies offer 6U and 12U

Table 6.2. TiNi FD04 Frangibolt Actuator

Mass	7 g
Power	15 W @ 9 VDC
Operating Temperature Range	−50 to +80 °C
Size	13.72 × 10.16 mm
Holding Capacity	667 N
Function Time	Typically 20 sec. @ 9 VDC
Life	50 cycles MIN

chassis or frames for purchase. However, it appears that at least the 6U offerings will likely have flight heritage within the year 2016.

Pumpkin Supernova 6U Pumpkin has developed what it has named the "Supernova," a 6U structure that features a machined aluminum modular architecture. The structure, shown in Figure 6.9, is designed to integrate with the Planetary Systems Corporation (PSC) Canisterized Satellite Dispenser, and includes accommodation for the PSC Separation Connector for power and data while integrated (Pumpkin, Inc., 2015b).

Innovative Solutions In Space 6U Innovative Solutions In Space (ISIS) has also adopted a modular approach to a 6U structure to maximize payload flexibility. The 6U structure shown in Figure 6.10 is designed for integration within the ISIS Launch and Deployment System, and although not yet flown, is currently used for multiple spacecraft slated for launch in the near future.

Figure 6.9. The 6U Supernova Structure Kit. Image courtesy of Pumpkin, Inc. (2015b).

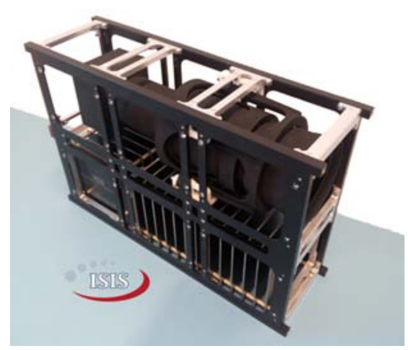


Figure 6.10. Innovation Solutions In Space Modular 6U Structures. Image courtesy of Innovative Solutions In Space (2015).

Additive Manufacturing Materials The use of additive manufacturing for spacecraft primary structures has been proposed for several years, but only now has this process been adopted by flight missions (it is important to note however, that additive manufacturing has been quite common for small spacecraft secondary structural elements for many years). Typically, the advantage of additive manufacturing is to free the designer from manufacturing constraints imposed by standard manufacturing processes and allow monolithic structural elements with complex geometry. In practice however, additive manufacturing has its own set of geometric constraints, but when these constraints are understood and respected, the designer can approach a design challenge with a larger tool set that has not been available in the recent past.

Windform Materials CRP Technology is using selective laser sintering (SLS) technology for their carbon filled polyamide based material, called Windform XT 2.0. Table 6.3 shows a summary of material properties published by CRP (CRP Technology s.r.l., 2015).

Table 6.3. Windform XT 2.0

Density	$1.097\,\mathrm{gcm}^{-3}$
Color	Black
Melting point	179.3°C
Tensile Strength	83.84 MPa
Tensile Modulus	8928.20 MPa
Resistivity, surface	$<10^8$ Ohm
Outgassing, TML	0.57 %

The Montana State PrintSat mission is a technology demonstrator spacecraft for the effectiveness of additive manufacturing using the Windform XT material. Figure 6.11 shows the complete spacecraft and Figure 6.12 shows the primary printed structure. The spacecraft is equipped with several sensors to investigate the properties of the material during its mission was launched on the ORS-4/ELaNa-7 mission from the PMRF aboard the Super Strypi LV (Dr. David Klumpar, 2015).

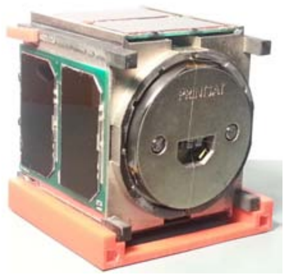


Figure 6.11. Flight configuration of PrintSat. Image courtesy of Dr. David Klumpar (2015).

Figure 6.12. Windform PrintSat Structure. Image courtesy of CRP Technology (2015).

The Morehead State University's Rapid Prototyped MEMS Propulsion and Radiation Test (RAMPART) spacecraft will also be demonstrating the rapidly prototyped Windform material during its mission. The entire structure is made of high phosphorus, electroless nickel plated material to provide radar reflectivity for tracking purposes. Benefits of the RAMPART propulsion system are the lightweight and specialized cell structures of the propellant tank made from Windform XT. The spacecraft was scheduled for launch in June 2013, but was delayed.

Accura Bluestone 3D Systems Corporation has developed a a stereolithographically fabricated composite material that shows promise for spacecraft structural applications. This material is currently being used as the main structural component for nozzles, tubing, and storage of a cold-gas propulsion system shown in Figure 6.13, originally developed at the University of Texas Austin and now being developed for several missions at Georgia Tech University. Table 6.4 shows a summary of material properties published by 3D Systems (3D Systems, Inc., 2015).

Table 6.4. Accura Bluestone

Density	1.78 gcm^{-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*

*To be measured in 2016

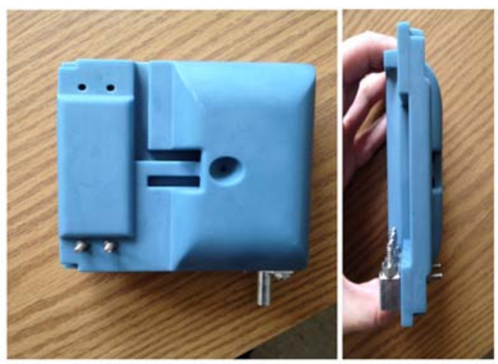


Figure 6.13. Cold Gas Propulsion Module fabricated using Accura Bluestone. Image courtesy of Steven Arestie, E. Glenn Lightsey, Brian Hudson (2012).

6.4 Radiation Effects and Mitigation Strategies

6.4.1 Shielding from the Space Environment

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 SEEs occur if used appropriately, and involves two basic methods: shielding with the spacecraft's pre-existing mass (including the external skin or chassis, and 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 secondaries 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. The final design consideration is due to the strong omni-directionality of most forms of particle radiation, where 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 EEE component. Essentially, completely enclosing critical components should not be considered a firm design constraint when other structural considerations exist.

6.4.2 Inherent Mass Shielding

Inherent mass shielding consists of utilizing the entirety of the pre-existing spacecraft's mass to shield sensitive electronic components that are not heavily dependent on their 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 this 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 and small business technology transfer investment.

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.

6.4.3 Ad Hoc Shielding

There are two types of ad hoc shielding utilized 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 microparticle powders. 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 (a method which optimizes volume and minimizes shield gaps) applications.

6.5 Conclusion

The landscape for small spacecraft structural design is expanding and the firms developing and offering solutions for spacecraft designers is expanding as well. There are now at least a few different approaches to off-the-shelf frames or chassis, each one with its own set of merits, as well as new vendors offering small-sat specific radiation shielding solutions. Most of the developments have been in the 3U cubesat class and there are now at least a few examples of mature structural designs for 6U class cubesats, with 12U designs being presented for future standardization. There have already been some very interesting uses of 3D printed materials, and it appears that the application of these materials for space flight missions is on the very near horizon, including exploiting the ad hoc nature of its manufacture for purpose-built radiation shielding. Whether or not the promised benefits of these materials outweigh those of more conventional materials in the near future remains to be seen.

References

3D Systems, Inc. (2015). *Accura Bluestone Technical Data.* http://www.3dsystems.com/sites/www.3dsystems.com/files/DS_Accura_Bluestone_US.pdf. (Accessed: 2015-11-19)

Complex Systems & Small Satellites. (2015). *C3S CubeSat Structure.* https://www.c3s.hu/portfolio-item/3u-cubesat-structure/. (Accessed: 2015-11-11)

Composite Technology Development. (2015). *STELOC Composite Booms.* http://www.ctd-materials.com/wordpress/?page_id=76. (Accessed: 2015-11-29)

CRP Technology. (2015). *Windform XT 2.0 for the PrintSat Mission.* http://www.windform.com/applications-aerospace.html. (Accessed: 2015-11-13)

CRP Technology s.r.l. (2015). *Windform XT 2.0.* http://www.windform.com/PDF/SCHEDA_WF_XT_2_0_ENG.pdf. (Accessed: 2015-11-13)

Dr. David Klumpar, K. M. (2015). *PrintSat Spacecraft.* http://ssel.montana.edu/printsat.html. (Accessed: 2015-11-13)

Honeybee Robotics. (2015a). *CubeSat Solar Array Drive Assembly.* http://www.honeybeerobotics.com/portfolio/cubesat-solar-array-drive-assembly/. (Accessed: 2015-12-02)

Honeybee Robotics. (2015b). *CubeSat Solar Array Drive Assembly Specifications.* http://www.honeybeerobotics.com/wp-content/uploads/2013/12/Honeybee-Robotics-CubeSat-SADA.pdf. (Accessed: 2015-12-02)

Innovative Solutions In Space. (2015). *Introducing the ISIS 6U CubeSat Structure.* http://www.isispace.nl/cms/index.php/news/latest-news/120-introducing-the-isis-6u-structure. (Accessed: 2015-11-27)

NanoAvionics. (2015). *NanoAvionics Structural Components.* http://n-avionics.com/structural. (Accessed: 2015-11-11)

Pumpkin, Inc. (2015a). . http://www.cubesatkit.com/images/cubesatkit_1u-revd-skeleton.jpg. (Accessed: 2015-11-08)

Pumpkin, Inc. (2015b). *6U Supernova Structure Kit.* http://www.cubesatkit.com/docs/SUPERNOVA_User_Manual-RevA0.pdf. (Accessed: 2015-11-08)

Pumpkin, Inc. (2015c). *System Chart.* http://www.cubesatkit.com/docs/cubesatkitsystemchart.pdf. (Accessed: 2015-11-08)

Radius Space. (2015). *Radius Space 1U-3U Structure.* http://www.radiusspace.com/img/full/Radius_Structure_1U-3U.jpg. (Accessed: 2015-11-11)

Steven Arestie, E. Glenn Lightsey, Brian Hudson. (2012). *Development of A Modular, Cold Gas Propulsion System for Small Satellite Applications.* http://www.jossonline.com/wp-content/uploads/2014/12/0102-Development-of-A-Modular-Cold-Gas-Propulsion-System-for-Small-Satellite-Applications.pdf. (Accessed: 2015-11-19)

Tethers Unlimited, Inc. (2015). *Cobra Gimbal.* http://www.tethers.com/SpecSheets/Brochure_Gimbal.pdf. (Accessed: 2015-12-02)

TiNi Aerospace. (2015). *Frangibolt Actuator FD04.* http://www.tiniaerospace.com/fcfd04.html. (Accessed: 2015-12-02)

7 Thermal Control System

7.1 Introduction

There is a defined temperature range for all spacecraft components that must be met for optimal function and this regulation of temperatures that occur throughout a spacecraft in orbit is controlled by thermal management techniques. Following the high demand for small spacecraft in the last decade, miniaturized thermal management systems are required to ensure proper thermal control requirements are met. While traditional thermal control techniques have been demonstrated on larger spacecraft, these existing techniques may require additional development for miniaturization and testing for small spacecraft application. This technology will still be considered state of the art, however not at TRL 9 for small spacecraft applications. Table 7.1 is a list of the current state of the art passive thermal techniques applicable for small spacecraft.

7.2 State of the Art

7.2.1 Passive Systems

Passive thermal control requires no input power for thermal regulation within 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 have been shown to be reliable. The integration of Multi-Layer Insulation (MLI), thermal coating, heat pipes, and sunshades are examples of passive methods to achieve thermal balance in a spacecraft. The use of MLI and surface coatings has been a traditional thermal technique that has been used on nearly every spacecraft since early spaceflight, and there has not been any modification of these methods for small spacecraft application. Cubesats such as Pharmasat, GeneSat, O/OREOS, SporeSat, YamSat, Compass-1, DelfiC-3, and minisatellites Bird, SDS-4, FASTRAC, and PICARD have all used MLI and coating to assist thermal regulation. Thermally isolated structural joints are often used for small spacecraft thermal management, where multiple washers with low thermal conductivity are stacked between fasteners and joined surfaces to limit heat transfer via conduction in specific places.

Thermal Insulation and Coating Thermal insulation acts as a thermal radiation barrier from incoming solar flux and also to prevent excessive heat dissipation. Typically used to maintain a temperature range for the electronics and battery during orbit, or more recently, for biological payloads, thermal insulation is typically in the form of MLI blankets but reflective tape has also been used. MLI is fairly delicate and drops drastically in performance if compressed, so using it outside of the small satellite that fits into a deployed (P-POD, NLAS) requires a lot of caution. 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 application does not perform as well for small spacecraft (cubeSat form factor) as they do on larger spacecraft. Surface coatings are typically less delicate and are more appropriate for exterior of a small spacecraft that will be deployed from a dispenser. Lastly, internal MLI blankets that do not receive direct solar radiation (sun light) can often be replaced by low emissivity coatings that perform identically in that context, using less volume and often cost less. Silvered tapes offer superior performance as efficient radiators, rejecting solar heat very effectively, but must be handled extremely carefully to maintain optical properties and don't always bond well to curved surfaces.

Dunmore Aerospace corporation has produced MLI blankets for aerospace use since the early 1980's and have since then participated in many US and European space missions (Dunmore

Aerospace Corporation, 2015). While their MLI blankets have been used on small spacecraft missions, their recent developments with STARcrest Spacecraft Materials has engineered a SATKIT consisting of DE330, DE076, DM116, and DM100 MLI blankets for cubesat application. These materials are constructed from previously flown MLI, however the actual KIT has TRL 8. Dunmore also offers polyimide film tape and MLI tape designed to insulate wires and cables on a spacecraft or aircraft and has a TRL of 8 for small spacecraft.

The alteration of the optical characteristics (solar absorptance and emittance) of a surface material by applying matte paint is another passive method of thermal control. While black paint will absorb all incident heat, white paint limits how much heat is absorbed from the surrounding environment due to its low absorption/emittance ratio (Anvari, Farhani, & Niaki, 2009). 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 (Soulage, 2013). AZ Technology, MAP, Astral Technology Unlimited, Inc., Lord Techmark, Inc., Sheldahl, Akzo Nobel Aerospace Coatings manufacture thermal coating (paint and tape) for aerospace use that has been demonstrated on multiple small spacecraft missions. Some examples of small spacecraft using thermal coatings include Picard (150 kg) which used white SG12FD paint on the Sun pointing face and cubesat YamSat which had black paint applied inside of the spacecraft for temperature maintenance.

Sun Shields The application of a sunshield, or sunshade, is common for spacecraft thermal control, although the implementation on a small spacecraft, especially for cubesat form factor, has been a recent addition for the improvement of thermal performance. Sierra Lobo has developed a deployable sunshield that will be flown on CryoCube-1, estimated launch in 2016. 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 (Sierra Lobo, 2014). Figure 7.1 displays the design of the sunshield used on CryoCube-1.

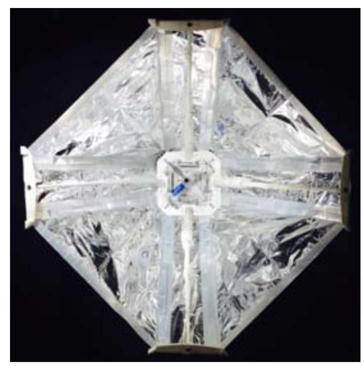


Figure 7.1. End view of Sun Shield on CryoCube-1 developed at Sierra Lobo. Image courtesy of Sierra Lobo (2014).

MLI Concepts Inc. also has extensive expertise in the design and development of stainless steel and titanium heat shields that will not break down due to heat or other stress (MLI Concepts, LLC., 2010), though this technology has been demonstrated on larger spacecraft only.

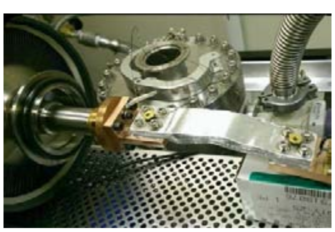


Figure 7.2. Thermal Management Technologies Aluminum thermal strap test. Image courtesy of Thermal Management Technologies (2015).

Thermal Straps Recent use of flexible thermal straps has become a convenient form of temperature control on small spacecraft as the required mass for the strap is limited with reduced stiffness between components. Flexible thermal straps can be applied to allow for passive heat transfer to a thermal sink and can be fitted to any particular length for design.

Thermal Management Technologies (TMT) has developed standard flexible thermal straps available in thin aluminum or copper foil layers or a copper braid; custom accommodations can be fabricated and tested for service (Thermal Management Technologies, 2015), see Figure 7.2. While these straps have been tested, they have not been flown on any small spacecraft missions.

Thermal straps are also being manufactured in materials other than the traditional aluminum and copper. Thermacore has utilized k-Technology in solid conduction in the design of lightweight thermal k-Core straps that supply a natural conductive path without including structural loads to the system and have shown to have greater conduction efficiency compared to traditional aluminum straps in testing (Thermacore, 2015). Here, the k-Core encapsulated graphite facilitates the heat dissipation in high-power electronics(Thermacore, 2015). This technology is fully designed and tested but has not flown on a small spacecraft.

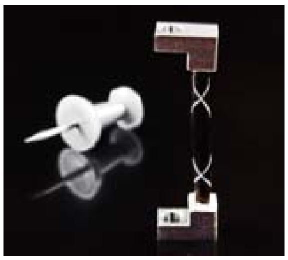


Figure 7.3. Graphite Fiber Thermal Straps (GFTS). Image courtesy of Technology Applications, Inc. (2015).

Technology Applications, Inc. has specialized in the testing and development of Graphite Fiber Thermal Straps (GFTS), with flight heritage on larger spacecraft missions (Orion and Spice). GFTS are known to be extremely lightweight and highly efficient and thermally conductive with unmatched vibration attenuation (Technology Applications, Inc., 2015), see Figure 7.3. While this technology has not been demonstrated or tested on small spacecraft platforms, the capability for small spacecraft applications is still applicable.

Thermotive Technology developed the Two Arm Flexible Thermal Strap (TAFTS) that is currently flying on JPL's PRISM (Portable Remote Imaging Spectrometer) instrument. For space infrared cameras, there is a requirement for extremely flexible direct cooling of mechanically-sensitive focal planes (Urquiza, Vasquez, Rodriguez, & Gorp, 2012). The design of TAFTS uses three "swaged terminals and a twisted section" that allows for significant enhanced elastic movement and elastics displacements in three planes, while a more conventional strap of the same conductance offers less flexibility and asymmetrical elasticity (Urquiza et al., 2012). Infrared cameras have flown on small spacecraft missions, although the TAFTS design has not.

Thermal Louvers Thermal louvers have not yet been integrated on small spacecraft due to volume and power constraints. 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 both are limited on a small spacecraft. Goddard Space Flight Center has developed a passive thermal louver for small spacecraft and will be space demonstrated on a 6U cubesat, Dellingr, where 14 W has been shown to be the power dissipation. This louver design uses bimetallic springs for control of the position of the flaps; when heat in the spacecraft rises, there is expansion in the springs due to the bimetallic properties of the spring causing the flaps to open which alters the thermal radiation of the exterior surface (NASA Goddard Space Flight Center, 2014). Similarly when the spacecraft cools and the flaps close, the exterior surface returns to the previous emissivity (NASA Goddard Space Flight Center, 2014). Figure 7.4 is a representation of the thermal lovers on Dellingr.

Figure 7.4. Passive Thermal Louver on 6U cubesat Dellingr. Image courtesy of NASA Goddard Space Flight Center (2014).

Deployable Radiators Similarly to thermal louvers, the utilization of deployable radiators on a small spacecraft is challenging due to the volume restrictions. Paint has been widely used to create a radiator-like surface, which has shown to be advantageous on smaller platforms. For a system that requires a large amount of heat dissipation regardless of incident thermal radiation intensity, a passive deployable radiator that is lightweight and simple in design would greatly enhance thermal performance.

Thermal Management Technologies is developing Thermally Efficient Deployable Radiators for small spacecraft that integrates an isothermal radiator surface with a high conductance hinge for high thermal efficiency (Thermal Management Technologies, 2015). This thermally conductive hinge allows for minimal temperature gradients between the radiator and spacecraft, as seen in Figure 7.5. The radiating surface uses graphite composite material for mass reduction and increased stiffness, where the typical radiator uniformity is greater than $0.1°\mathrm{C\,W^{-1}\,m^{-1}}$ (Thermal Management Technologies, 2015). This technology is currently in the development and testing phase.

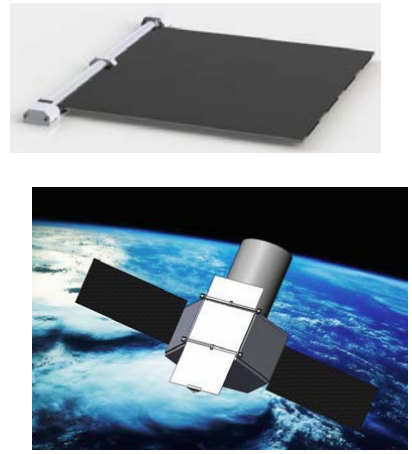


Figure 7.5. TMT Conductive Hinge (top) and Deployable Radiator for Small Satellite Model (bottom). Image courtesy of Thermal Management Technologies (2015).

The design of a flexible deployable radiator for small spacecraft was proposed, developed and tested by Shoya Ono and Hosei Nagano and colleagues from Kaneka Corporation and JAXA. This design can deploy or stow the radiation area depending on the environment temperature for proper heat dissipation control and has an overall volume of $0.5 \times 360 \times 560$ mm and 0.287 kg total mass, see Figure 7.6. The fin is passively stowed and deployed by an actuator that consists of a shape memory alloy and bias spring. To increase both radiator size and the value of 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 (Ono et al., 2015). Testing for the deployment and stowing was 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 (Ono et al., 2015).

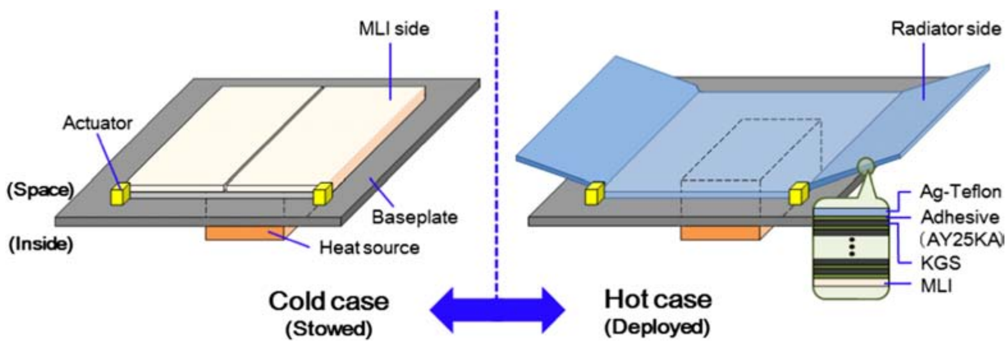


Figure 7.6. Flexible radiator conceptual diagram. Image courtesy of Ono et al. (2015).

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, which was utilized on BIRD (92 kg), but there are also flat plates that are rectangular stainless steel tubing sandwiched between two aluminum plates and charged with a working fluid inside (Nakamura et al., 2013). Small spacecraft SDS-4 (50 kg) successfully incorporated this flat plate design that was developed at JAXA, as seen in Figure 7.7. Although this technology has been applied on a 50 kg small spacecraft, additional fabrication and testing may be required for cubesat platform applications. For cubesat design, the TRL for passive heat pipes are TRL 6.

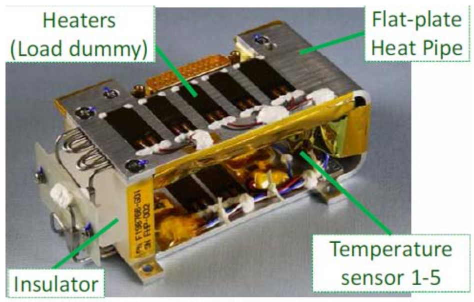


Figure 7.7. FOX flight model heat pipe developed at JAXA. Image courtesy of Nakamura et al. (2013).

Table 7.1. Passive Thermal Systems

Product	Manufacturer	Status
MLI Blanket	Sheldahl, Dunmore, Aerospace, Fabrication and Materials, MLI Concepts Inc.	TRL 9
Paint	AZ Technology, MAP, Astral Technology Unlimited, Inc., Dunmore Aerospace	TRL 9
Sun Shields	Sierra Lobo	TRL 8
Flexible Thermal Straps	Thermal Management Technologies, Thermacore, Technology Applications, Inc., Thermotive Technology	TRL 9 for metal straps, TRL 8 for composite straps
Thermal Louvers	NASA Goddard Space Flight Center	TRL 8
Deployable Radiators	Thermal Management Technologies, Kaneka Corporation/JAXA collaboration	TRL 6
Passive Heat Pipe	Thermacore, Inc. and Advanced Cooling Technology, Inc.	TRL 6
Passive Thermal Louver	NASA Goddard Space Flight Center	TRL 8

7.2.2 Active Systems

Active thermal methods for spacecraft thermal control rely on input power for operation, are associated with higher precision and have been shown to be more effective (Hogstrom, K., 2013). Typical active thermal devices include electrical resistance heaters, coolers or the use of cryogenic materials. Until spacecraft designers are able to miniaturize existing actively controlled thermal techniques, the utilization 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 and coolers 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.

Thermal Straps Active thermal straps have been shown to increase thermal performance, especially in a design that is associated with high concentrated heat fluxes on the electronics. The advanced thermally conductive path on the strap supplies a reliable mitigation method for reducing hot spots while also limiting integration overhead and space. Load Path Aerospace Structures currently have Flexible and Enhanced Active Thermal Straps (FEATS) that are capable of heat dissipation up to $50\,\mathrm{W\,cm^{-2}}$ and cooling capacity of $35\,\mathrm{W}$ (Load Path, Aerospace Structures, Design, Test and Materials, 2015). While these have not yet flown on small spacecraft missions, they have been developed and tested for small spacecraft.

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 the passive control for the entire spacecraft system to maintain thermal regulation in eclipses. As biological payloads are becoming more common on small spacecraft, the biology have their own specified temperature maintenance requirements. NASA Ames biological nanosats, GeneSat, PharmaSat, O/OREOS, SporeSat, EcAMSat, and Biosentinel, all utilize actively-controlled resistance heaters for precise temperature maintenance for their biological payloads with close loop temperature feedback to maintain the biology temperatures. Minco Products, Inc. manufactures flexible strip heaters equipped with polyimide insulation. These heaters are TRL 9 for small spacecraft missions.

Cryocoolers There have been recent improvements in the cooling technologies for small spacecraft. Cryogenic coolers, or 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 $50\,\mathrm{K}$ (Hon, Kesler, & Sigurdson, 2009). Instruments such as imaging spectrometers, interferometers and MWIR sensors use cryocoolers to function at the extremely low temperatures required. Cryocube-1 will be the first cubesat mission that will perform cryogenic management tests (fluid location sensing, slosh characterization and cryogenic fluid transfer) on orbit in 2016. The 3U will carry gas onboard and will be passively cooled and liquefied using a cryotank developed at Sierra Lobo, Inc.

Creare developed an Ultra Low Power (ULP) cryocooler, a single-stage turbo-Brayton cryocooler that operates between a cryogenic heat rejection temperature and the primary load temperature. Components include a cryogenic compressor, a recuperative heat exchanger, and a turboalternator,

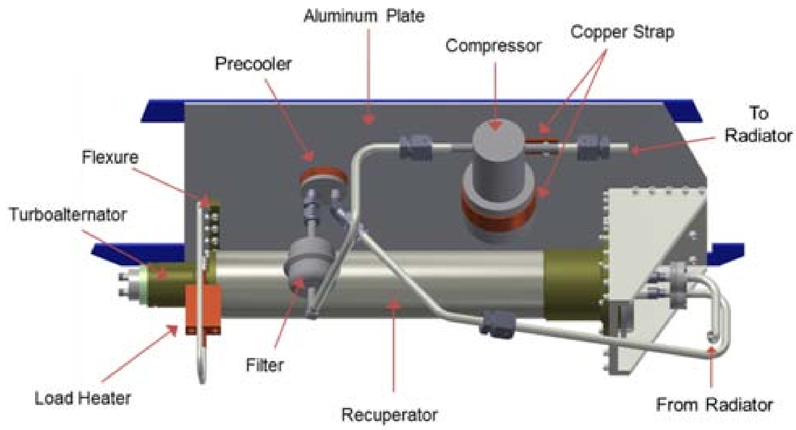


Figure 7.8. Configuration of primary mechanical UPL cryocooler components from Creare. Image courtesy of Zagarola et al. (2012).

where 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 (Zagarola et al., 2012), see Figure 7.8. This cryocooler is designed to operate at cold end temperatures of 30 to 70 K, loads of up to 3 W, and heat rejection temperatures of up to 210 K by changing only the charge pressure and turbo machine operating speeds. This technology has competed testing and fabrication (TRL 7).

Ricor-USA, Inc. developed the K562S, a rotary Stirling mini micro-cooler, that has a cooling capacity of 200 mW at 95 K and 300 mW at 110 K that has been used in several small gimbals designed for military applications. Ricor also developed K508N a Stirling $\frac{1}{2}$ W micro cooler, that has cooling capacity 500 mW at 77 K and 700 mW at 77 K that is suitable for use on a small spacecraft, see Figure 7.9 and for both mini coolers. These coolers are TRL 7 for small spacecraft applications.

Figure 7.9. Ricor-USA K562S Mini-cooler (top) and Ricor-USA K508N 1/2 W Micro Cooler (bottom). Image courtesy of Ricor-USA Cryogenic and Vacuum Systems (2015).

Sunpower, Inc. developed the CryoTel DS1.5 Stirling 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 77 K using 30 W power with a 1.2 kg mass (Sunpower, 2015). Sunpower also offers MT-F, mini-cooler that has a nominal heat lift of 5 W at 77 K, using 80 W power with a total mass of 2.1 kg, see Figure 7.10 for both coolers. While the MT-F technology has been successfully demonstrated in applications such as High Temperature Superconductivity (HTS) filters, high altitude balloons, refrigeration, germanium detectors, IR detectors, radio telescopes and laser diode cooling (Sunpower, 2015), it has not been applied to a small spacecraft mission.

Northrop Grumman designed a Micro Pulse Tube cooler that is a split configuration cooler that incorporates a coaxial cold head connected via a transfer line to a vibrationally balanced linear compressor, see Figure 7.12. This micro compressor has been scaled from a flight proven TRL 9 high efficiency cooler (HEC) compressor. The cooler has an operational range of 35 to 40 K and a

Figure 7.10. CryoTel DS1.5 1.4 W Cryocooler (left) and CryoTel MT-F 5 W Cryocooler (right). Image courtesy of Sunpower (2015).

heat rejection temperature of 300 K, using 80 W of input power, has 750 mW refrigeration at 40 K and a total mass of 7.4 kg (Durand, Tward, Toma, & Nguyen, 2014).

Lockheed Martin Space Systems Company engineered a pulse tube micro-cryocooler, a simplified version of a Stirling cryocooler, consisting of a compressor driving a coaxial pulse tube coldhead, see Figure 7.11. The unit has a mass of 0.345 kg for the entire thermal mechanical unit, and is compact enough to be packaged in $\frac{1}{2}$U of a cubesat (Olson & Nast, 2013). The microcooler design underwent qualification testing at TRL 6 and is compatible for small spacecraft missions.

Figure 7.11. Lockheed Martin TRL6 Micro-cryocooler. Cryocooler photograph provided courtesy of Lockheed Martin Corporation.

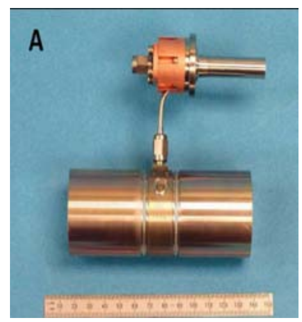


Figure 7.12. Flight design PT microcooler and its flight configuration with attached reservoir tank. Image courtesy of Durand et al. (2014).

Table 7.2. Active Thermal Systems

Product	Manufacturer	Status
Electrical Heaters	Minco Products, Inc. and All Flex Flexible Circuits, LLC.	TRL 9
Mini Cryocoolers	Ricor-USA, Inc., Creare, Sunpower Inc., Northrop Grumman, and Lockheed Martin Space Systems Company	TRL 7
Flexible and Enhanced Active Thermal Straps (FEATS)	LoadPath	TRL 7/8

7.3 On the Horizon

Traditional thermal control technologies for spacecraft will not always be able to be immediately integrated into small spacecraft platforms. As mentioned in the introduction of this chapter, the technology that is demonstrated on larger spacecraft may need to be altered slightly for small spacecraft compatibility and will not be automatically TRL 9. This section discusses some technology that is being proposed and developed for small spacecraft thermal control, and is not ready for space flight.

Thermal Straps Thermotive has developed Pyrovo Pyrolytic Graphite Film (Pyrovo PGF) thermal straps that have already flown in optical cooling applications in high altitude cameras and avionics and are planned to be used in several upcoming space flight instruments in 2016. Pyrovo PGF straps use pyrolytic graphite wrapped in a HEPA filter-vented $4\,\mu$m thick aluminized Mylar blanket and have no exposed graphite. The specific thermal conductivity of this material has shown to be 10× better than aluminum and 20× better than copper, as seen in Figure 7.13 (Thermotive, 2014). While these straps have not flown in space on a small spacecraft mission, they are planned to be included on several upcoming space flight instruments in 2016 (TRL 6).

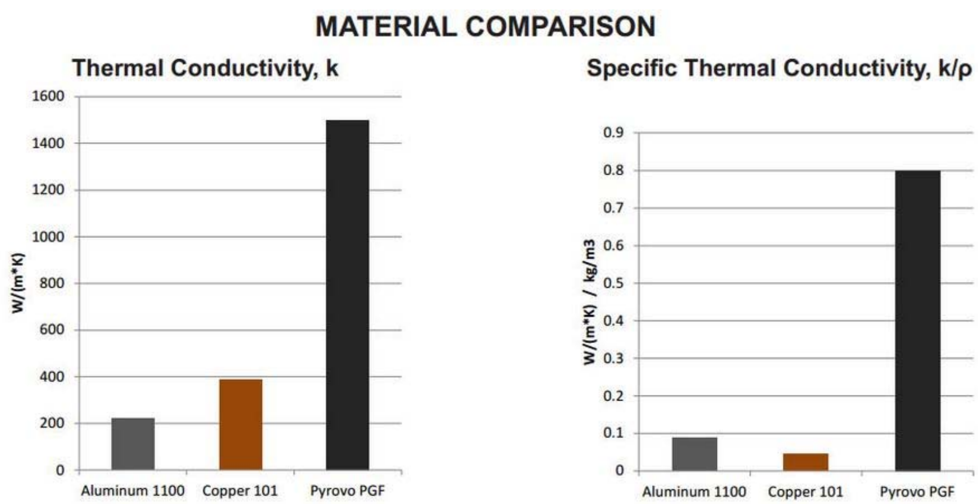


Figure 7.13. Thermotive Pyrovo PGF Material Comparison. Image courtesy of Thermotive (2014).

Deployable Radiators Thermotive is researching the design of a deployable passive radiator for hosted payload instruments and cubesats, Folding Elastic Thermal Surface (FETS). 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 use and has TRL 4/5 (Thermotive, 2014).

Storage Units 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, 2015). Thermal Management Technologies is developing a phase-changing thermal storage unit (TSU) design that considers desired phaseshades-change temperatures, interfaces, temperature stability, stored energy, and heat removal methodologies, see Figure 7.14. A complete fabrication of this device will allow the user to control temperature peaks, stable temperatures and/or energy

Figure 7.14. 44°C, 2100 J CubeSat Thermal Storage Unit. Image courtesy of Thermal Management Technologies (2015).

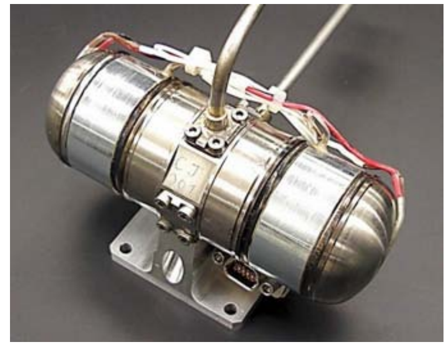


Figure 7.15. JT Circulator. Circulator photograph provided courtesy of Lockheed Martin Corporation.

storage (Thermal Management Technologies, 2015). Active Space Technologies also has storage units under development that integrates online design support and high cryogenic enthalpy. Both technologies are at TRL 5 for small spacecraft use.

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, see Figure 7.15. 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 (Champagne et al., 2015). This design is TRL 3.

7.4 Conclusion

As thermal management on small spacecraft is limited by mass, volume and power constraints, traditional passive technologies, such as MLI, paints, coatings 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 examined, designed and tested for small spacecraft platform application. Passive louvers and sun shields have been proposed and developed for small spacecraft and will tentatively fly in 2016 (Dellingr and CryoCube-1). Deployable radiators and various types of composite thermal straps have also been fabricated and tested for small spacecraft utilization in the past few years and are offered from numerous vendors. 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 broaden small spacecraft ability to use optical sensors and imaging spectrometers. Thermal storage units are being developed that will better control amount of heat dissipation as well as storing energy for future use.

References

Anvari, A., Farhani, F., & Niaki, K. (2009). Comparative study on space qualified paints used for thermal control of a small satellite. *Iranian Journal of Chemical Engineering, Vol. 6, No. 2*.

Champagne, P., Olson, J. R., Nast, T., Roth, E., Collaco, A., Kaldas, G., … Loung, V. (2015). *Development of a J-T Micro Compressor* (Tech. Rep.). Palo Alto, CA 94304, USA: Advanced Technology Center, Lockheed Martin Corporation.

Dunmore Aerospace Corporation. (2015). *Dunmore: Aerospace.* `http://www.dunmore.com/industries/aerospace.html`. (Accessed: 2015-08-10)

Durand, D., Tward, E., Toma, G., & Nguyen, T. (2014). *Efficient high capacity space micro-cooler.* Northrop Grumman Aerospace Systems Approved for Public Release; NGAS 14-1119, 6/02/14.

Hogstrom, K. (2013). State-of-the-Art Thermal Analysis Methods and Validations for Small Spacecraft. *Ae 241 Literature Survey*.

Hon, R., Kesler, C., & Sigurdson, D. (2009). Integrated testing of a complete low cost space cryocooler system..

Load Path, Aerospace Structures, Design, Test and Materials. (2015). *Flexible and Enhanced Active Thermal Straps (FEATS).* Small Sat Conference Brochure.

MLI Concepts, LLC. (2010). *Products: Multi-Layer Insulation (MLI).* `http://www.mliconcepts.com/Products/Products.html`. (Accessed: 2015-08-10)

Nakamura, Y., Nishijo, K., Murakami, N., Kawashima, K., Horikawa, Y., Yamamoto, K., … Inoue, K. (2013). Small Demonstration Satellite-4 (SDS-4): Development, Flgith Results, and Lessons Learned in JAXA's Microsatellite Project. *27th Annual AIAA/USU Conference on Small Satellites*.

NASA Goddard Space Flight Center. (2014). *Dellingr.* `https://techport.nasa.gov/externalFactSheetExport?objectId=14545`. (Accessed: 2015-08-28)

Olson, J., & Nast, T. (2013). *Lockheed martin microcryocooler* (Tech. Rep.). Palo Alto, CA 94304, USA: Advanced Technology Center, Lockheed Martin Corporation.

Ono, S., Nagano, H., Nishikawa, Y., Mishiro, M., Tachikiawa, S., & Ogawa, H. (2015). Thermophysical properties of a high-thermal-conductive graphite sheet and application to a deployable/stowable radiator. *Thermophysics and Heat Transfer*.

Ricor-USA Cryogenic and Vacuum Systems. (2015). *K562S Integral Stirling Low Power Mini Microcooler and K508N Highly Reliable Integral Stirling 1/2W Micro Cooler.* `www.ricor.com`.

Sierra Lobo. (2014). *CryoCube-1.* `http://www.sierralobo.com/cryocube/`. (Accessed: 2015-08-12)

Soulage, M. (2013). *Personal correspondence.*

Sunpower, I. (2015). *Cryotel® ds 1.5.* `http://sunpowerinc.com/cryocoolers/cryotel-family/ds15/`. (Accessed: 2015-09-01)

Technology Applications, Inc. (2015). *Graphite Fiber Thermal Straps (GFTS).* `http://www.techapps.com/gfts`. (Accessed: 2015-09-30)

Thermacore. (2015). *Thermal straps: Efficient cooling without structural loading.* `http://www.thermacore.com/products/thermal-straps.aspx`. (Accessed: 2015-09-30)

Thermal Management Technologies. (2015). *Flexible thermal straps.* `http://tmtsdl.com/products.html#ftStraps`. (Accessed: 2015-08-20)

Thermotive. (2014). *Products.* `http://thermotive.com/thermalstraps.html`. (Accessed: 2015-09-01)

Urquiza, E., Vasquez, C., Rodriguez, J., & Gorp, B. V. (2012). Development and testing of an innovative two-arm focal-plane thermal strap (TAFTS). *Cryogenics*.

Zagarola, M., Hill, R., Gagne, J., & Kaszeta, R. (2012). Ultra low power cryo-refrigerator for space applications. *International Workshop on Instrumentation for Planetary Missions*.

8 Command and Data Handling

8.1 Introduction

There are two primary trends in small spacecraft command and data handling (C&DH). The desire to incorporate small spacecraft, especially in the cubesat class, into more complex science and technology applications in LEO and deep space or interplanetary missions requires increased system reliability and performance. In the case of the smaller spacecraft, these objectives are complicated by the use of highly integrated systems and the need for power and mass efficiency.

At the other end of the spectrum, low-cost easy-to-develop systems that take advantage of open source software and hardware are providing an easy entry into space systems development, especially for those who lack specific spacecraft expertise or for the hobbyist.

8.2 State of the art

Since the publication of the first edition of this report, several cubesats using commercial-off-the-shelf (COTS) components and integrated systems have successfully flown in the LEO environment, over short mission durations of typically less than one year.

A variety of C&DH development for cubesats has spanned in-house development to new companies that specialize in cubesat avionics and 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.

In anticipation of the extended duration in LEO and deep space missions, vendors are incorporating radiation hardened or radiation tolerant designs in their cubesat avionics packages.

8.2.1 Form Factor

The CompactPCI and PC/104 form factors continue to be the industry standard electronics bus systems with multiple vendors offering components that will integrate into systems that can be space rated.

The PC/104 board dimension continues to be the baseline for cubesat configurations. Many vendors have adopted the use of stackable "daughter" or "mezzanine" boards in order to simplify connection between subsystem elements and payloads, as well as to accommodate advances in technologies while maintaining compatibility with existing designs. A few vendors provide a modular package, which allows users to select from a variety of computational processors.

8.2.2 On-Board Computing

Microcontrollers and FPGAs Small spacecraft, and especially cubesat developers, continue to use microcontrollers and field programmable gate arrays (FPGAs) supporting a variety of different processor cores. FPGAs have successful legacy in space and continue to lend themselves to high levels of integration providing peripherals, on-chip memories and improved power performance, factors that influence the choice of on board computing at present. See Table 8.1 for current state of the art highly integrated on-board computing systems for small spacecraft use.

Many power efficient microcontrollers used in cubesats feature ARM processors and a variety of on-chip peripherals, especially communications such as universal serial bus (USB), controller area network (CAN), as well as I2C interfaces and serial peripheral interface (SPI). There has also

Table 8.1. Sample of Highly Integrated On-board Computing Systems

Product	Manufacturer	Processor	Status
Nanomind A712D	GOMSPACE	ARM7	TRL 9
ISIS OBC	ISIS	ARM9	TRL 9
Pluggable Socketed Processor Module	Pumpkin	C8051F120, PIC24F256110, PIC 24F256GB210, MSP430F1612, MSP430F1611, MSP4302618	TRL 9
MODAS	Utah State University SDL	TI320C6713DSP	TRL 9
Proton X Box	Space Micro	P200K (TI DSP); P400K (Freescale PowerPC Dual Core); P300K (FPGA Virtex 5 or 7)	TRL 9
Proton 2X Box	Space Micro	P300K(TI DSP); P300K FPGA (Virtex 5 or 7); P400K (Freescale P2020 dual core PowerPC processor)	TRL 9
Intrepid	Tyvak	ATMEL AT91SAM9G20	TRL 9
Q7	Xiphos	Xilinx Zynq 7020 ARM dual core Cortex A9, Actel ProASIC3 Control FPGA	TRL 9
Q6	Xiphos	Xilinx Spartan-6, Actel ProASIC3 Control FPGA	TRL 9
Q5	Xiphos	PowerPC 405	TRL 9
ArduSat	NanoSatisfi	ATMEL ATmega328P	TRL 9

been an increase in the number of microcontrollers that integrate flash memory, as most of their advantages are centered on programmability.

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 providers are working towards providing simplified tool sets and cost effective basic evaluation boards.

Smartphone Based Processing Further demonstrating COTS hardware, NASA's PhoneSat 1.0 and SSTL's STRAND-1 flew cubesats that used Google Nexus One smartphones as the central processor. Smartphones exploit a large market with a fast design cycle, and incorporate several key features that are used in spacecraft, such as cameras, radio links, accelerometers and high performance computer processors. The smartphone cores used on those early spacecraft were based upon the Qualcomm Snapdragon system on chip (SoC) with a 1 GHz Scorpion processor running the Android operating system. Phonesat 1.0 simply flew the phone in a cubesat chassis along with a battery pack for power and a UHF beacon radio.

The hobbyist market that has subsequently emerged from smartphone app development experienced the same I/O bottlenecks and mounting problems observed by these smartphone spacecraft. Consequently, a range of low-power microprocessors are now available, although still based on ARM and often running Android, but providing better modularity. No smartphone based cubesat avionics kits are available commercially at this time.

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 (Wooster, Boswell, Stakem, & Cowan-Sharp, 2007). Finally, Intel has entered the market with their Edison system. The dual-core x86-64 SoC was targeted at "Internet of Things" applications but the Edison has proven 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 set of relatively familiar API 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, ranging 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.

Table 8.2. Sample of Highly Integrated On-board Computing System Manufacturers

ATMEL	Honeywell	STMicroelectronics
BAE Systems	Intel	Texas Instruments
Broadreach	Intersil	3D Plus
C-MAC Microtechnology	Maxwell Technologies	Xilinx
Cobham (Aeroflex)	Microsemi (Actel)	Arduino
Freescale	Space Micro, Inc.	BeagleBone

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.

There are many manufacturers that provide a variety of electronic components that are considered high reliability and space rated and can be seen in Table 8.2. 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).

8.2.4 Bus Electrical Interfaces and I/O

Cubesat class spacecraft continue to utilize those interfaces that are commonly used 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).
- Multi Media 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.

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, $\pm 10\%$	3.3-5 V	3.3 V	3.3 & 5 V	3.3 V	3.3 V	3.3 V
Organization (bits/die)	512k$\times$8	16M$\times$8	16M$\times$8; 32M$\times$8	128k$\times$8	16k$\times$8	
Data Retention (@70°C)	N/A	N/A	10 years	10 years	10 years	10 years
Endurance (Erase/Write cycles)	Unlimited	Unlimited	10^6	10^{13}	10^{13}	10^{13}
Access time	10 ns	25 ns	50 ns after page ready; 200 μs 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-med (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	
Package	4 MB	128 MB	128-256 MB	1 MB	1.5 MB (12 chip package)	

Table 8.4. Commercial cubesat EPS

Manufacturer	Product	Contact
Pumpkin	CubeSat KitTM Linear EPS	www.cubesatkit.com
Gomspace	NanoPower Modules	www.gomspace.com
Innovative Solutions in Space (ISIS)	Crystalspace P1U "Vasik"	www.cubesatshop.com
Clydespace	Variety of systems from 1-6U	www.clyde-space.com

- 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.

8.2.5 Electronic Power Supplies

A number of developers still design their EPS in-house. This is usually the case when the payload has power control needs and requirements that cannot be met by the commercially available suppliers. As the EPS is a critical system for the spacecraft, developers will typically utilize high reliability or space rated components.

There are several commercially available EPS for the cubesat platform. These systems provide voltages and regulation typically utilized in embedded systems such as 3.3 V and 5 V.

These systems also provide an array of features to address end user needs, such as short circuit protection, over current and over/under voltage protection, telemetry, battery charging and monitoring, reset capability and more depending upon the vendor. Many of these systems have flight heritage and are therefore greater than TRL 6. Table 8.4 provides a short list of vendors who provide EPS solutions for the cubesat platform.

8.3 On the Horizon

Many C&DH systems will continue to follow the trends set for embedded systems. Short duration missions in LEO will continue to take advantage of the advances made by industry leaders who provide embedded systems technologies and components. In keeping with the low cost rapid development theme of the cubesat-based missions, many COTS solutions are available for spacecraft developers.

Radiation mitigation solutions are being implemented by developers who need to address those concerns as applied to deep space and long duration LEO missions. A brief discussion about those techniques is provided in subsection 8.4.

Also trending in the cubesat development arena is the use of open source solutions. A number of C&DH systems being developed are utilizing Linux as their OS. This is allowing them to take advantage of open source SW that has been developed and tested (Wooster et al., 2007). NASA has developed open source software to support a number of missions. Others developers are using the open source in its truest sense, providing software libraries and on-line tools to aid in the development of their space systems. A brief discussion on open source is provided in subsection 8.5.

8.4 Radiation mitigation and tolerance schemes

Deep space and long duration LEO missions will require developers to incorporate radiation mitigation into their respective designs. The cubesat platform has traditionally utilized readily available COTS components. Use of COTS parts has allowed for low cost C&DH development while also allowing the developers to take advantages 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, use of these components has an impact to the overall costs 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 development of an overall radiation tolerant design as discussed in the following section.

8.4.1 Radiation mitigation and tolerance schemes

For space applications, radiation can damage electronics in two ways. Total ionizing dose (TID) is the amount of cumulative radiation received. Single event effects (SEE) is the disturbance created by single particles hitting the electronics (Nguyen, 2015). Total dose is measured in krad and can affect transistor performance. Single event upsets (SEU) can affect the logic state of memory. A single event latchup (SEL) can affect the output transistors on CMOS logic, potentially causing a high-current state. The purpose of this section is to summarize techniques used to mitigate system failures caused by radiation effects.

8.4.2 Component Selection

Memory

FRAM (Ferroelectric RAM) is a non-volatile random access memory that is persistent like Flash memory. FRAM memory cells are latched using a PZT film structure which is more likely to maintain state during a single event effect than traditional capacitive latches found in RAM (Ball Aerospace & Technologies Corp, 2015; Henkel, 1996).

Imaging

Charge couple devices (CCD) and complementary metal oxide semiconductors (CMOS) are image sensors that are useful in radiation environments. However, CCD's are preferred in space applications while the CMOS detectors is a newer technology for rad hardened image sensors. (Bardoux, Penquer, Gilard, Ecoffet, & Auvergne, 2012; Chapman, 2015; Holbert, 2015; NASA Goddard Space Flight Center, 2015a, 2015b)

8.4.3 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, that resets the processor when it 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. (Mauere, Fraeman, Martin, & Roth, 2008)

Communication watchdog timer

A dedicated communication watchdog timer circuit can monitor command 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 latchup (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 to 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 needed operationally.

8.4.4 Memory Protection

ECC memory

Error-correcting code 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 unusable and/or correct single-bit errors. The memory controller is responsible for managing the ECC memory during read and write operations. (LaBel et al., 1996)

Software EDAC

Bit errors can be detected and corrected using software. In general, 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 value, 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.

8.4.5 Communication Protection

Shared bus monitoring (I2C)

I2C is a standard communication protocol for sharing device peripherals. I2C consists of a clock and data line. Individual peripherals on the bus use these common lines to communicate with a master controller. In the event that an individual device locks up communication, the master controller can monitor and reset the device to restore communication for all devices.

Shared bus switching Another option is to decouple the clock and data lines so that each peripheral has it's 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 a way to reconfigure those assignments in flight.

CRC

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. CRC's help detect data corruption but cannot be used to correct the defective data.

Forward error correction

FEC transmits redundant data to help the receiver recover corrupted data. In it's 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. Mauere et al. (2008)

8.4.6 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 the case that the primary version is corrupt.

8.5 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.

8.5.1 CFE/CFS

The Core Flight Executive (cFE) is an application development and runtime environment developed by Goddard Space Flight Center. cFE includes core services like messaging, timekeeping, events, and table-driven commanding and configuration (Fitzsimmons, 2012; NASA Goddard Space Flight Center, 2015a).

8.5.2 COSMOS

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 (Ball Aerospace & Technologies Corp, 2015).

8.5.3 Linux

Linux is currently supported by several spacecraft avionics providers including Space Micro and Tyvak. Additional software modules are needed for space applications. Such modules may include memory scrubbing, a safe mode controller, watchdog functionality, and other reliability services (NASA Goddard Space Flight Center, 2015b).

8.6 Conclusion

System level solutions are in demand and a majority of the small spacecraft bus developers utilize 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 the wide range of small spacecraft developers, professional and amateur.

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, especially in the cubesat class, will need to address impacts of radiation in deep space missions and extended duration missions in LEO. Several processor manufacturers and board level integrators are addressing the need for radiation hardened and radiation tolerant designs. Some board level integrators have also undertaken radiation testing of their integrated systems. Many integrated systems providers, are utilizing radiation hardened processors or FPGAs from manufacturers such as XILINX, ATMEL, Aeroflex.

Open source software and hardware hold a lot of promise for commercial and government spacecraft developers. Making a project open source is the first step. The next step is to socialize the software and encourage developers to not only use but to contribute back flight-proven algorithms, software modules, and hardware components.

Cubesats are playing a large role in rapidly developed low cost missions in space, as they are establishing technology demonstrations and short duration science missions in LEO. NASA and other space agencies are now exploring their application in deep space missions. The cubesat community will provide innovative solutions to address the reliability requirements necessary for those missions, while attempting to maintain the low cost approach associated with the platform. Complete avionics packages are available to those who seek an integrated solution. At the other extreme, open source DIY kits are available to those who seek a low cost way to explore developing their own C&DH system and spacecraft.

References

Ball Aerospace & Technologies Corp. (2015). *The user interface for command and control of embedded systems.* `http://cosmosrb.com/`. (Accessed: 2015-10-20)

Bardoux, A., Penquer, A., Gilard, O., Ecoffet, R., & Auvergne, M. (2012). Radiation effects on image sensors. In *International conference on space optics.*

Chapman, T. (2015). *Radiation tolerances.* `http://www.photonics.com/EDU/Handbook.aspx?AID=41473`. (Accessed: 2015-10-20)

Fitzsimmons, S. (2012). Open-source software for cubesat satellites. In *Proceedings of the AIAA/USU Conference on Small Satellites.* Logan, Utah.

Henkel, H. (1996). *Total dose radiation tests at fram non-volatile memories.* http://www.cypress.com/file/57011/download. (Accessed: 2015-10-20)

Holbert, K. E. (2015). *Single effect events.* http://holbert.faculty.asu.edu/eee560/see.html. (Accessed: 2015-10-20)

LaBel, K. A., Gates, M. M., Moran, A. K., Marshall, P. W., Barth, J., Stassinopoulos, E., ... Dale, C. J. (1996). Commercial microelectronics technologies for applications in the satellite radiation environment. In *Aerospace applications conference* (Vol. 1). Aspen, CO. http://radhome.gsfc.nasa.gov/radhome/papers/aspen.htm. (Accessed: 2015-10-20) doi: 10.1109/AERO.1996.495897

Mauere, R., Fraeman, M., Martin, M., & Roth, D. (2008). Harsh environments: Space radiation environment, effects, and migitation. *Johns Hopkins APL Technical Digest*, *28*(1).

NASA Goddard Space Flight Center. (2015a). *Core flight software system.* https://gsfctechnology.gsfc.nasa.gov/TechSheets/CFSS_Goddard_09.pdf. (Accessed: 2015-10-20)

NASA Goddard Space Flight Center. (2015b). *GSFC Open Source Software.* http://opensource.gsfc.nasa.gov/. (Accessed: 2015-10-20)

Nguyen, M. (2015). Fpga advances improve radiation mitigation for remote-sensing satellites. *COTS Journal*, *17*(8).

Wooster, P., Boswell, D., Stakem, P., & Cowan-Sharp, J. (2007). Open source software for small satellites. In *Proceedings of the AIAA/USU Conference on Small Satellites.* Logan, Utah.

9 Communications

9.1 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 device that both receives and transmits is called a transceiver. 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. Spacecraft-to-spacecraft communications is sometimes referred to as an InterSatellite Link (ISL).

Traditionally, communication between Earth and spacecraft is based in the radio spectrum (from about 30 MHz to 40 GHz). The different communication bands as defined by IEEE (2009) that are typically used for spacecraft include:

- Very High Frequency (VHF): 30 to 300 MHz
- Ultra High Frequency (UHF): 300 MHz to 3 GHz
- L band: 1 to 2 GHz
- S band: 2 to 4 GHz
- C band: 4 to 8 GHz
- X band: 8 to 12 GHz
- Ku band: 12 to 18 GHz
- K band: 18 to 27 GHz
- Ka band: 27 to 40 GHz
- Optical (Laser Communication): 100 to 800 THz

The radio spectrum used for spacecraft communications is also shown graphically in Figure 9.1.

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 results in higher data rates), up into the X- through Ka-bands. Higher data rates

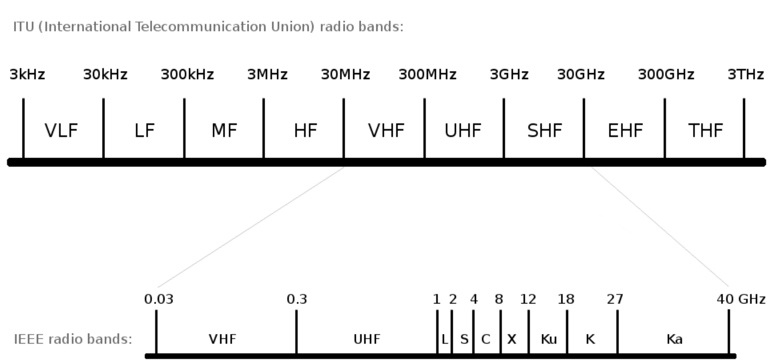


Figure 9.1. Radio spectrum used for spacecraft communication.

Figure 9.2. UHF deployable (4) monopole antennas for use on cubesats. Image courtesy of GOMSpace.

Figure 9.3. Cubesat-compatible S-band patch antenna. Image courtesy of IQ Wireless.

are more readily achievable with higher frequencies because data rate is proportional to 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 (Wertz, Everett, & Puschell, 2011, p. 641).

Received signal power will decrease as the transmission distance gets larger, thus larger spacecraft on deep space missions almost always 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 section 5). For example, an inflatable dish antenna is one proposed solution (Babuscia, Corbin, Knapp, Jensen-Clem, & de Loo Sara Seager, 2013).

Thus far, cubesats have not operated beyond LEO, and this has allowed them 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. Whip or tape antennas, such as the one shown in Figure 9.2, are easily deployable from a cubesat and are generally used for VHF and UHF communications. Patch antennas, such as the one shown in Figure 9.3, 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 (Altunc et al., 2015), and beyond. A key advantage of higher frequency (especially for cubesats) is that antenna aperture decreases but gain remains similar. This is advantageous for ground systems too. One major disadvantage is that higher frequencies get readily absorbed by the atmosphere. 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.

Figure 9.4. Example of software defined radio, tunable in the range 70 MHz to 6 GHz. Image courtesy of GOMSpace.

Another trend that aids in the improvement of RF based communication systems is the development of software defined radio (SDR). By using Field Programmable Gate Arrays (FPGAs), SDRs have great flexibility that allows them to be used with multiple bands, filtering and modulation schemes, without much (if any) change to hardware (Wertz et al., 2011, p. 636). Furthermore, such characteristics can be changed in-flight by uploading new settings from the ground. SDRs are especially attractive for use on cubesats as they can be made increasingly small and efficient as electronics become smaller and require less power (see Figure 9.4). Since 2012, NASA has been operating the Space Communications and Navigation (SCaN) Testbed on the International Space Station, which was created for the purpose of SDR TRL advancement, among other things (Johnson, Reinhart, & Kacpura, 2012).

Laser based communication ("lasercom") has already been demonstrated with larger spacecraft such as LADEE (National Aeronautics and Space Administration, 2013c). The era for lasercom on cubesats is just beginning, with technology demonstration missions planned for 2015 and 2016.

In the following sections, TRL 6+ technology that is relevant to the cubesat form factor is listed in tables organized by operating frequency.

9.2 State of the art

9.2.1 VHF and UHF

VHF and UHF frequencies are mature bands used for cubesats communication, with several radio developers to choose from. TRL 7 and higher technologies are listed in Table 9.1. Note that Clyde Space's VUTRX transceiver was developed by F'SATI (the French South African Institute of Technology) at CPUT (Cape Peninsula University of Technology) (French South African Institute of Technology, 2015). More information on BitBeam radios can be found in Lurie (2014), while more information on L3 Communications' Cadet Radio can be found in Kneller, Hyer, McIntyre, Jones, and Swenson (2012).

Typically, a small patch antenna (see Figure 9.3) or whip antenna is used to transmit VHF and UHF. Aside from the TRL 9 antennas listed in Table 9.1, other deployable, higher gain antennas (as seen in Figure 9.5) are being developed, including a TRL 6 deployable quadrifilar helical UHF through S-band antenna by Helical Communication Technologies (HCT), and a deployable helical UHF antenna by Northrop Grumman Aerospace Systems (Ochoa, Hummer, & Ciffone, 2014).

9.2.2 L-band

In L-band, cubesats can take advantage of legacy space communications networks such as GlobalStar and Iridium by using network specific transponders to relay information to and from Earth. An additional advantage is that these networks remove dependence on dedicated groundstation equipment, as discussed further in section 11.

Figure 9.5. Example of deployable quadrifilar helical antenna. Image courtesy of Helical Communication Technologies.

Figure 9.6. SNaP spacecraft with Haigh-Farr's deployable UHF Crossed Dipole antenna. Image courtesy of Haigh Farr.

Table 9.1. Developers and products for use in VHF/ UHF

Product	Manufacturer	Status
Lithium-1	Astronautical Development LLC	TRL 9
CSK Phasing Board	Astronautical Development LLC	TRL 9
BBSDR	BitBeam Inc.	TRL 8
BBUHF	BitBeam Inc.	TRL 8
VUTRX	Clyde Space Ltd.	TRL 9
NanoCom AX100	GOMSpace ApS	TRL 8
NanoCom ANT430	GOMSpace ApS	TRL 9
NanoCom SDR	GOMSpace ApS	TRL 7
P/N 17100	Haigh-Farr Inc.	TRL 9
TRXUV	ISIS B.V.	TRL 9
TRXVU	ISIS B.V.	TRL 8
Deployable Antenna System for CubeSats	ISIS B.V.	TRL 9
Cadet	L3 Communications Inc.	TRL 9

Examples of network-specific transponders are shown in Table 9.2. Note that NearSpaceLaunch's EyeStar-D2 Satellite Duplex radio has flight heritage, but no large file transfer was possible due to an unplanned 2 rpm spin rate (Voss, Dailey, Crowley, Bennett, & White, 2014). Also, sci_Zone is developing its next generation of simplex radio, STX3, as well as a duplex radio.

The multiband HCT quadrifilar helical antenna mentioned in section 9.2.1 can also operate in L-band.

Table 9.2. Developers and products for use in L-band

Product	Manufacturer	Status
9602 SBD	Iridium Communications Inc.	TRL 9
EyeStar-S2	NearSpace Launch Inc. (NSL)	TRL 9
EyeStar-D2	NearSpace Launch Inc. (NSL)	TRL 8
STX2 Simplex	sci_Zone, Inc	TRL 9

9.2.3 S-band

Examples of TRL 7+ S-band communication technology are shown in Table 9.3. A cubesat-compatible S-band transmitter is shown in Figure 9.7. Note that the Clyde Space products SANT and STX were developed by F'SATI at CPUT. Haigh-Farr's S-band antennas are scheduled to fly on the CPOD 3U cubesat mission, scheduled for launch in 2016.

Regarding lower TRL technology, L3 Communications' Cadet Nanosat Radio (see Table 9.1) is also configurable to be used in S-band, although this has not been demonstrated at the time of publication. LJT & Associates have developed 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 (White, Morgan, & Murbach, 2007). Also, Syrlinks develops an S-Band transceiver that has flight heritage, though to the knowledge of the author it has not been flown on a cubesat mission. 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 to the knowledge of the author they have not flown on a cubesat mission.

Figure 9.7. Cubesat-compatible S-band transmitter, to be used with either amateur or commercial bands. Image courtesy of Clyde Space.

Many antennas are available in S-band, including a stacked patch S-band antenna being developed by NewSpace Systems and the HCT quadrifilar helical antenna mentioned in section 9.2.1. AntDevCo, IQ Wireless, Surrey Satellite Technology and many others make S-band patch antennas that could be compatible with cubesats. ISIS B.V. resells the S-band patch antenna, and transmitter and receiver for IQ Wireless' HISPICO communication system.

The unlicensed ISM (Industrial, Scientific, and Medical) bands have been utilized for cubesat communications as well. Notably, a group at Singapore's Nanyang Technological University used a 2.4-GHz ZigBee radio on its VELOX-I mission to demonstrate that COTS land-based wireless systems can be used for inter-cubesat communication (Xie, Lee, Low, & Gunawan, 2014). Similarly, there are investigations underway for using wireless COTS products, such as bluetooth-compatible hardware, for *intra*-satellite communications (Schoemaker & Bouwmeeste, 2014).

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 (Hatziathanasiou & McLaren, 2014).

Table 9.3. Manufacturers and products for use in S-band

Product	Manufacturer	Status
Beryllium 2	Astronautical Development LLC	TRL 9
SANT	Clyde Space Ltd.	TRL 9
STX	Clyde Space Ltd.	TRL 9
P/N 3745	Haigh-Farr Inc.	TRL 8
P/N 3756	Haigh-Farr Inc.	TRL 8
SCR-100	Innoflight Inc.	TRL 9
HISPICO	IQ Wireless GmbH	TRL 9
SLINK	IQ Wireless GmbH	TRL 7
TXS	ISIS B.V.	TRL 8
CSR-SDR-S/S	Vulcan Wireless Inc.	TRL 8

9.2.4 X-band

X-band transmitters (such as that in Figure 9.8) have recently become a reality for cubesats because of the advent of commercially available Monolithic Microwave Integrated Circuits (MMICs). There has been much effort recently from industry, universities and government centers alike to develop communications systems at this wavelength (Palo et al., 2014).

Figure 9.8. X-band high-gain antenna and pointing mechanism. Image courtesy of Surrey Space.

Table 9.4 displays TRL 9 cubesat compatible X-band communication hardware. Note that AntDevCo's "evolved" wire antennas were designed 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 were only 25 kg in mass. AntDevCo also develops X-band patch antennas. It should also be noted that Planet Labs uses a proprietary X-band radio (Boshuizen, Mason, Klupar, & Spanhake, 2014).

Surrey Satellite Technology developed a high-gain X-band antenna and corresponding pointing mechanism (see Figure 9.8), and an X-band transmitter that have flight heritage on spacecraft less than 180 kg in mass, though to the knowledge of the author have not flown on a cubesat mission. Similarly, Haigh-Farr's small-satellite-compatible X-band antenna flew on the suborbital SOAREX-8 mission.

JPL has also developed a cubesat compatible transponder for deep space (Duncan, Smith, & Aguirre, 2014), while CU Boulder and Goddard Space Flight Center jointly developed an X-band SDR that is now being sold by Blue Canyon Technologies (Altunc et al., 2015). Lower TRL technologies include an X-band transmitter from NewSpace Systems.

Table 9.4. Manufacturers and products for use in X-band

Product	Manufacturer	Status
Evolved X-band wire antennas	Antenna Development Corporation Inc. (AntDevCo)	TRL 9
Quadrifilar Helix Antenna (X-band)	Antenna Development Corporation Inc. (AntDevCo)	TRL 9
HDR-TM	Syrlinks	TRL 9

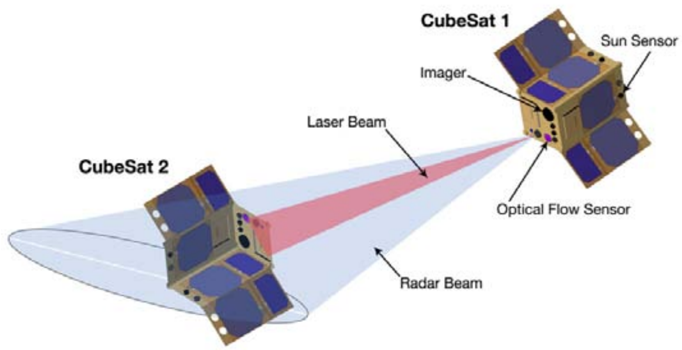


Figure 9.9. Conceptual drawing of laser communication between two cubesats for OCSD mission. Image courtesy of National Aeronautics and Space Administration (2015).

9.2.5 Lasercom

Lasercom for cubesats has yet to become a TRL 9 technology, but it is quickly gaining ground. Already, Aerospace Corporation launched one of three cubesats in its AeroCube Optical Communication and Sensor Demonstration (OCSD) program (Welle, Janson, Rowen, & Rose, 2015) on October 8, 2015 (see Figure 9.9). Also, Fibertek is working on a (currently TRL 6) 6U lasercom system. For both of these ventures, lasers are hosted onboard the cubesat(s). A 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 section 9.3.2).

9.3 On the Horizon

9.3.1 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 Aquila Space, Micro Aerospace Solutions, NewSpace Systems, and Tethers Unlimited.

Aquila Space already has an operational Ka-band transmitter on two 6U spacecraft; however, the utility of these systems has only been minimally demonstrated and Aquila Space is currently developing the next generation of the product. A Ka-band transmitter is shown in Figure 9.11. Micro Aerospace Solutions has a TRL 5 Ku/Ka-band transceiver with deployable 60 cm cubesat dish antenna (Lyons, Platt, Reeve, Rockeberger, & Tamir, 2015). Tethers Unlimited has a TRL 5 K-band SDR called SWIFT-KTX.

At the higher frequencies, rain fade becomes a significant problem for communications between a spacecraft and Earth (Pelton, 2006). Nonetheless, the benefits have justified further research by both industry and government alike. At the Jet Propulsion Laboratory (JPL), ISARA (Integrated Solar Array and Reflectarray Antenna) is being developed for use on a 3U cubesat (National Aeronautics and Space Administration, 2014). Essentially, the back of the spacecraft's solar panels are used as a Ka-band antenna reflector. A Ka-band communication system is being developed by JPL for the cubesat Mars Cube One (MarCO) mission (*JPL Studies Missions, Tech for Future Interplanetary Cubesats*, 2015).

9.3.2 Asymmetric laser communications

Asymmetric laser communication utilizes a remotely generated laser (i.e. 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 (see Figure 9.10). The laser is located on Earth, where power and volume constraints are not as tight, while the communications payload on the spacecraft requires only a few Watts for operation. SPAWAR is developing this technology using a MEMS based MRR (Wayne et al., 2015), while NASA Ames Research Center is developing a similar capability using a modulating quantum well (MQW) device as the MRR (Salas, Stupl, & Mason, 2012).

9.3.3 Transparent Antennas

When deployable solar panels are not an option, a cubesat's surface is prime real estate for solar cells. One way to maximize exposed surface area on a cubesat is to create communications antennas that are optically transparent. Groups at the University of Houston (Montano et al., 2014) and Utah State University (Genc, Turpin, Yasin, & Baktur, 2012) have developed prototypes of these small, optically transparent antennas.

9.3.4 Intercubesat Communications and Operations

There are multiple advantages to communicating between spacecraft. As cubesat missions become more automated, constellations could exchange information to maintain precise positions without input from the ground. Data can be relayed between spacecraft to increase the coverage from limited ground stations. Finally, intercubesat 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.

Though transponders are well established in the spacecraft world, networked swarms of cubesats that pass information amongst each other and then eventually to ground have yet to be demonstrated. Developing networked swarms is less of a hardware engineering problem than a systems and software engineering problem, as demonstrated by NASA Ames Research Center's Edison Demonstration of Smallsat Networks (EDSN) mission (Hanson, Chartres, Sanchez, & Oyadomari, 2014), see Figure 9.12. Ames' follow up Nodes cubesat mission is scheduled to deploy from the International Space Station in early 2016.

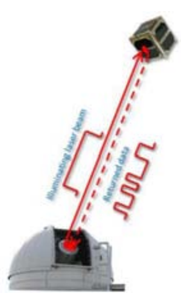


Figure 9.10. Scheme for using land based laser to transmit data from cubesat using on-board MRR. Image courtesy of Salas et al. (2012).

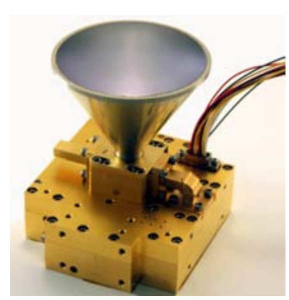


Figure 9.11. Ka-band transmitter with a horn antenna. Image courtesy of Aquila Space.

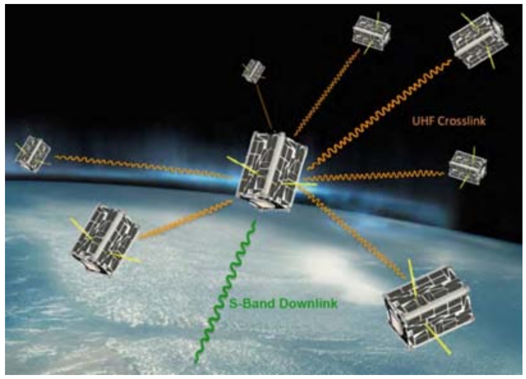


Figure 9.12. Scheme for inter-cubesat communication for EDSN mission. Image courtesy of National Aeronautics and Space Administration (2013b).

Similarly, the Cubesat Proximity Operations Demonstration (CPOD) mission "will demonstrate rendezvous, proximity operations and docking using two 3U cubesats" (National Aeronautics and Space Administration, 2013a), and is led by Tyvak NanoSatellite Systems, LLC.

9.4 Conclusion

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. The use of even higher RF frequencies and laser communication already has some flight heritage on cubesats, but with limited (or yet to be demonstrated) performance. Ka-band systems for cubesats are currently in development, but TRL status is still relatively low. On the other hand, laser communication is a spaceflight ready technology that will most likely see increased performance in the near future for onboard laser systems. Alternatively, a few groups are working on asymmetric laser communication, but it is still a relatively low TRL technology.

References

Altunc, S., Kegege, O., Bundick, S., Shaw, H., Schaire, S., Bussey, G., … O'Conor, D. (2015). X-band CubeSat Communication System Demonstration. In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Babuscia, A., Corbin, B., Knapp, M., Jensen-Clem, R., & de Loo Sara Seager, M. V. (2013). Inflatable antenna for cubesats: Motivation for development and antenna design. *Acta Astronautica*, *91*, 322-332.

Boshuizen, C. R., Mason, J., Klupar, P., & Spanhake, S. (2014). Results from the planet labs flock constellation. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Duncan, C. B., Smith, A. E., & Aguirre, F. H. (2014). Iris Transponder–Communications and Navigation for Deep Space. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

French South African Institute of Technology. (2015). *Products.* `http://www.cput.ac.za/blogs/fsati/products`. (Accessed: 2015-11-02)

Genc, A., Turpin, T., Yasin, T., & Baktur, R. (2012). Active integrated meshed patch antennas for small satellites. *Microwave and Optical Technology Letters*, *54*(7), 1593-1595.

Hanson, J., Chartres, J., Sanchez, H., & Oyadomari, K. (2014). The EDSN Intersatellite Communications Architecture. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Hatziathanasiou, I., & McLaren, C. (2014). Flexible S-Band TTC (Telemetry, Tracking, and Command) for Small Spacecraft in LEO. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

IEEE. (2009). *IEEE Standard Letter Designations for Radar-Frequency Bands.* IEEE Std. 521-2002. (Approved 12 September 2002, Reaffirmed 17 June 2009)

Johnson, S. K., Reinhart, R. C., & Kacpura, T. J. (2012). Connect's approach for the development of three software defined radios for space application. In *2012 IEEE Aerospace Conference.* Big Sky, Montana.

JPL Studies Missions, Tech for Future Interplanetary Cubesats. (2015). `http://spacenews.com/jpl-studies-missions-and-technologies-for-future-interplanetary-cubesats`. (Accessed: 2015-10-01)

Kneller, E. W., Hyer, K. L., McIntyre, T., Jones, D. K., & Swenson, C. (2012). Cadet: A High Data Rate Software Defined Radio for SmallSat Applications. In *26th Annual AIAA/USU Conference on Small Satellites.*

Lurie, H. (2014). Modular software defined radios for space to earth communications. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Lyons, R., Platt, D., Reeve, J., Rockeberger, D., & Tamir, R. (2015). Enhanced small satellite communication system for remote planetary exploration. In *66th International Astronautical Congress.* Jersusalem, Israel.

Montano, R., Neveu, N., Palacio, S., Martinez, E., Jackson, D. R., Fink, J. C. P. W., & Provence, R. S. (2014). Development of low-profile antennas for cubesats. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

National Aeronautics and Space Administration. (2013a). *Cubesat Proximity Operations Demonstration (CPOD).* `https://www.nasa.gov/directorates/spacetech/small_spacecraft/cpod_project.html#.VhxVjrwy360`. (Accessed: 2015-10-12)

National Aeronautics and Space Administration. (2013b). *Edison Demonstration of Smallsat Networks Mission: A Swarm of Advanced, Affordable, COTS-based Nanosatellites that Enable Cross-Link Communication and Multipoint Physics.* (NASA Facts)

National Aeronautics and Space Administration. (2013c). *NASA Laser Communication System Sets Record with Data Transmissions to and from Moon.* `http://www.nasa.gov/press/2013/october/nasa-laser-communication-system-sets-record-with-data-transmissions-to-and-from/#.VfHATrwy0Yp`. (Accessed: 2015-09-10)

National Aeronautics and Space Administration. (2014). *Integrated Solar Array and Reflectarray Antenna (ISARA) for High Bandwidth Cubesats.* `https://www.nasa.gov/sites/default/files/files/ISARA_Fact_Sheet-15Oct14.pdf`. (NASA Facts)

National Aeronautics and Space Administration. (2015). *Optical Communications and Sensor Demonstration (OCSD).* `http://www.nasa.gov/images/content/745978main_ocsd_cubesats_full.jpg`. (Accessed: 2015-09-11)

Ochoa, D., Hummer, K., & Ciffone, M. (2014). Deployable Helical Antenna for Nano-Satellites. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Palo, S., O'Connor, D., DeVito, E., Kohnert, R., Crum, G., & Altunc, S. (2014). Expanding CubeSat Capabilities with a Low Cost Transceiver. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Pelton, J. N. (2006). *The Basics of Satellite Communications.* Professional Education International, Inc.

Salas, A. G., Stupl, J., & Mason, J. (2012). Modulating retro-reflectors: technology, link budgets and applications. In *63rd International Astronautical Congress.* Naples, Italy.

Schoemaker, R., & Bouwmeeste, J. (2014). Evaluation of bluetooth low energy wireless internal data communication for nanosatellites. In *Small Satellites Systems and Services Symposium.* Porto Petro, Majorca, Spain.

Voss, H. D., Dailey, J. F., Crowley, J. C., Bennett, B., & White, A. J. (2014). TSAT GLobalstar ELaNa-5 Extremely Low-Earth Orbit (ELEO) Satellite. In *28th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Wayne, D., Obukhov, D., Phipps, A., Tran, M., Book, K., & Lovern, M. (2015). Design and Testing of a CubeSat-Sized Retroreflector Payload. In *29th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Welle, R. P., Janson, S., Rowen, D., & Rose, T. (2015). Cubesat-scale laser communications. In *31st Space Symposium, Technical Track.* Colorado Springs.

Wertz, J. R., Everett, D. F., & Puschell, J. J. (Eds.). (2011). *Space Mission Engineering: The New SMAD.* Microcosm Press.

White, B., Morgan, H., & Murbach, M. (2007). SOAREX-VI Re-entry Flight Test Experiment - Electronic Systems of the Slotted Compression Ramp (SCRAMP) Probe. In *International Planetary Probe Workshop - IPPW-5.* Bordeaux, France.

Xie, S., Lee, G. X., Low, K.-S., & Gunawan, E. (2014). Wireless sensor network for satellite applications: A survey and case study. *Unmanned Systems*, *02*.

10 Integration, Launch and Deployment

10.1 Introduction

In 2014, one hundred and thirty seven small spacecraft were launched versus forty eight larger spacecraft. Forecasts show that the balance will shift even more towards small spacecraft in the near future. State of the art technologies in launch vehicles, integration, and deployment systems are responding to the changing small spacecraft market to support new, advanced missions with diverse technologies that will take small spacecraft further into both space and the future.

Since launch vehicle capabilities usually exceed the requirements of the primary customer, there is usually enough residual mass, volume, and other performance margins available for delivery of small spacecraft on a mission. Small spacecraft can exploit this surplus capacity for an inexpensive ride to space. A large market of adapters and deployment technologies has been created to compactly house multiple small spacecraft on existing launchers. These technologies provide both a secure attachment to the launcher as well as mechanisms for departure at the appropriate time. This ride-share method is the first and still the primary way of putting small spacecraft into orbit, but the new technological advancements show that the popularity of classical ride-sharing might slowly decrease in the upcoming years. Dedicated ride-sharing, where an integrator books a complete launch and sells the available capacity to multiple spacecraft operators without the presence of a primary customer, is a new and interesting approach in the sector.

Although not a new idea, using orbital maneuvering systems to deliver small spacecraft to intended orbits is another growing technology. Several commercial companies are developing orbital tugs to be launched with state of the art launch vehicles to an approximate orbit, but then propel themselves to another orbit with their on-board propulsion system where they will deploy their hosted small spacecraft.

In the future, the expanding capabilities of small payloads 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 payload may be the best method of ascent. This will enable fields from technology development to hard sciences to take advantage of the quick iteration time and low capital cost of small spacecraft to yield new and exciting advances in space capabilities and understanding.

10.2 State of the Art

10.2.1 Launch Integration Services

Generally, the launch vehicle customer decides whether secondary payloads will share a ride with a primary payload and if so, how these secondary payloads are dispensed. In most cases, the launch vehicle (LV) customer is the primary payload. However, there are cases where a program or integration company can determine ride-share possibilities. More flexibility may be available to secondary payloads that are funded through such a program, although the mission schedule is generally decided by the primary payload. Typical ride-share integration services are general services provided by these integration companies that focus on LV integrations and do not vary due to mission requirements of the primary payload. Standardized services include system testing, engineering development support, hardware of the dispenser, and necessary integration such as spacecraft-to-dispenser and dispenser-to-LV. Ride-share integration services may depend heavily on the primary payload and can include de-integration (e.g., executing a separation maneuver), mission and science-specific services, special analyses related to hardware and integration services, and isolated venting, shock, vibration, and thermal environmental control.

Examples of launch integration companies are given below. These companies purchase the excess capacity on existing rockets and integrate as many small payloads as possible into this capacity, therefore contribute the usage of the launch vehicle with higher efficiency.

Adaptive Launch Solutions (ALS): Adaptive Launch Solutions provides launch integration services for small spacecraft on Atlas and Delta launch vehicles. The company is responsible for mission integration, thermal, coupled load, contamination, vibration, acoustic, shock, circuit, power, and venting models, analysis and test. ALS develops Auxiliary Payload Support Unit mission software providing sequenced power switching and separation validation to each auxiliary payload separation system (Adaptive Launch Solutions, 2015).

Commercial Space Technologies (CST): Commercial Space Technologies Ltd. is a consultancy company registered and based in London, with a representative office in Moscow. CST has negotiated and procured LVs for small spacecraft customers, having managed the interaction between launch provider and customer for 33 successful missions. This has been achieved with the use of five different LVs launched from three different launch sites (Commercial Space Technologies, 2015).

ISIS: Innovative Solutions in Space (ISIS) is a spacecraft company based in the Netherlands and established in 2006. The company is focused on spacecraft in the range of 1 to 20 kg and supplying components, and launch services. In June 2014, the company sent 23 cubesats into orbit on a Dnepr rocket and deployed them from their QuadPack dispenser. ISIS is in charge of the QB50 launch campaign scheduled for 2016, an initiative to send fifty university-built cubesats to conduct research in Earth's lower thermosphere (Innovative Solutions in Space B.V., 2015).

Qinetiq: QinetiQ North America (QNA) is a company with expertise in launch vehicle procurement, design, analysis, manufacturing oversight, integration, testing, mission management and launch. The company is supporting over twenty of the manifested Falcon 9 missions (Qinetiq, 2015).

Moog CSA Engineering: Moog CSA, located in Mountain View, CA, has been assisting commercial and military aerospace customers for more than thirty years to provide vibration isolation systems, tuned mass dampers for vibration control, softride spacecraft isolation systems, shock test services, and spacecraft transport shipping containers. The company also provides integration support for its customers (Moog CSA Engineering, 2015).

Nanoracks: Nanoracks, founded in 2009, is a company located in Houston, Texas, which hosts accommodation and an array of equipment for experiments on ISS. The company offers ISS-deployment services to its customers since 2014. In 2015, NanoRacks teamed up with Blue Origin to offer services for the New Shepard Suborbital Vehicle (NanoRacks LLC, 2015a).

Spaceflight Services: Spaceflight Services, founded in 2010 and based in Seattle, provides routine access to space for deployed and hosted small payloads by using published commercial pricing, standard interfaces, and frequent flight opportunities. Specific integration services provided include engineering analysis, spacecraft-to-dispenser and LV integration, flight service, and standard interface options for payloads. Spaceflight has put its first payload into orbit in 2013, has launched eighty one spacecraft since then and has over one hundred and thirty five spacecraft to deploy through

2018 (Spaceflight Services, 2015). The company's SSPS (Spaceflight Secondary Payload System) is designed to transport secondary and hosted payloads to space using the excess capacity on commercial launch vehicles. The SSPS can accommodate up to five 300 kg spacecraft, or many smaller spacecraft, on each of its five ports and operates independently from the primary launch vehicle to simplify payload and mission integration (European Space Agency, 2015a). The company is also developing a space tug (SHERPA), which builds upon the capabilities of the SSPS by incorporating propulsion and power generation subsystems, which can maneuver its secondary payloads to higher LEO altitudes, GEO, or even interplanetary trajectories. The first SHERPA mission is manifested on a SpaceX Falcon 9 early in 2016 with eighty nine payloads on board (Spaceflight Services, 2015).

UTIAS/SFL: The University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS/SFL) provides launch services for small spacecraft. The laboratory has arranged launches for more than ten spacecraft from different countries since 2002. Past launches have included Indian (PSLV) and Russian (Rockot, COSMOS-3M, Dnepr, Soyuz) vehicles. The laboratory has a dispenser system called the XPOD which can be used for any size of spacecraft up to 16 kg (UTIAS/SFL, 2015).

TriSept Corporation: TriSept Corporation has been integrating spacecraft ranging from the size of school buses to cubesats over the past twenty one years. Specific to small spacecraft, the company has physically integrated over seventy four payloads on both suborbital, LEO, and GEO launches on multiple spacecraft missions. TriSept provides spacecraft providers a total mission integration service, from concept development, interface requirements definition, launch vehicle selection and contracting, mission analyses, integration hardware provisions, fitchecks and pathfinders, integration, test, and payload certification, to launch and spacecraft deployment. The company currently serves as the lead integrator for the Operationally Responsive Space (ORS) Office, managing the Office's complex multiple spacecraft ride-share missions, such as the ORS-3 mission, which consisted of thirty one distinct payloads in November 2013, and the ORS-4 mission, which is set to launch thirteen payloads on the first launch of the Super Strypi small launch vehicle. TriSept Corporation is also developing the FANTM-RiDE family of dispenser systems and manifesting several traditional and dedicated ride-share launch missions to serve the small spacecraft industry (Lim, 2015).

Surrey Satellite Technology Ltd (SSTL): SSTL, majority-owned by EADS Astrium, builds and operates small spacecraft. On the launcher side, the company negotiates with launch providers to procure cost effective launch opportunities (Surrey Satellite Technology Ltd, 2015).

Tyvak Nano-Satellite Systems LLC: Tyvak Nano-Satellite Systems LLC provides launch services for small spacecraft and has launch experience with payloads ranging from 1 kg to 100 kg. To date over 120 spacecraft have been successfully launched and 40 additional spacecraft are currently manifested. The integration services for NASA's first inter-planetary cubesat (MarCO) mission to Mars is handled by the company. Tyvak provides a complete launch support solution including development of launch vehicle payload interfaces and associated documentation, spacecraft testing and qualification, development of spacecraft accommodations including standardized deployment systems, launch manifesting documentation including frequency allocation and ODAR analysis. To support its launch activities the company offers a number of standardized deployers including systems compatible with 1U, 3U, 6U and 12U spacecraft (Puig-Suari, 2015).

10.2.2 Dedicated Launchers of Small Spacecraft

In the context of this report, launch vehicles with total LEO capacity of 500 kg or less are considered to be dedicated launchers for small payloads. Small spacecraft have been in orbit for more than fifteen years. However, their popularity (and the annual number of small spacecraft launches) has not been significant until 2013, therefore a robust market of small launchers has not still yet developed. As the capabilities of small spacecraft are increasing, they are starting to drive the demand in the market. This section summarizes the current launch vehicles that have operated since 2000 (or plan to operate in the near future) to serve as dedicted launchers for these small spacecraft, and Table 10.2 summarizes primary launchers.

Pegasus: The Pegasus (Figure 10.1), an air-launched vehicle built by Orbital Sciences, is a small- to medium-lift launcher that has a heritage of successful launches since 1996. The system is able to deliver 450 kg to LEO with three solid stages. Different variants of the vehicle have a flight history of forty two missions between since 1990, thirty six of which are fully successful. The rocket's variant carried NASA Interface Region Imaging Spectrograph (IRIS) mission (183 kg) in June 2013. There are two Pegasus launches on the manifest dedicated for small spacecrafts in 2016 and 2017. The first mission will carry eight Cyclone Global Navigation Satellites (CYGNSS) (20 kg each) to space, and the second mission will inject the Ionospheric Connection Explorer (ICON) (279 kg) into orbit (Clark, 2014; Orbital ATK, 2015b). The system is operational with a TRL of 9.

Figure 10.1. Pegasus Launch System, mounted underneath a Lockheed 1011 jet. Image courtesy of Orbital ATK.

Minotaur: The Minotaur launcher family, also produced by Orbital Sciences, is another medium lift vehicle currently available. Out of the entire family, the Minotaur I (Figure 10.2) is more suited to small spacecraft since it has the lowest payload capacity and cost. The vehicle has conducted eleven missions with a 100% success rate, delivering sixty two spacecraft into orbit. The Minotaur I is designed with four solid stages from a converted Minuteman ballistic missile. With a payload capacity of 580 kg to LEO, the vehicle can carry many small spacecraft into orbit in a single mission.

Figure 10.2. Minotaur I Launch Vehicle. Image courtesy of NASA.

Figure 10.3. VLS-1 on the launch pad before the explosion in 2003. Image courtesy of IAE/FAB.

On 20 November 2013, a Minotaur I placed twenty eight small spacecraft (all but one were cubesats) and two experiment packages into orbit.

A larger member of the family, the Minotaur V, is a five-stage vehicle and is designed to place up to 630 kg of payload into a GTO, or 340 kg on a trans-lunar trajectory. The vehicle made its maiden flight in 2013 carrying the Lunar Atmosphere and Dust Environment Explorer (LADEE) (383 kg) spacecraft. However it has not yet carried any orbital payload (Orbital ATK, 2015a). Since the system is operational, the TRL is 9.

Super Strypi: Another vehicle on market which can be called as a dedicated small spacecraft carrier is Super Strypi. This vehicle, also known as the Low Earth Orbiting Nanosatellite Integrated Defense Autonomous System (LEONIDAS), is a three-stage launcher developed jointly by the Innovative Satellite Launch Program at the University of Hawaii in cooperation with Sandia National Laboratories and Aerojet. The vehicle has a simple, rail-launched, spin-stabilized design with fixed fins and cold gas attitude control system for second stage and third stage maneuvering and orbital insertion. Payload-to-orbit is about 275 kg to 400 km Sun synchronous orbit from Pacific Missile Range Facility (PMRF) in Kauai, Hawaii and about 320 kg to 400 km equatorial orbit from US east coast launch sites (Aerojet Rocketdyne, 2015). The unsuccessful first flight of the system occurred in October 2015. The TRL of the system is 6. The system is designed to integrate payloads with the NASA Ames Nanosatellite Launch Adapter System (NLAS).

10.2.3 Launchers Which Offer Ride-Sharing Opportunities for Small Spacecraft

As seen from the previous section, there are currently only a few launchers that allows small spacecraft to ride as primary payloads. The majority of small spacecraft are carried to orbit as secondary payloads, utilizing the excess launch capability of the larger rockets. Standard ride-sharing consists of a primary mission with surplus mass, volume, and performance margins which are used by other spacecraft. These spacecraft are also called secondary payloads, auxiliary payloads or piggyback

Table 10.1. Primary Payload Launchers

Product	Manufacturer	LEO Capacity	Number of Secondary Payloads Launched To Date	Description	Launch Method	Status
Minotaur 1	Orbital ATK	4-stage, all solid	580 kg	>46	Land	TRL 9
Minotaur 5	Orbital ATK	5-stage, all solid	630 kg (to GTO)	0	Land	TRL 9
Pegasus	Orbital ATK	3-stage, all solid	450 kg	0	Air	TRL 9
Super Strypi	University of Hawaii, Sandia National Laboratories, Aerojet	3-stage, all solid	275 kg to 400 km SSO, 320 kg to 400 km equatorial	0	Land	TRL 6

spacecraft. For both educational and commercial small spacecraft, several initiatives have helped provide these opportunities. NASA's cubesat launch initiative, for example, has provided rides to a number of schools and NASA centers. As of August 2015, thirty seven cubesats have been launched, and sixteen more are scheduled to go into space in the next twelve months within this program (National Aeronautics and Space Administration, 2015b).

From the secondary payload designers' perspective, ride-share arrangements provide far more options for immediate launch at high TRL. 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 payload. On the other hand, there are downsides of hitching a ride. The launch date and trajectory is determined in favor of the primary payload and the smaller craft have to take what is available. Also in some cases, they need to be delivered to the launch operator and be integrated on the adapter weeks before the actual launch date. Generally the secondary payloads are given permission to be powered on and deployed once the launch vehicle has successfully completed its primary mission. This section lists the launch vehicles which offered ride-share opportunities to small spacecraft in the last fifteen years and Table 10.2 summarizes these launch vehicles.

Antares: The Antares (Figure 10.4), known as Taurus II during its early development, made its inaugural flight on 21 April 2013. It carried four cubesats (three Phonesats from NASA Ames and one Dove from Planet Labs). After this demonstration flight, the vehicle had three successful flights to ISS with its primary payload Cygnus Cargo Vehicle on board. The vehicle had a catastrophic failure during its launch on 28 October 2014 with Arkyd-3 spacecraft (Planetary Resources) and a RACE cubesat (NASA JPL/UT-Austin cubesat) on board. The next launch of the vehicle is planned for 2016. Since the system is operational, the TRL is 9.

Figure 10.4. Antares. Image courtesy of Orbital ATK.

Figure 10.5. Ariane 5. Image courtesy of ESA/CNES/Arianespace–Photo Optique Video CSG.

Ariane 5: Ariane 5 (Figure 10.5)is a European heavy lift launch vehicle to deliver payloads into geostationary transfer orbit (GTO) or LEO. Although Ariane 5 is a workhorse for Europe, there have been very few secondary missions in the past atop this vehicle. The first example was Amsat P3D, a 400 kg amateur radio spacecraft, which was injected into highly elliptical orbit in 2000. The SMART-1 spacecraft (367 kg) was flown as a secondary payload into geostationary transfer orbit in 2003 and then traveled to orbit the Moon using its own propulsion system. In 2009, two demonstration spacecraft for the infrared warning system (SPIRALE), each weighing 120 kg, hitched a ride to elliptical equatorial orbit. The Ariane 5 is able to carry up to eight 100 kg (standard) payloads or four 180 kg (banana) payloads on its ASAP (Ariane Structure for Auxiliary Payload) platform (Leschly, Sprague, & Rademacher, 1999). Since the system is operational, the TRL is 9.

Atlas & Delta: The Evolved Expendable Launch Vehicle (EELV) program's boosters, the Atlas and Delta, have been common secondary launchers for small spacecraft programs to date. The EELV Secondary Payload Adapter (ESPA ring) has flown everything from larger payloads like the NASA LCROSS (Lunar Crater Observation and Sensing Satellite) mission to several cubesats in Poly Picosatellite Orbital Deployers (P-PODs).

The Atlas V (Figure 10.6) can deliver from 9,800 kg to almost 19,000 kg into a 200 km LEO orbit at 28.7° inclination depending on configuration (United Launch Alliance, LLC, 2015a). Starting with its maiden launch in August 2002, the vehicle has had a near-perfect success rate. The vehicle had carried more than thirty secondary payloads to orbit to date. Since the system is operational, the TRL is 9.

The Delta II (Figure 10.7) can deliver from approximately 1,870 kg to 3,470 kg to LEO depending on configuration (United Launch Alliance, LLC, 2015b). In 2000 the 6 kg Munin (Swedish Institute of Space Physics), and in 2003 the 64 kg Chipsat (NASA) and the 28 kg XSS 10 (AFRL), were launched atop a Delta II. Also in 2011, the vehicle carried five cubesats as a part of the NASA's ELANA program. Another member of the family, the Delta IV, can deliver from 9,200 kg to over 28,000 kg to a 200 km LEO at 28.7° inclination depending on configuration (United Launch Alliance,

Figure 10.6. Atlas 5. Image courtesy of NASA.

Figure 10.7. Delta 2. Image courtesy of NASA.

LLC, 2015c). The vehicle carried AFRL's 70 kg ANGELS spacecraft as a secondary payload in 2014. The Delta IV Heavy is the most powerful member of the family with 29,000 kg carrying capacity to LEO. In 2004, the vehicle allowed a ride for AFRL's two Nanosat-2 spacecraft (23 kg each). Since these systems are operational, the TRL is 9.

Dnepr: The Dnepr launch vehicle had its first flight in 1999 and has had twenty successful launches since then. The baseline version can lift 3600 kg into a 300 km LEO at 50.6° inclination, or 2300 kg to a 300 km SSO at 98.0° inclination. This Russian vehicle has been used extensively by secondary payloads since its first flights. It has carried more than 120 small spacecraft (200 kg or less) to date. During April 2007 launch, the vehicle lifted thirteen small spacecraft (each less than 35 kg) together with one 165 kg satellite. In November 2013, it carried thirty two spacecraft into orbit, thirty of which were satellites weighing less than 150 kg (including 23 cubesats). In June 2014, it carried thirty seven spacecraft into orbit, thirty six of which were satellites weighing less than 185 kg (including twenty six cubesats). This launch is still the record for the most satellites orbited in a single launch (excluding the payloads carried to ISS via cargo missions). Since the system is operational, the TRL is 9.

Falcon 9: The Falcon family of rockets from Space Exploration Technologies (SpaceX) is proving to be another valuable asset to the small spacecraft community. SpaceX's only current launcher is the Falcon 9 (Figure 10.8), a two-stage LOX/RP-1 vehicle capable of lifting over 13,000 kg to LEO (Space Exploration Technologies Corp., 2015). SpaceX's contracts with NASA to provide cargo services and eventually crewed missions to the International Space Station means those opportunities to ride-share will continue into the far future. Of all the 19 launches to date, 17 have been fully successful. Although it is capable, Falcon 9 has not been very active for carrying secondary payloads. Only during its second mission in 2010, it lifted eight cubesats together with its primary Dragon payload. However, aboard the Dragon module, it carries many cubesats to ISS which were then deployed into space from the deployers at the station. Since the system is operational, the TRL is 9.

Figure 10.8. Falcon 9. Image courtesy of SpaceX.

Figure 10.9. H-IIA. Image courtesy of JAXA.

H-IIA/B: The H-IIA/B are two Japanese launch systems. The H-IIA (Figure 10.9) first flew in 2001 and has been launched twenty eight times by October 2015 with a single failure. HII-B performed its maiden flight in 2009 and five successful launches since then. HII-A is able to carry 15000 kg to LEO whereas HII-B can carry up to 16500 kg to this orbit (Japan Aerospace Exploration Agency, 2015). During its launches, HII-A carried more than twenty five small spacecraft into orbit, seven of which were cubesats. HII-B did not directly injected any payloads to orbit yet, but it carried fourteen cubesats aboard the HTV in 2012, 2013 and 2015; these spacecraft were deployed the Kibo module of the ISS. Since the system is operational, the TRL is 9.

Long March: The Chinese Long March family (Figure 10.10) has not been very active for flying secondary payloads to date, however the new member of the family, Long March 6, lifted twenty small spacecraft in September 2015, at weights ranging from 1.5 kg to 130 kg. Since the system is operational, the TRL is 9.

Figure 10.10. Long March. Image courtesy of CALT.

Figure 10.11. Minotaur-C. Image courtesy of OSC.

Minotaur-C: First launched in 1994, Minotaur-C (Figure 10.11)) has six successful launches and three failures to date. The last successful flight of the vehicle was in 2004. No small spacecraft had been carried by Minotaur-C to date (one of the failed missions had three 1U cubesats on board), but considering its capabilities the vehicle's TRL is 9.

PSLV: The Polar Satellite Launch Vehicle (PSLV)(Figure 10.12) is a launch system developed and operated by the Indian Space Research Organisation. The vehicle had thirty launches since its maiden flight in 1993, twenty eight of which were fully successful. To date, the vehicle has carried more than thirty five small spacecraft as secondary payloads into orbit in various sizes. Since the system is operational, the TRL is 9.

Rockot: Rockot (Figure 10.13 is a Russian space launch vehicle that can launch a payload of 1,950 kg into a 200 km LEO with 63° inclination. The system has its first orbital mission in 1994 followed by twenty five missions, three of which fully or partially failed. The only mission that Rockot carried secondary payloads on was in 2003, where the vehicle lifted six cubesats and two small spacecraft of 65 kg. Since the system is operational, the TRL is 9.

Figure 10.12. PSLV. Image courtesy of ISRO.

Figure 10.13. Rockot. Image courtesy of russianspaceweb.com.

Soyuz: Soyuz (Figure 10.14) is a Russian launch vehicle family with large heritage of missions and currently the only man-rated launcher to the ISS. The first Soyuz had its maiden flight in 1966. With the retirement of Soyuz-U in 2015, only two variants of the family are in use from now on: Soyuz-FG and Soyuz-2. Dedicated to manned launches, since its first flight in 2001, Soyuz-FG has only once carried secondary payloads, delivering three small spacecraft to orbit during its July 2012 mission. Soyuz-2, on the other hand, has lifted more than twenty secondary payloads. Since the system is operational, the TRL is 9.

Vega: The first Vega (Figure 10.15) lifted off on 13 February 2012 from French Guiana carrying eight small spacecraft (ALMASat 1, e-st@r, Goliat, MaSat-1, PW-Sat, ROBUSTA, Unicubesat-GG, XaTcobeo). The second mission in 2013 carried one cubesat (ESTCUBE 1) and two other small spacecraft (Vnredsat 1 and Proba V). The vehicle has had three more successful launches, but none

Figure 10.14. Soyuz. Image courtesy of Arianespace.

Figure 10.15. Vega. Image courtesy of Arianespace.

of them contained small spacecraft. Vega will launch a block of nine Skybox Imaging spacecraft in 2016-2017 (Foust, 2015b). Since the system is operational, the TRL is 9.

Table 10.2: Secondary Payload Launchers

Product	Manufacturer	LEO Capacity	Description	Number of Secondary Payloads Launched To Date	Launch Method	Status
Antares	Orbital Sciences	5000 kg	2-stage, liquid+solid	>4	Land	TRL 9
Ariane 5	European Space Agency	20000 kg	2-stage, all liquid (+solid boosters)	4 (?)	Land	TRL 9
Atlas V	United Launch Alliance	19000 kg	2-stage, all liquid (+solid boosters)	>45	Land	TRL 9
Delta II	United Launch Alliance	3470 kg	2/3-stage, all liquid	>11	Land	TRL 9
Delta IV	United Launch Alliance	28000 kg	2-stage, all liquid (+solid boosters)	1 (?)	Land	TRL 9

Table 10.2: Secondary Payload Launchers

Product	Manufacturer	LEO Capacity	Description	Number of Secondary Payloads Launched To Date	Launch Method	Status
Dnepr	Yuzhny Machine-Building Plant	4500 kg	3-stage, all liquid	>122	Land	TRL 9
Falcon 9	Space Exploration Technologies	13150 kg	2-stage, all liquid	>19	Land	TRL 9
H-IIA/B	Mitsubishi Heavy Industries	10000 kg / 16500 kg	2-stage, all liquid (+solid boosters)	>31	Land	TRL 9
Long March	China Academy of Launch Vehicle Technology	11200 kg	3-stage, all liquid	>22	Land	TRL 9
Minotaur-C	Orbital Sciences	1320 kg	4-stage, all solid	0	Land	TRL 9
PSLV	Indian Space Research Organization	3250 kg	4-stage, solid&liquid (+solid boosters)	>52	Land	TRL 9
Rokot	Eurockot Launch Services	1950 kg	3-stage, all liquid	>8	Land	TRL 9
Soyuz	OKB-1, TsSKB-Progress	7800 kg	3-stage, all liquid (+liquid boosters)	>26	Land	TRL 9
Vega	European Space Agency	1500 kg	3+1 stage, solid&liquid	>11	Land	TRL 9

10.2.4 Dedicated Ride-Share

A dedicated ride-share is a mission where a third party integrator purchases an entire launch from a launch vehicle provider and then contracts, manifests, and integrates multiple small spacecraft on that mission in the absence of a primary payload. This approach removes the constraint of the small spacecraft providers to adhere to a primary spacecraft provider's mission requirements and provides the small spacecraft the ability to control more of the mission parameters. Dedicated ride-share is expected to increase the number and frequency of launch opportunities for small spacecraft, while at the same time, providing the cost benefit of splitting the launch cost and capacity on a single mission. Until now, two companies have announced their dedicated ride-share contracts, but more mission of this type will possibly follow.

Spaceflight Services: The company purchased a SpaceX Falcon 9 rocket for its first dedicated ride-share mission to SSO in late 2017. This launch will be named the "2017 Sun Synch Express". The mission manifest includes more than twenty spacecraft ranging from 3U cubesats up to 575 kg spacecraft (Foust, 2015a).

TriSept Corporation: TriSept Corporation will be another integrator offering dedicated ride-share missions with its FANTM-RIDE system. Although the schedule of the first dedicated flight is not officially announced, an 2015 report states that this mission, sRS-1, may be planned for 2017 (Secondary Payload Rideshare Association, 2015).

10.2.5 Orbital Maneuvering Systems

One of the main disadvantages of riding as a secondary payload (even on a dedicated ride-share mission) is the inability to launch into your desired orbit. The primary payload determines the orbital destination, so the secondary payload orbit usually does not perfectly match the customer's needs. However, by using a space tug, secondary payloads will be able to maneuver much closer into their desired orbits.

Figure 10.16. SHERPA. Image courtesy of Spaceflight Industries.

SHERPA: SHERPA (Shuttle Expendable Rocket for Payload Augmentation)(Figure 10.16) is a free-flying space tug, which is able to maneuver a total of 1500 kg payload, developed by Spaceflight Services. The system features five 61 cm diameter ports, each capable of carrying payloads weighing up to 300 kg.

The system includes the ESPA ring from Moog CSA Engineering, the QuadPack cubesat deployer from Innovative Solutions in Space, LightBand as the separation system for non-containerized spacecraft from Planetary Systems Corporation, launch vehicle separation system from RUAG, and command and data handling subsystem from Andrews Space. The first mission, scheduled for 2016, is planned to deliver eighty nine payloads (in total over 1200 kg) into SSO atop a Falcon 9 vehicle.

To provide the capability to perform LEO altitude shifts, or maneuvers to a geosynchronous transfer orbit and trans-lunar injection orbits, the upcoming variants of the system will incorporate a propulsion system, solar arrays, and an Attitude Determination and Control System. The propulsion system will be able to supply a maximum of $2200\,\mathrm{m\,s^{-1}}$ Δv for orbit change maneuvers.

The solar arrays will be able to offer 50 W power to each of the five ports. The company is also planning to have multiple SHERPA rings on a single launch vehicle in the future (European Space Agency, 2015b).

10.2.6 Orbital and Suborbital Rides

Beyond launch or deployment of payloads into orbit, there are opportunities for customers who want to fly their experiment for a shorter duration on a suborbital flight or who want to recover their experiment after it is exposed to the space environment for a period of time. Various companies and systems have developed to serve these needs.

Nanoracks Internal Payloads: NanoRacks offers an in-orbit system that provides payload opportunities on the International Space Station using the cubesat form factor. The company has different microgravity experiment opportunities at the U.S. National Lab on the ISS such as Nanohubs, NanoRacks Platform-3 (Figure 10.17), NanoRacks Centrifuge, NanoRacks Microscope, and NanoRacks MixStix. Each of these systems offer different test opportunities under microgravity conditions (NanoRacks LLC, 2015c).

Nanoracks External Platform (NREP): This system is able to accommodate up to nine 4U cubesat-size payloads outside of the International Space Station, with direct exposure to the space environment, for a standard mission duration of fifteen weeks. Attached to ISS, the system allows for high data rates, access to station power and data, payload return, risk mitigation, and frequent service for its customers. It will be used for various applications such as sensor testing, biological testing, flight qualification, and materials testing. The NREP (Figure 10.18) was launched to the ISS in August 2015, and is scheduled to be operational starting early spring 2016 (NanoRacks LLC, 2015b).

Figure 10.17. NanoRacks Platform 3 image with centrifuge housing. Image courtesy of Nanoracks.

Figure 10.18. NanoRacks External Payload Platform. Image courtesy of Nanoracks.

Figure 10.19. Terrestrial Return Vehicle Concept. Image courtesy of Intuitive Machines.

Terrestrial Return Vehicle (TRV): The Terrestrial Return Vehicle (Figure 10.19) is a commercial service being developed by Intuitive Machines and NASA and aims to deliver payloads from the ISS back to Earth. The system is designed to be stored in the habitable volume of the ISS until required. When loaded up with its cargo, it will be deployed from the Japanese Experiment Module (JEM) airlock and make a controlled reentry by using its guidance and propulsion systems. Finally the craft's airfoil is deployed and it touches down at its designated spaceport. The first re-entry flight of the TRV from the ISS is scheduled for 2016 (Intuitive Machines LLC, 2015).

10.2.7 Dispensers for Cubesats

The cubesat form factor is a very common standard for spacecraft smaller than 10 kg and there exist well established dispensers and adaptors for them. The focus of this section is on integration systems conforming to the cubesat architecture. The dispensers are summarized in Table 10.3)

P-POD: The cubesat form lends itself to container based integration systems. While several systems exist, the standard deployer is the Poly Picosatellite Orbital Deployer, or P-POD.

The P-POD (Figure 10.20) is a rectangular aluminum container which can hold up to $100 \times 100 \times 340$ mm of deployable spacecraft, either three 1U cubesats or one 3U cubesat, or a mix of intermediate sizes. The container acts as a Faraday cage, so hosted payloads meet electromagnetic compatibility (EMC) standards. Deployment is achieved by a pusher plate and spring ejection system. The main driver spring is aligned with the central axis of the P-POD. If more than one spacecraft is loaded, additional spring plungers placed between cubesats are used to provide initial separation between payloads. The interior is anodized with a PTFE-impregnated solution to ensure smooth deployment. The tubular design of the P-POD prevents rotation of the cubesats during ejection, ensuring linear trajectories. The exit velocity of the cubesat is designed to be $1.6\,\mathrm{m\,s^{-1}}$, though the central spring may be replaced to achieve different exit velocities. Typically P-PODs are connected to a larger secondary payload interface and not directly to the launch vehicle.

P-POD, with TRL 9, had an extensive heritage on several launch vehicles (Atlas V, Delta II, TaurusXL, Minotaur I & IV, Falcon 1 & 9, Vega, Dnepr, Rokot) with the deployment of over one

Table 10.3. Small spacecraft deployers

Product	Manufacturer	Status
P-POD	Spaceflight, Inc.	TRL 9
T-POD	University of Tokyo	TRL 9
X-POD	UTIAS Space Flight Laboratory	TRL 9
ISIPOD	ISIS	TRL 9
J-SSOD	Japan Aerospace Exploration Agency (JAXA)	TRL 9
Rocket POD	Ecliptic Enterprises	
NLAS	NASA Ames Research Center	TRL 9
NPSCul	Naval Postgraduate School	TRL 9
Canisterized Satellite Dispenser (CSD)	Planetary Systems Corporation	TRL ?
AFT Bulkhead Carrier	United Launch Alliance	TRL 9
C-adapter platform	United Launch Alliance	TRL 9

hundred cubesats with 100% success rate (Puig-Suari, 2015).

NanoRacks CubeSat Deployer (NRCSD): Nanoracks cubesat deployer (Figure 10.21) is a system to deploy cubesats into orbit from the Japanese Experiment Module of International Space Station. The NRCSD is a rectangular tube that consists of anodized aluminum plates, base plate assembly, access panels, and deployer doors. The NRCSD deployer doors are located on the forward end, the base plate assembly is located on the aft end, and access panels are provided on the top. The cubesats are ejected using a spring and plunger combination at the rear of the deployer. Each NRCSD is capable of holding 6U of cubesats and the system is able to deploy 48U during a full airlock cycle (NanoRacks LLC, 2015d; National Aeronautics and Space Administration, 2015a).

Figure 10.20. P-POD. Image courtesy of California Polytechnic State University.

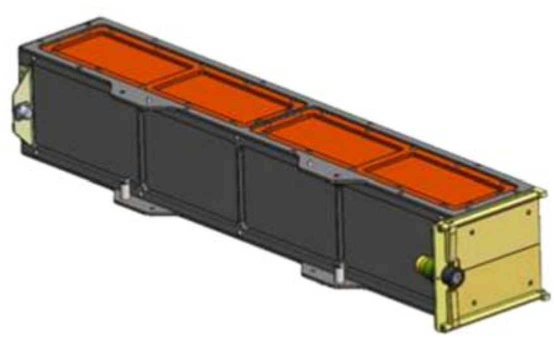


Figure 10.21. NanoRacks cubesat Deployer. Image courtesy of Nanoracks.

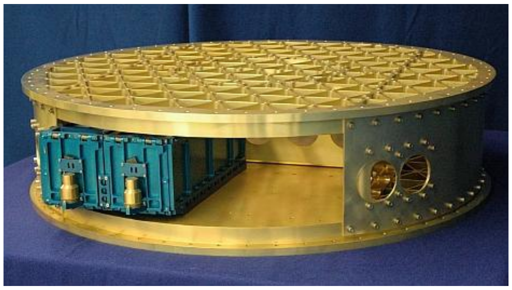


Figure 10.23. NLAS. Image courtesy of NASA Ames Research Center.

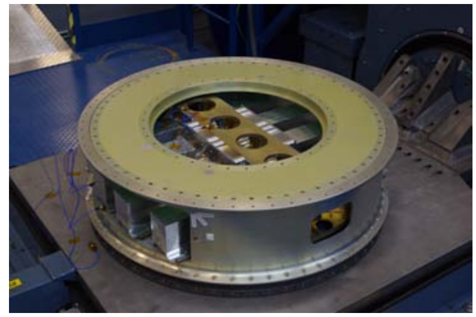


Figure 10.24. Cubestack. Image courtesy of MOOG CSA Engineering, LoadPath.

Canisterized Satellite Dispenser (CSD): The Canisterized Satellite Dispenser (Figure 10.22) is a deployment mechanism for small secondary or tertiary payloads developed by Planetary Systems Corporation. It supports 3U, 6U, 12U, and 27U form factors within a range of 1-30 kg (Planetary Systems Corporation, 2015).

Nanosatellite Launch Adapter System (NLAS): NLAS (Figure 10.23), developed by NASA Ames Research Center and the Operationally Responsive Space Office of the United States Air Force, is a secondary payload adapter system as well as a deployer. It is composed of a 6U deployer, an adapter structure and a sequencer. The NLAS adapter structure is able to deploy 24U of cubesats. The system is designed to accommodate spacecraft measuring 1U, 1.5U, 2U, 3U and 6U for deployment into orbit. Each dispenser can accommodate a total payload weight of up to 14 kg. To increase the number of secondary payloads, multiple NLAS wafers can be stacked on the launch vehicle.

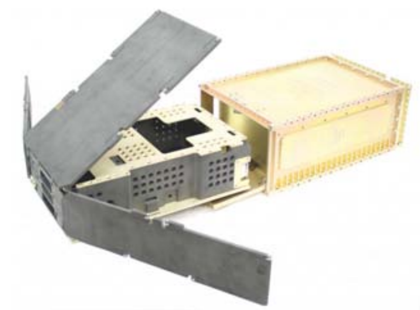


Figure 10.22. Canisterized Satellite Dispenser. Image courtesy of Planetary Systems Corporation.

Cubestack: CubeStack (Figure 10.24), developed by Moog CSA Engineering and LoadPath LLC, is similar to the NASA Ames Nanosatellite Launch Adapter System (NLAS) to launch cubesats in a wafer configuration. Like NLAS, CubeStack accommodates eight 3U dispensers, four 6U dispensers, or other combinations of 3U and 6U dispensers. CubeStack is compatible with the Minotaur, Athena, Taurus, Pegasus and Falcon launch vehicles. The dispenser was used during the ORS-3 mission in November 2013 (Moog Inc., 2015).

ESPA Six-U Mount (SUM): The ESPA Six-U Mount (Figure 10.25), developed by Moog CSA Engineering, mounts a pair of 3U cubesats or a single 6U cubesat on an ESPA ring port. The cubesats are tertiary payloads that share the port with a secondary spacecraft and deploy after secondary separation. One 6U or two 3Us can be deployed from each port. Up to six SUMs can be included on an ESPA ring.

FANTM-RiDE: The FANTM-RiDE (Figure 10.26) small spacecraft dispenser is developed by TriSept Corporation and Moog CSA. It aims to deploy cubesats from an ESPA ring compatible volume ($610 \times 610 \times 710$ mm). Both 3U and 6U spacecraft can be attached along interior dispenser walls, leaving space for a central spacecraft. It is compatible with multiple vehicles and adapters. It is designed to be mass tuned, meaning that it maintains the same mass properties regardless of its contents. This property allows for late schedule additions or removals from the launch schedule without affecting coupled load analyses. The integration services of the system is provided by TriSept Corporation (Lim, 2015).

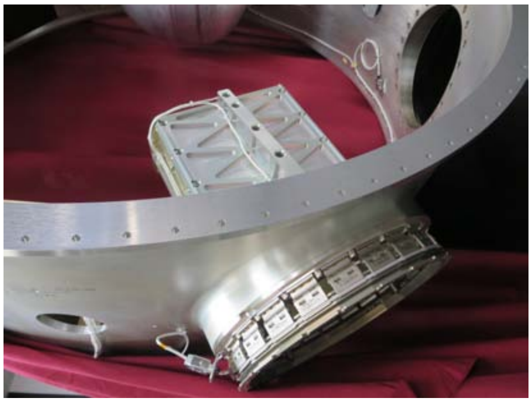


Figure 10.25. ESPA SUM. Image courtesy of Moog CSA Engineering.

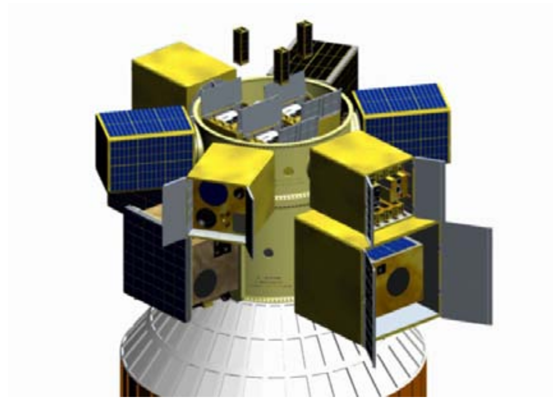


Figure 10.26. FANTM-RiDE. Image courtesy of MOOG CSA Engineering, TriSept Corporation.

Rail-POD: The Rail-POD (Figure 10.27) is a dispenser developed by Tyvak to deploy 1U, 3U and 6U spacecraft, with a smaller mass penalty. Thus it is targeted at smaller launch vehicles with tighter mass margins.

RocketPod: Ecliptic Enterprises develops on-board imaging systems for use with rockets, spacecraft, and other remote platforms. However, the company also provides cost-effective space-access solutions for small space payloads. Rocket Pod carries cubesat secondary payloads on the exterior of rockets. The device may also be mounted on the interior of the payload fairing or on adapter ring such as ESPA or CAP. Ejection is achieved via a spring-loaded mechanism like the P-POD dispensers.

Japanese Experiment Module Small Satellite Orbital Deployer (J-SSOD): The J-SSOD was the first dispenser to deploy small spacecraft from the International Space Station. It holds up to three 1U cubesats per case, six in total, though other sizes up to $550 \times 550 \times 350$ mm size may also be used. The system is able to deploy 6U during a full airlock cycle. The first use of the system was performed in October 2012, deploying the RAIKO, FITSAT-1, WE WISH, NanoRacks cubesat-1/F-1 and TechEdSat cubesats.

Naval Postgraduate School Cubesat Launcher (NPSCuL): The NPSCuL (Figure 10.28) is an adapter that can attach multiple P-PODs to a single ESPA slot. There are two varieties of NPSCuL, Standard and Lite. NPSCuL-Standard has ten slots for 3U or 5U dispensers. Additionally 6U dispensers can be accommodated by using two adjacent 3U slots. NPSCuL-Lite has eight slots which can similarly accommodate 3U or 6U dispensers.

Figure 10.27. Tyvak 6U Rail-POD Dispenser. Image courtesy of Tyvak Nano-Satellite Systems LLC.

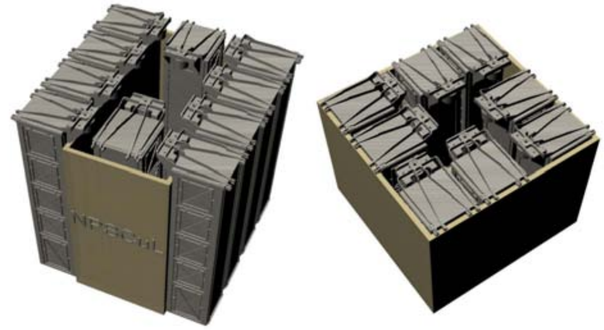


Figure 10.28. NPSCuL and NPSCuL-Lite. Image courtesy of Naval Postgraduate School.

ISIPOD: ISIPOD (Figure 10.29), developed by ISIS, is a launch adapter for small spacecraft that adheres to the cubesat interface standard. The system is able to deploy 1U, 2U and 3U cubesats.

XPOD: X-POD (Figure 10.30), developed by University of Toronto Institute for Aerospace Studies Space Flight Laboratory, is a cubesat deployer for 1U, 2U, and 3U cubesats. The maiden flight of the system was 2008 on a PSLV launch.

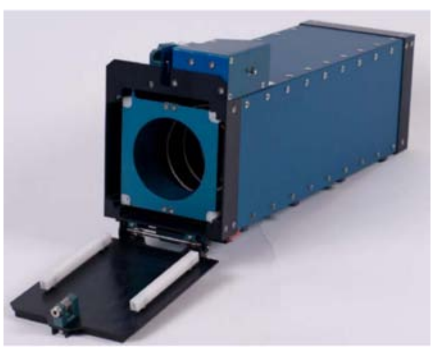


Figure 10.29. ISIPOD. Image courtesy of ISIS.

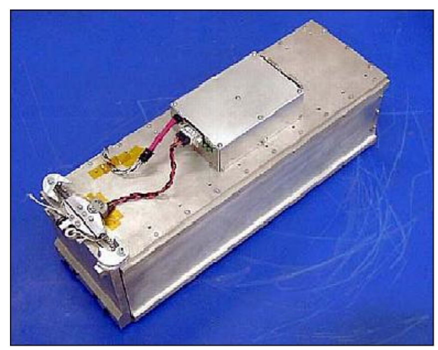


Figure 10.30. XPOD. Image courtesy of UTIAS/SFL.

10.2.8 Other Adapters for Small Spacecraft

Non-cubesat payloads have fewer available integration systems since integration systems in this class are usually custom designed for specific missions. This section lists the available larger adapters for small spacecraft.

EELV Secondary Payload Adapter (ESPA): The ESPA ring (Figure 10.31) is a multi-payload adapter for large primary spacecraft and six auxiliary spacecraft with a twenty four inch port diameter developed by Moog CSA. It can support six payloads up to 318 kg each. It was used for the first time for the STP-1 mission in 2007. The LRO/LCROSS (2009), OG2 Constellation 1 (2014) and AFSPC-4 (2014) and OG2 Constellation 2 (2015) missions followed. The ESPA Grande (Figure 10.32) is a fifteen-inch version of the ESPA adapter. It can carry four 181 kg payloads.

Figure 10.31. ESPA Ring. Image courtesy of Moog CSA Engineering.

Figure 10.32. ESPA Grande Ring. Image courtesy of Moog CSA Engineering, Orbcomm.

AFT Bulkhead Carrier (ABC): When redesigning the Atlas V Centaur upper stage pressure system, the Office of Space Launch (OSL) replaced three helium tanks with two larger tanks leaving a volume of $508 \times 508 \times 762$ mm at the aft end of the upper stage. OSL seized the opportunity to convert this excess volume into secondary payload space. This location offers several advantages despite its proximity to the upper stage thruster. In particular, the secondary payload is completely isolated from the primary, thereby relaxing electromagnetic interference and contamination concerns of the primary payload. The adapter carries up to 80 kg by utilizing the plate and struts previously used to house the helium tank. ABC (Figure 10.33), which made its first flight in 2010, can launch up to twenty four cubesats to orbit.

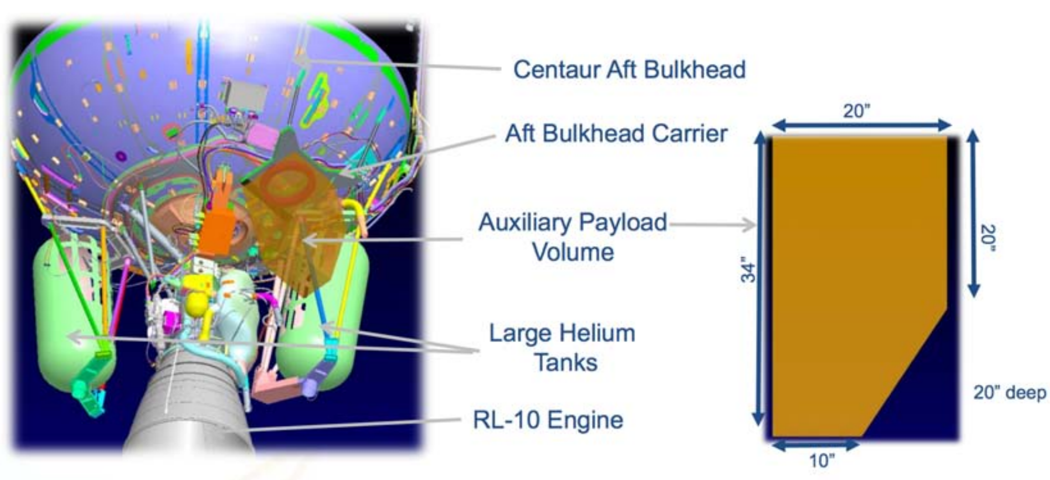


Figure 10.33. ABC. Image courtesy of National Reconnaissance Office.

C-Adaptor Platform (CAP): The C-Adapter Platform (Figure 10.34), developed by Adaptive Launch Solutions, is a cantilevered platform capable of carrying up to 45 kg in a volume of $230 \times 310 \times 330$ mm. The platform is attached to a C-adapter ring via a 203 mm clampband and is compatible with Atlas V and Delta IV launch vehicles. C-rings, mounted in the forward adapter of the Centaur upper stage, are essentially large aluminum rings used as an interface between payload integration systems and ground support equipment. Four CAPs can be integrated per C-adapter. Each cap has a carrying capacity of 90 kg. The first flight of the system was in 2010.

AQUILA: The Aquila adapter (Figure 10.35), developed by Adaptive Launch Systems, is able to support a primary payload mass of up to 6350 kg. It can be used with Atlas V and Delta IV launch vehicles.

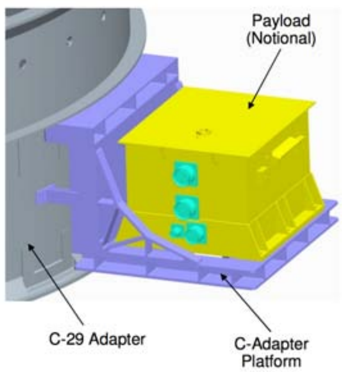


Figure 10.34. CAP. Image courtesy of ULA.

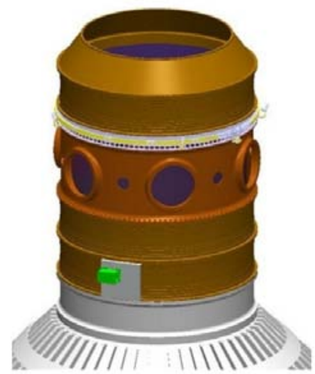


Figure 10.35. AQUILA. Image courtesy of ULA.

10.2.9 Separation Systems

While many separation systems like the POD deployers make use of a compressed spring mechanism, band systems are also quite common. Lightband and Marman clamp separation systems are widely used, particularly for larger spacecraft. Lightband (Figure 10.36) is a motorized separation system that ranges from 203 mm to 965 mm in diameter. Smaller Lightband systems are used to deploy ESPA class spacecraft, while larger variations may be used to separate the entire ESPA ring itself. Lightband's motorized separation system eliminates the need for pyrotechnic separation, and thus deployment results in lower shock and 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 payload in place. Sierra Nevada produces a Marman band separation system known as Qwksep, which uses a series of separation springs to help deploy the payload after clamp band release. Depending on the launch vehicle, separation systems may already be in place and available to secondary payloads.

10.3 On The Horizon

10.3.1 Launch Integration Services

AU Launch Services: AU Launch Services, found in 2015, is an Adelaide-based Australian consulting group that works as an integrator between cubesat manufacturers and overseas launch providers.

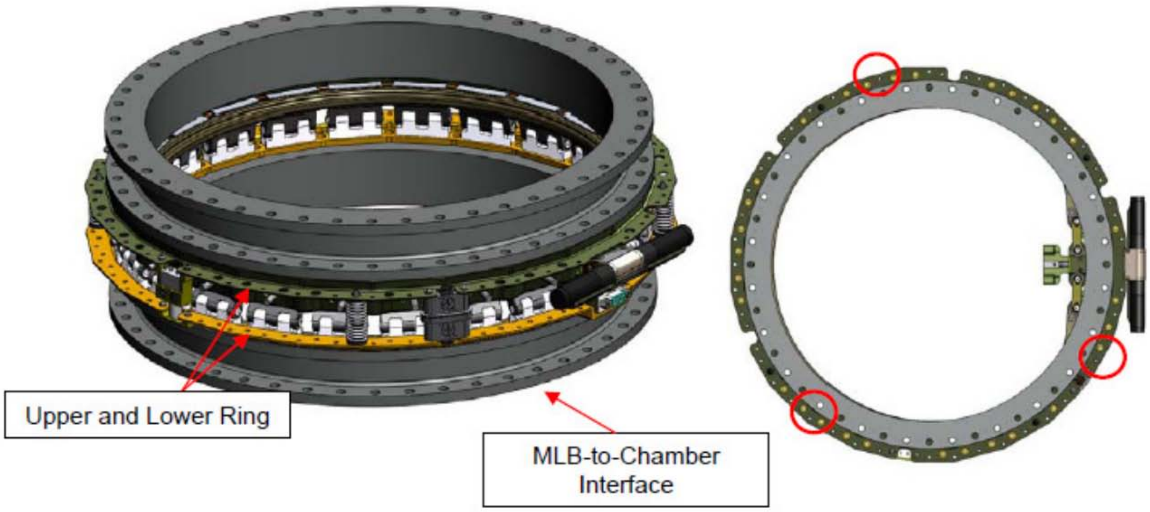


Figure 10.36. MkII Motorized Lightband. Image courtesy of Planetary Systems Corporation.

10.3.2 Dedicated Launchers for Small Spacecraft

As the capabilities and numbers of small spacecraft increase, the traditional ride-share or piggyback approaches become less and less convenient. The surge in demand for launch opportunities has also stimulated the development of dedicated launchers for them. Although many are still in low TRLs, there are at least twenty five new launcher projects started in the recent years which aim to carry small spacecraft. Similar to the state of the art section, the launch vehicles with LEO capacity of 500 kg and less are considered in this section of the report and are summarized in Table 10.4

Austral Launch Vehicle-2: The Austral Launch Vehicle (ALV) (Figure 10.37 and Figure 10.38) is a partially reusable small spacecraft launch vehicle family. The project has been in development since 2011. The ALV project consists of the development of four progressively more complex and expensive vehicles, starting from ALV-0 with ALV-3 being the commercial launch vehicle. The ALV is planned to launch vertically and after stage separation will deploy a swiveling, oblique wing and a nose-mounted piston engine, flying back to the launch site as a large UAV. The ALV-2 design

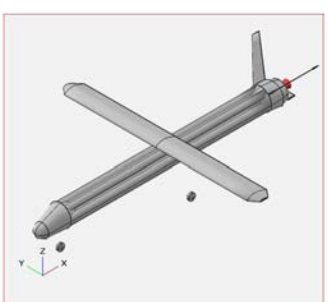


Figure 10.37. Austral Launch Vehicle Concept. Image courtesy of Heliaq Advanced Engineering.

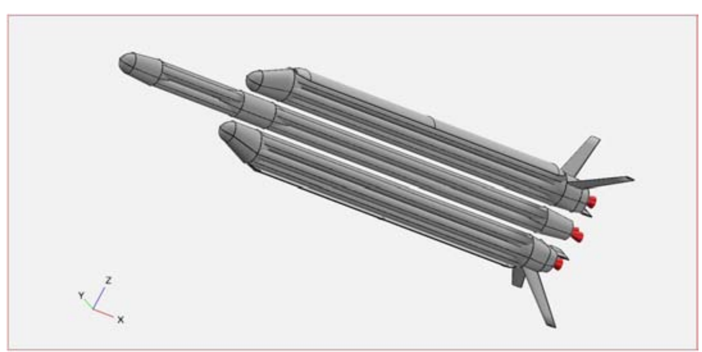


Figure 10.38. Austral Launch Vehicle Concept. Image courtesy of Heliaq Advanced Engineering.

is modular by utilizing various combinations of boosters and upper stages, it will be capable to accommodate 3U (w/ one booster) to 27 U (with 6 boosters) payloads. The payload accommodation will conform to the Planetary Systems' Canisterised Satellite Dispenser (CSD) specifications. First flight of the ALV-0 small-scale test vehicle was held in December 2015. The ALV-2 vehicle is currently in the conceptual design phase and the first orbital flight of this version is expected in 2018-2019. The company is running several other projects in parallel including the development of the LOX/Methane rocket engines. First test firing of the upper stage engine is planned for 2016 (Heliaq Advanced Engineering, 2015).

Aurora S: Aurora is a family of launch vehicles under development by Conspire Technology, an Alabama based company, founded in 2013. The family is planned to consist of three members: Aurora S, Aurora X, and Aurora Air. Aurora S is the two-stage small launch vehicle currently being developed to launch small spacecraft to orbit, whose first stage will be an air-breathing engine. The system is planned to reach hypersonic velocities below 30 km altitude with no on-board oxidizer. Aurora S development is currently in the design and development phase on the system level. Propulsion system hot firing tests are planned between 2017 and 2019, and the flight testing is estimated to begin in 2022. The company estimates to begin launch services in 2025 for a launch cost of $4M. The technologies developed and demonstrated through Aurora S will then be scaled up for more powerful vehicles, Aurora X and Aurora Air, with greater payload capacity. The TRL of the system is 2-3 (Conspire Technology Inc., 2015).

Figure 10.39. Bloostar Concept. Image courtesy of Zero2Infinity.

Bloostar: Zero2Infinity's Bloostar launch vehicle (Figure 10.39) uses a balloon as a first-stage. A helium balloon will be launched from a ship and will carry the system to over 20 km altitude, where the rocket is ignited. The system will be able to insert a 75 kg payload into a 600 km polar orbit. Payload accommodation can host a single spacecraft or multiple payloads. The company states that in the event of a launch abort, the high-altitude balloon will be detached from the platform and the platform will descend with a parachute (Zero2Infinity, 2015b). The system will use liquid oxygen and liquid methane as propellants. The first stage will carry the system to 250 km altitude

Figure 10.40. DNLV Concept. Image courtesy of Independence-X Aerospace.

and an inertial speed of $3.7\,\mathrm{km\,s^{-1}}$. After the second stage operation, the system will achieve an altitude of 530 km with velocity of $5.4\,\mathrm{km\,s^{-1}}$. The third and final stage will fire at least twice with a coast period to achieve the final orbit (Reyes, 2014). Preliminary testing of the system has already started. In September 2013, an inflatable flexible pressurized vehicle flew to 27 km under a balloon. A test version of the pressure-fed light hydrocarbon/oxygen engine was fired in September 2014. The engine was ignited several times and the cooling system functioned well. The first small-scale prototype launch is planned for 2016 (Zero2Infinity, 2015b). The TRL of the system is 5. Zero2Infinity expects the system to be operational in 2018(Zero2Infinity, 2015a).

CubeCab: CubeCab is a new company which aims to provide launches specifically for 1U and 3U cubesats to 400 km polar orbit. The system will be released from an F-104 jet. The company estimates its first launch date in late 2017 or 2018. The company is currently manufacturing their components, therefore the TRL of the system is 4 (Cubecab, 2015).

Dedicated Nano Launch Vehicle (DNLV): The DNLV (Figure 10.40) is a launch vehicle under consideration by Independence-X Aerospace located in Malaysia. The vehicle is planned to carry a 100 kg payload to a 500 km SSO. The first flight of the system is planned for 2019. The TRL of the system is 2 (Yamin, 2015).

Demi-Sprite: The Scorpius Space Launch Company (SSLC), the sister company of Microcosm, is developing the Demi-Sprite (Figure 10.41) as part of its line of modular Scorpius vehicles. The Demi-Sprite is one of the smallest vehicles in the line. The launcher will be able to put 160 kg payloads into LEO. It consists of a core stage surrounded by six identical pods that compose first and second stages. Key to the vehicle's simplicity is the absence of turbopumps for pressurizing its LOX and RP-1 propellants. The only moving parts on the vehicle are valves and gimbals. The system aims to provides true launch-on-demand service within 8 hours of arrival of the payload at the launch site (Scorpius Space Launch Company, 2015). The core technologies have been validated in two successful suborbital flights with the Scorpius SR-S and SR-XM vehicles, therefore the TRL of the system is set to 5.

Figure 10.41. Demi-Sprite Mode. Image courtesy of Microcosm Inc.

DreamChaser: The Dream Chaser (Figure 10.42), developed by Sierra Nevada Corporation Space Systems, has been developed for both crew and cargo transportation to LEO. The vehicle will also be able to support satellite servicing and deployment missions. The orbital test flight of the vehicle is planned for 2017.

Figure 10.42. Dream Chaser Concept. Image courtesy of Sierra Nevada Corporation.

Electron: Rocket Lab Ltd. is a New Zealand based company that designs and fabricates sounding rockets, small spacecraft launch systems, and propulsion systems. The company's Electron launch vehicle (Figure 10.43) is a two-stage system which uses turbo-pumped LOX/RP-1 engines. The pumps are battery-powered electric motors rather than a gas generator, expander, or preburner. The system is designed to lift 150 kg to 500 km SSO and the company states it can be tailored to circular or elliptical orbits between 45° and 98° inclination. The first Electron launch is planned for 2016, with commercial operations scheduled to begin in 2017. The company plans to provide one hundred annual launches (Rocket Lab Ltd, 2015). Electron is one of the three systems which has awarded by NASA's Venture Class Launch Services (VCLS) for cubesat missions to LEO. The vehicle's demonstration flight under this program is expected in early 2017.

Figure 10.43. Electron Model. Image courtesy of Rocket Lab.

Firefly Alpha: FireFly Space Systems is a private aerospace firm based in Austin, Texas that intends to launch small and medium-sized spacecraft to orbit. Their design, Firefly Alpha (Figure 10.44) is an all-composite vehicle designed to launch 400 kg payloads to LEO or 200 kg payloads to SSO. The system is propelled with two nearly-identical liquid (LOX/methane) stages. The first stage contains ten identical engine cores, which facilitates mass production (FireFly Space Systems, 2015). The vehicle is slated for its first orbital launch in 2018 which will be followed by four more.

The company aims to have twelve additional launches in 2019. The upgraded version, Firefly-β (Firefly Beta), to be introduced at a later date, will use two strap-on boosters. Firefly Alpha is one of the three systems which has awarded by NASA's Venture Class Launch Services (VCLS) for cubesat missions to LEO.

Figure 10.44. Firefly Alpha Concept. Image courtesy of Firefly Space Systems.

GOLauncher 2: GOLauncher 2 (Figure 10.45), developed by Generation Orbit Launch Services, is an air launched two-stage rocket system using LOX/RP-1 as propellants. The system will be capable of placing payloads of up to 45 kg into LEO at 0° to 98.7° inclination. The system uses a Gulfstream business jet to carry its rocket up into high altitudes. A date for the first launch has not been set yet (Generation Orbit Launch Services, Inc., 2015; Henry, 2015).

Figure 10.45. GOLauncher System mounted underneath a Gulfstream jet. Image courtesy of Generation Orbit.

Haas 2C: The Haas 2C launch vehicle (Figure 10.46), currently under development by Arca Space Corporation, is a two-stage system both fueled with liquid oxygen and kerosene. The company was originally established in 1999 as a non-profit organization in Romania. In 2004, as part of the Ansari X-Prize Competition, it successfully launched its first rocket. ARCA selected Spaceport America as their launch site and launch activities are scheduled to start in 2016 (Arca Space Corporation, 2015; SpaceDaily, 2015).

Figure 10.46. Haas 2C System. Image courtesy of Arca Space Sorporation.

LauncherOne: Virgin Galactic's LauncherOne (Figure 10.47) development began in mid-2012. The system, once released from its carrier Boeing 747 aircraft, will use two rocket engines for its orbital flights: "NewtonThree" main stage engine, and "NewtonFour" upper stage engine. The company has already performed a 90 second hot firing of the NewtonThree engine. Virgin Galactic recently increased the launch capacity of the system to 400 kg to LEO and 200 kg to SSO(Virgin Galactic, 2015). LauncherOne is one of the three systems which has awarded by NASA's Venture Class Launch Services (VCLS) for cubesat missions to LEO and the company expects to begin orbital flight tests by 2017 (Foust, 2015c).

Figure 10.47. LauncherOne. Image courtesy of Virgin Galactic.

Lynx Mark III: XCOR Aerospace develops the Lynx family of vehicles. Lynx (Figure 10.48) is a piloted, two-seat, fully reusable liquid rocket-powered vehicle that takes-off and lands horizontally. The Lynx Mark III system is an advanced version of this system which will carry an external top-mounted dorsal pod that can hold upper stages capable of inserting a small spacecraft into LEO. The pod will be able to deliver a 10-15 kg payload to 400 km circular orbit at 28° inclination.

The company is planning to initiate flight tests for Lynx Mark I prototype in 2016. Several technologies for Mark III will be demonstrated during these tests. Specifically for Mark III, analysis and experimental results verifying key predictions have been conducted, therefore the TRL of the system is 3 (Papadopoulos, 2015).

Figure 10.48. Lynx Mark III Concept. Image courtesy of XCOR.

Microwave Energy Transmission to Earth Orbit Rocket (METEOR): METEOR (Figure 10.49), under development by Escape Dynamics, Inc., is a single-stage-to-orbit spaceplane powered by beamed microwave energy. The system utilizes microwave energy to deliver power to a reusable spaceplane as it ascends into Low Earth Orbit. Microwave energy is beamed onto a heat exchanger located on the spaceplane and coupled into thermal energy which in turn is transferred to the hydrogen propellant. This heated hydrogen is flowed through a turbopump and exhausted out of an aerospike nozzle. The company states that the system will allow specific impulses above 750 s, greater than the theoretical limits of chemical rockets at 460 s, and will initially be capable of launching up to a 200 kg payload into orbit, scaling up to 1,000 kg payloads in the future. Considering the current status of the technology development of the system, the TRL is 3. There is no schedule for the flight tests yet but it is likely that the maiden flight of the system will be in 2020s (Escape Dynamics, Inc., 2015).

Figure 10.49. METEOR Concept. Image courtesy of Escape Dynamics.

Microsat Launch Vehicle (VLM-1): A partnership between Brazil and the German Space Agency (DLR) aims to develop a rocket for launching payloads of 150 kg into equatorial and polar orbits. The system, the VLM-1, is planned to have three stages of solid rocket motors (Messier, 2015a). There are no estimated date for the system's first launch.

M-OV: M-OV (Figure 10.50) is an orbital launch vehicled developed by the Miami-based MISHAAL Aerospace Corporation founded in 2010. The vehicle intends to deliver spacecraft in 363 kg to 454 kg class to LEO (MISHAAL Aerospace Corporation, 2015).

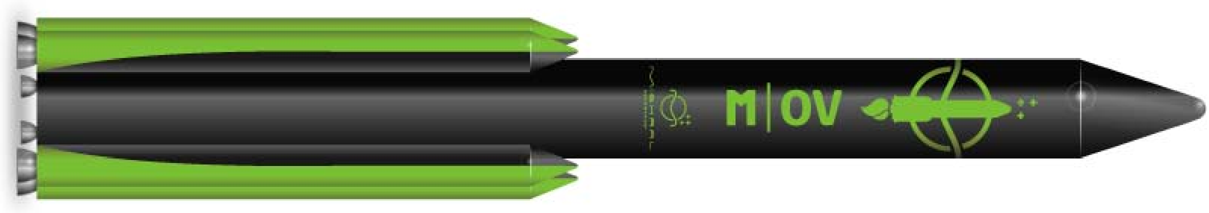


Figure 10.50. M-OV. Image courtesy of MISHALL Aerosapace Corporation.

Nanosat Launch Vehicle (NLV): The NLV (Figure 10.51) is a two-stage vehicle developed by Garvey Spacecraft Corporation. The company's initial goal is to deliver 10 kg payloads into 250 km LEO. A larger version will then be designed to place spacecraft weighing up to 20 kg into a 450 km orbit (Garvey Spacecraft Corporation, 2015; Messier, 2015b, 2015c). The vehicle will be launched from Pacific Spaceport Complex Alaska (PSCA) on Kodiak Island (Messier, 2015d). As of 2015, the static testing of NLV engines is ongoing and there are various subsystems with higher TRLs. Therefore the TRL of this system is 4.

Neptune N5: The Neptune Modular Series are launch systems developed by Interorbital Systems. Different members of the family are assembled from identical Common Propulsion Modules (CPMs).

Figure 10.51. NLV Concept. Image courtesy of Garvey Spacecraft Corporation.

A single CPM is able to lift 145 kg to 310 km apogee on sub-orbital trajectory for $350,000 for dedicated launch. The CPM test vehicle has been successfully flight-tested on suborbital flights in 2014 with several cubesats onboard, and the first commercial launch in scheduled in Q2 2016.

The N5 (Figure 10.52) is an orbital launch vehicle with five CPMs and able to lift a 30 kg payload to a circular polar orbit of 310 km. The first orbital launch is scheduled for Q4 2016 with a price tag of $1M for a dedicated launch. The N7 is a four-stage launch vehicle assembled from seven CPMs and a solid upper stage. It has a maximum payload capacity of 60 kg to a polar, circular orbit of 310 km. The company plans to take this system into operation by early 2017. The N9 maiden launch is projected for mid 2017 and will offer a 75 kg to a 145 km circular polar orbit capability (Milliron, 2015).

Figure 10.52. N5 Concept. Image courtesy of Interorbital Systems.

North Star Launch Vehicle (NSLV): In January 2013, Nammo and the Andøya Rocket Range spaceport announced that they will be developing a three stage orbital cubesat launch vehicle system called North Star (Figure 10.53) that will use a hybrid motor, clustered in different numbers and arrangements, and will be able to deliver a 20-25 kg spacecraft into 250-350 km polar orbit. The first flight of NSLV is scheduled to take place in 2021 from Andøya Rocket Range, Norway (Boiron, Faenza, Haemmerli, & Verberne, 2015; Nammo AS, 2015; Verberne, Boiron, Faenza, & Haemmerli, 2015).

Sagitarius Airborne Launch System (SALS): Celestia Aerospace, located in Barcelona, is developing the airborne Sagitarius Launch System. The system will be composed of the Mig-29UB

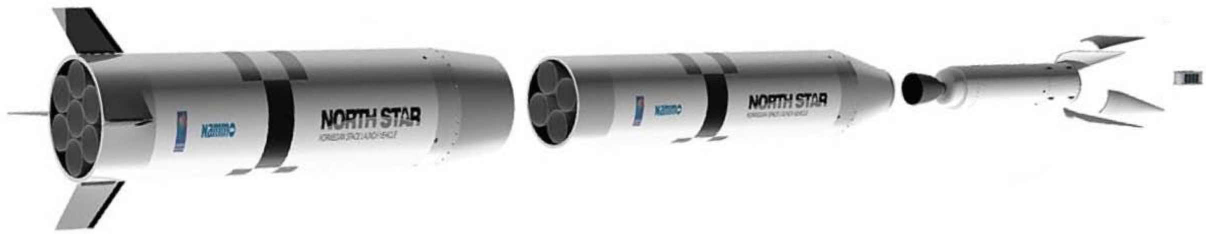


Figure 10.53. NorthStar Concept. Image courtesy of Nammo AS.

jets as carrier planes and the SpaceArrow rockets for the orbital injection phase. Each launch will be able to lift sixteen 1U sized cubesats to space, either in a configuration of four cubesats aboard a SpaceArrow SM rocket, or in a configuration of sixteen cubesats aboard a single SpaceArrow CM rocket. The rocket will then deliver the payloads into orbits between 400 and 600 km altitude. Celestia intends to perform its maiden flight in 2016 from a Spanish airport (SpaceMart, 2014).

SALVO: The system is under development by Ventions LLC for DARPA's SALVO program. It will be capable of launching a single 5 kg 3U cubesat at a time. The rocket will be carried to the required altitude with a F-15 jet.

SOAR: Swiss Space Systems (S3) is a company which plans to provide orbital launches of miniaturized spacecraft and manned suborbital spaceflights. The airborne system will lift small spacecraft up to 250 kg payloads atop an A300 jetliner (Figure 10.54). Once released from the plane, the suborbital reusable shuttle will carry its payload to an altitude of 700 km. The first flight of the system is planned in 2018 to carry the CleanSpace One spacecraft which will possibly be the first active debris-removal mission performed (École Polytechnique Fédérale de Lausanne, 2015).

Figure 10.54. SOAR shuttle atop Airbus A300. Image courtesy of S3.

Figure 10.55. Stratolaunch Air Launch System. Image courtesy of Stratolaunch Systems.

Stratolaunch Air Launch System: The Stratolaunch Air Launch System (Figure 10.55) includes a carrier aircraft, a launch vehicle and integration system. The aircraft segment, which will be the largest aircraft ever built with its wingspan of 127 m, will be powered by six Boeing 747 engines to lift a multi-stage rocket up to 10 km. The production of this segment by Scaled Composites is ongoing and the plane is scheduled to make its first test flight in 2016 (Wall, 2015). For the rocket segment, Vulcan Aerospace has not yet selected a launch system to be used (Zimmerman, 2015). Therefore the TRL of the complete system is 3.

Vulcan: The Vulcan rocket (Figure 10.56) is a launch vehicle currently under development by United Launch Alliance (ULA). The vehicle will be powered by the BE-4 rocket engine currently under development with Blue Origin and solid rocket boosters to be provided by Orbital ATK. The company plans to integrate an inflatable aerodynamic decelerator and parachutes to its first-stage boosters which will allow midair capture and recovery of the boosters by a helicopter. The system is scheduled to have its maiden flight in 2019 (Ray, 2015; Shalal, 2015). According to ULA, the Vulcan can replace company's Atlas V and Delta IV launch vehicles in 2020s.

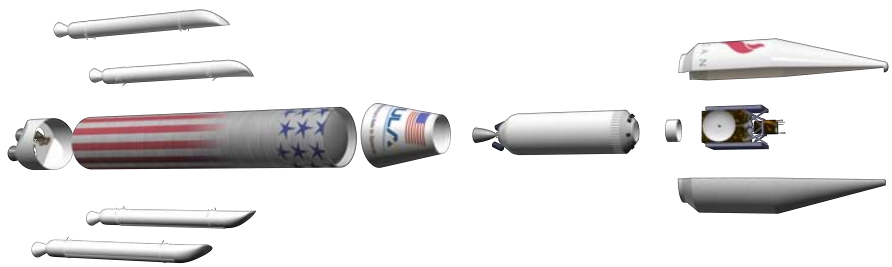


Figure 10.56. Vulcan. Image courtesy of ULA.

VLS-1: The VLS-1 (Figure 10.3), the Brazilian small spacecraft launcher has been under development since 1979 however has no successful missions yet. The new prototype is expected to carry a payload of 200 to 400 kg to polar orbit. Since the system had various engine tests, the TRL is 5 (Lele, 2015).

Table 10.4: Launchers on the Horizon

Product	Manufacturer	LEO Capacity	Planned First Flight	Launch Method	Status
Austral Launch Vehicle	Heliaq	80-550 kg to low SSO	2019	Land / Air	TRL 2-3
Aurora S	Conspire Technology	225 kg 500 km SSO	2025	Land	TRL 2-3
Bloostar	zero2infinity	75 kg to 600 km SSO	2018	Baloon	TRL 5
CubeCab	CubeCab	5 kg to 400 km	2018	Air (F-104 Fighter Jet)	TRL 4
Dedicated Nano Launch Vehicle (DNLV)	Independence-X Aerospace	100 kg to 500 km	2019	Land	TRL 2

Table 10.4: Launchers on the Horizon

Product	Manufacturer	LEO Capacity	Planned First Flight	Launch Method	Status
Demi-Sprite	Scorpius Space Launch Company / Microcosm	160 kg	?	Land	TRL 5
Dream Chaser	Lockheed Martin (for Sierra Nevada Corporation)	?	2017	Atop another launcher	TRL 5
Electron	Rocket Lab	150 kg to 500 km SSO	2017	Land	TRL 5
Firefly	Firefly Space Systems	400 kg	2018	Land	TRL 4
GOLauncher 2	Generation Orbit Launch Services	30 kg to 425 km, 30 deg.	?	Air (Gulfstream Jets)	TRL 4
Haas 2C	ARCA Space Corp.	400 kg	2016	Land	TRL 4
LauncherOne	Virgin Galactic	225 kg	2017	Air (Boeing 747)	TRL 5
Lynx Mark III	XCOR Aerospace	15 kg to 400 km, 28 deg.	?	Land (Horizontal)	TRL 3
METEOR	Escape Dynamics	200 kg	2020+	Land	TRL 3
Microsat Launch Vehicle (VLM)	Brazilian Space Agency (AEB), German Space Agency (DLR)	150 kg to 300 km	?	Land	TRL 2
M-OV	MISHAAL Aerospace	454 kg	?	Land	TRL 3
Nanosat Launch Vehicle (NLV)	Garvey Spacecraft Corporation	20 kg to 450 km	?	Land	TRL 4
Neptune N5/N7	Interorbital Systems	40 kg to 310 km, 75 kg to 310 km	2017	Land	TRL 5
North Star Launch Vehicle (NSLV)	Nammo Group	20 kg to 350 km	2021	Land	TRL 3

Table 10.4: Launchers on the Horizon

Product	Manufacturer	LEO Capacity	Planned First Flight	Launch Method	Status
Sagitarius Launch System	Celestia Aerospace	16 nanosats to 600 km	2016	Air (Mig-29UM fighter jet)	TRL 4
SALVO (Small Air Launch Vehicle to Orbit)	Ventions LLC	5	?	Air (F-15E figher jet)	TRL 3
SLS (Space Launch System)	Boeing, ATK, Pratt & Whitney Rocketdyne, NASA, and others	5	2018	Land	TRL 5
SOAR	Swiss Space Systems	250 kg	2018	Land	TRL 4
Stratolaunch Air Launch System	Vulcan Aerospace	?	?	Air (Stratolaunch)	TRL 3
Vulcan (Next Generation Launch System - NGLS)	United Launch Alliance	?	2019	Land	TRL ?
VLS-1	Brazil	?	?	Land	TRL 5

10.3.3 Payload Adaptors and Orbital Maneuvering Systems

Multi-payload Utility Lite Electric (MULE) Stage: The MULE Stage (Figure 10.57), developed jointly by Busek Space Propulsion, Adaptive Launch Solutions, and Oakman Aerospace is a maneuvering system based on an ESPA ring. The system, with its onboard propulsion and power systems, will be capable of providing 10 m s^{-1} Δv to deliver four 180 kg payloads to a variety of orbits and Earth Escape missions.

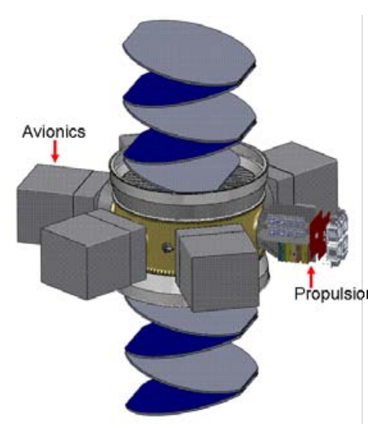


Figure 10.57. MULE Stage. Image courtesy of ULA.

HatchBasket: The HatchBasket (Figure 10.58), developed by Altius Space Machines partnering with Nanoracks, is a concept that enables small spacecraft (up to forty 3U cubesats from one ESPA-class spacecraft) to be launched to a higher altitude than is possible from normal ISS deployments. The HatchBasket, as the name

Table 10.5. Payload Adapters on the Horizon

Product	Manufacturer	Description	Status
Orbital Maneuvering System	Moog CSA	Propulsion system is integrated into ESPA ring allowing adapter to act as an independent spacecraft	TRL 5
MULE Stage	Oakman Aerospace (Avionics), Busek Space Propulsion (Hall Thrusters), Adaptive Launch Solutions (S/C Integration)	Propulsion system is integrated into ESPA ring allowing adapter to act as an independent spacecraft	TRL 2
HatchBasket	Altius Space Machines, NanoRacks	Propulsion system is integrated into ESPA ring allowing adapter to act as an independent spacecraft	TRL 2
Propulsive Cubestack	Moog / Loadpath	Propulsion system is integrated into cubestack dispender allowing it to act as an independent spacecraft	TRL 2
PAM-G	ISRO	Propulsive forth stage of GSLV	TRL 2

suggests, would replace the conventional hatch. After the Cygnus cargo vehicle completes its mission at the ISS, it would maneuver to a higher altitude using propellant reserved for contingencies during the approach to the station, then deploy the payloads. Cygnus could go up to altitudes of 500 km and still have enough propellant for deorbiting.

Propulsive CubeStack: The Propulsive CubeStack (Figure 10.59) system is proposed by Moog and Loadpath, where a propulsive stage is added to the cubestack adapter. This system is currently under concept development (Maly, 2014).

Payload Assist Module for GSLV (PAM-G): The PAM-G, under development by Indian Space Research Organisation, will be capable of lifting payloads to higher orbits after its separation from GSLV. It will be powered by a hypergolic liquid motor with restart capability, derived from PSLV's fourth stage.

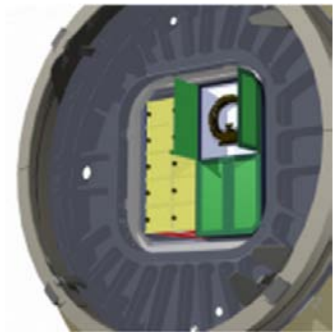


Figure 10.58. Hatchbasket. Image courtesy of Altius Space Machines.

Figure 10.59. Propulsive Cubestack. Image courtesy of Moog Inc..

10.4 Conclusion

A wide variety of integration and deployment systems exist to provide rideshare opportunities for small spacecraft on existing launch vehicles. While leveraging excess payload space will continue to be profitable into the future, dedicated launch vehicles and new integration systems are becoming popular to fully utilize the advantages provided by small spacecraft. Dedicated launch vehicles may be used to take advantage of rapid iteration 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 payloads. Advanced systems may be used to host secondary payloads on orbit to increase mission lifetime, expand mission capabilities, and enable orbit maneuvering. In the future these technologies may yield exciting advances in space capabilities.

References

Adaptive Launch Solutions. (2015). *Launch integration service.* `http://www.adaptivelaunch.com`. (Accessed: 2015-09-11)

Aerojet Rocketdyne. (2015). *Super Strypi.* `http://www.rocket.com/super-strypi`. (Accessed: 2015-09-09)

Arca Space Corporation. (2015). *Haas 2c.* `http://www.arcaspace.com/en/haas2c.htm`. (Accessed: 2015-10-06)

Boiron, A. J., Faenza, M. G., Haemmerli, B., & Verberne, O. (2015). Hybrid rocket motor upscaling and development test campaign at nammo raufoss. In *51st AIAA/SAE/ASEE Joint Propulsion Conference.* Orlando, FL. doi: 10.2514/6.2015-4044

Clark, S. (2014). Pegasus rocket selected to launch ICON satellite. *Spaceflight Now*. `http://spaceflightnow.com/2014/11/20/pegasus-rocket-selected-to-launch-icon-satellite`. (Accessed: 2015-09-09)

Commercial Space Technologies. (2015). *Launch integration service.* `http://commercialspace.co.uk/en/about/`. (Accessed: 2015-09-11)

Conspire Technology Inc. (2015). *Aurora S Launch Vehicle Status - September 2015* (Tech. Rep.). Huntsville, Alabama: Author

Cubecab. (2015). *CubeSats to LEO.* `http://cubecab.com`. (Accessed: 2015-10-06)

École Polytechnique Fédérale de Lausanne. (2015). *Orbital cleanup satellite to be launched in partnership with s3 orbital.* `http://actu.epfl.ch/news/orbital-cleanup-satellite-to-be-launched-in-partne`. (Accessed: 2015-10-04)

Escape Dynamics, Inc. (2015). *NASA SST-SoA Request for Information* (Tech. Rep.). 9596 Metro Airport Ave., Broomfield, CO 80021: Author

European Space Agency. (2015a). *Sherpa rideshare mission.* https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/sherpa. (Accessed: 2015-09-12)

European Space Agency. (2015b). *SHERPA Rideshare Mission.* https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/sherpa. (Accessed: 2015-10-10)

FireFly Space Systems. (2015). *Firefly space systems.* http://www.fireflyspace.com. (Accessed: 2015-10-06)

Foust, J. (2015a). Spaceflight Industries Buys Falcon 9 Launch. *SpaceNews*. http://spacenews.com/spaceflight-industries-buys-falcon-9-launch. (Accessed: 2015-10-10)

Foust, J. (2015b). Vega To Launch Skybox Satellites. *SpaceNews*. http://spacenews.com/vega-to-launch-skybox-satellites/#sthash.mGJeLSWc.dpuf. (Accessed: 2015-09-08)

Foust, J. (2015c). Virgin galactic's launcherone on schedule for 2016 first launch. *SpaceNews*. http://spacenews.com/virgin-galactics-launcherone-on-schedule-for-2016-first-launch. (Accessed: 2015-10-06)

Garvey Spacecraft Corporation. (2015). *Nanosat Launch Vehicle (NLV).* http://www.garvspace.com/NLV.htm. (Accessed: 2015-10-07)

Generation Orbit Launch Services, Inc. (2015). *GOLauncher 2.* http://www.generationorbit.com/golauncher2.html. (Accessed: 2015-10-06)

Heliaq Advanced Engineering. (2015). *Heliaq advanced engineering - developer of the austral launch vehicle.* http://heliaq.com. (Accessed: 2015-10-05)

Henry, C. (2015). Generation Orbit Gains GOLauncher 2 Commitments, Plans GOLauncher 3. *SatelliteToday*. http://www.satellitetoday.com/launch/2015/06/05/generation-orbit-gains-golauncher2-commitments-plans-golauncher-3. (Accessed: 2015-10-06)

Innovative Solutions in Space B.V. (2015). *Launch integration service.* http://www.isispace.nl. (Accessed: 2015-09-11)

Intuitive Machines LLC. (2015). *Terrestrial return vehicle.* https://intuitivemachines.com/Aerospace/trv/. (Accessed: 2015-10-10)

Japan Aerospace Exploration Agency. (2015). *H-iia launch vehicle.* http://global.jaxa.jp/projects/rockets/h2a. (Accessed: 2015-09-13)

Lele, A. (2015). The need for a launch vehicle development organization: Learning from brazil's experience. *The Space Review*. http://www.thespacereview.com/article/2753/1. (Accessed: 2015-09-09)

Leschly, K., Sprague, G., & Rademacher, J. (1999). Carrier spacecraft using Ariane-5 GTO piggyback launch. *Acta Astronautica*, *45*.

Lim, D. (2015). *Trisept response to NASA RFI for inputs to the small spacecraft technology state of the art report* (Tech. Rep.). 14425 Penrose Place, Suite 270, Chantilly, Virginia 20151: TriSept Corporation.

Maly, J. (2014). Cubesat payload accommodations and propulsive adapters. In *11th annual cubesat developer's workshop.* San Louis Obispo, California. http://mstl.atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop2014/Maly_Cubesat_Payload_Accommodations.pdf. (Accessed: 2015-10-04)

Messier, D. (2015a). Agreement signed for brazilian/german microsat launcher. *Parabolic Arc*. http://www.parabolicarc.com/2015/01/11/agreement-signed-braziliangerman-microsat-launcher. (Accessed: 2015-10-06)

Messier, D. (2015b). Garvey Spacecraft Performs Successful Static Test at FAR. *Parabolic Arc*. http://www.parabolicarc.com/2014/04/05/garvey. (Accessed: 2015-10-07)

Messier, D. (2015c). Garvey Spacecraft Performs Successful Static Test at FAR. *Parabolic Arc*. http://www.parabolicarc.com/2014/04/05/garvey. (Accessed: 2015-10-07)

Messier, D. (2015d). Garvey spacecraft to conduct flights out of alaska. *Parabolic Arc*. http://www.parabolicarc.com/2015/06/09/garvey-spacecraft-conduct-flights-alaska. (Accessed: 2015-10-07)

Milliron, R. (2015). *Ultra Low-Cost Space Access: Interorbital Systems' NEPTUNE Rocket System Goes Operational* (Tech. Rep.). Mojave, CA: Interorbital Systems.

MISHAAL Aerospace Corporation. (2015). *The m-ov orbital vehicle.* http://www.mishaalaerospace.com/orbital-vehicle. (Accessed: 2015-10-07)

Moog CSA Engineering. (2015). *Launch integration service.* http://www.csaengineering.com. (Accessed: 2015-09-11)

Moog Inc. (2015). *ESPA Ring & Payload Adapters.* http://moog.com/products/spacecraft-payload-interfaces. (Accessed: 2015-10-02)

Nammo AS. (2015). *The Responsive, Green, and Affordable Satellite Launch Service* (Tech. Rep.). Nammo Raufoss AS, P.O. Box 162, NO-2831 Raufoss, Norway: Author.

NanoRacks LLC. (2015a). *Launch integration service.* http://nanoracks.com. (Accessed: 2015-09-11)

NanoRacks LLC. (2015b). *Nonaracks - external platform.* http://nanoracks.com/products/external-platform. (Accessed: 2015-10-08)

NanoRacks LLC. (2015c). *Nonaracks - internal payloads.* http://nanoracks.com/products/internal-payloads. (Accessed: 2015-10-08)

NanoRacks LLC. (2015d). *Smallsat Deployment.* http://nanoracks.com/products/smallsat-deployment/. (Accessed: 2015-10-10)

National Aeronautics and Space Administration. (2015a). *NanoRacks CubeSat Deployer.* http://www.nasa.gov/mission_pages/station/research/experiments/1350.html. (Accessed: 2015-11-04)

National Aeronautics and Space Administration. (2015b). *NASA Opens New CubeSat Opportunities for Low-Cost Space Exploration.* http://www.nasa.gov/press-release/nasa-opens-new-cubesat-opportunities-for-low-cost-space-exploration. (Accessed: 2015-09-13)

Orbital ATK. (2015a). *Minotaur.* https://www.orbitalatk.com/flight-systems/space-launch-vehicles/minotaur. (Accessed: 2015-09-09)

Orbital ATK. (2015b). *NASA Selects Orbital's Pegasus Rocket to Launch 8 CYGNSS Science Satellites.* https://www.orbitalatk.com/news-room/releaseorbital.asp?prid=9. (Accessed: 2015-09-09)

Papadopoulos, K. (2015). *Nasa request for information on state of the art small spacecraft technology* (Tech. Rep.). 2901 Enterprise Lane, Midland, TX: XCOR Aerospace, Inc.

Planetary Systems Corporation. (2015). *Planetary systems corporation.* http://www.planetarysystemscorp.com. (Accessed: 2015-10-02)

Puig-Suari, J. (2015). *Tyvak Nanosatellite Systems Response to NASA RFI: NNA15ZRD001L* (Tech. Rep.). Irvine, California: Tyvak NanoSatellite Systems Inc.

Qinetiq. (2015). *Launch integration service.* https://www.qinetiq-na.com. (Accessed: 2015-09-11)

Ray, J. (2015). ULA unveils its future with the Vulcan rocket family. *Spaceflight Now*. http://spaceflightnow.com/2015/04/13/ula-unveils-its-future-with-the-vulcan-rocket-family. (Accessed: 2015-10-04)

Reyes, T. (2014). Balloon launcher Zero2Infinity Sets Its Sights to the Stars. *UniverseToday*. http://www.universetoday.com/115391/balloon-launcher-zero2infinity-sets-its-sights-to-the-stars. (Accessed: 2015-10-05)

Rocket Lab Ltd. (2015). *Electron.* http://www.rocketlabusa.com. (Accessed: 2015-10-06)

Scorpius Space Launch Company. (2015). *Critical Technologies for Next Generation Launch Systems and Spacecraft.* http://www.scorpius.com. (Accessed: 2015-10-06)

Secondary Payload Rideshare Association. (2015). Secondary Payload Adapters and Interfaces. In *17th Annual Small Payload Rideshare Symposium.* https://www.sprsa.org/sites/default/files/conference-presentation/Rideshare2015_Secondary-Adapters_Tech-Committee_Maly-Rev0.pdf. (Accessed: 2015-10-10)

Shalal, A. (2015). Launch provider picks Orbital ATK rocket motors in Aerojet setback. *Reuters*. http://www.reuters.com/article/2015/09/22/lockheedmartin-boeing-orbitalatk-idUSL1N11S2VW20150922. (Accessed: 2015-10-04)

Space Exploration Technologies Corp. (2015). *Falcon 9.* http://www.spacex.com/falcon9. (Accessed: 2015-09-10)

SpaceDaily. (2015). Spaceport America and ARCA to jointly test Launch Vehicles and High Altitude UAVs. *SpaceDaily*. http://www.spacedaily.com/reports/Spaceport_America_and_ARCA_to_jointly_test_Launch_Vehicles_and_High_Altitude_UAVs_999.html. (Accessed: 2015-10-06)

Spaceflight Services. (2015). *Launch integration service.* http://www.spaceflightindustries.com. (Accessed: 2015-09-11)

SpaceMart. (2014). A new approach to the delivery of satellites to orbit. *SpaceMart*. http://www.spacemart.com/reports/A_new_approach_to_the_delivery_of_satellites_to_orbit_999.html. (Accessed: 2015-10-07)

Surrey Satellite Technology Ltd. (2015). *Surrey Satellite Technology Ltd.* http://www.sstl.co.uk. (Accessed: 2015-09-10)

United Launch Alliance, LLC. (2015a). *Atlas V: Maximum Flexibility and Reliability.* http://www.ulalaunch.com/products_atlasv.aspx. (Accessed: 2015-09-10)

United Launch Alliance, LLC. (2015b). *Delta II: The Industry Workhorse.* http://www.ulalaunch.com/products_deltaii.aspx. (Accessed: 2015-09-10)

United Launch Alliance, LLC. (2015c). *Delta IV: The 21st Century Launch Solution.* http://www.ulalaunch.com/products_deltaiv.aspx. (Accessed: 2015-09-10)

UTIAS/SFL. (2015). *Products & services: Low-cost launch service.* http://utias-sfl.net/?page_id=233. (Accessed: 2015-09-10)

Verberne, O., Boiron, A. J., Faenza, M. G., & Haemmerli, B. (2015). Development of the north star sounding rocket: Getting ready for the first demonstration launch. In *51st aiaa/sae/asee joint propulsion conference.* Orlando, FL. doi: 10.2514/6.2015-4045

Virgin Galactic. (2015). *We're building rockets that will launch the small satellite revolution.* http://www.virgingalactic.com/satellite-launch. (Accessed: 2015-10-06)

Wall, M. (2015). Paul allen launches 'vulcan aerospace' to boost private space travel. *space.com*. http://www.space.com/29117-vulcan-aerospace-paul-allen-private-spaceflight.html. (Accessed: 2015-10-04)

Yamin, I. (2015). *DNLV Launch Vehicle Specifications* (Tech. Rep.). Office 8, Biotechnology Incubation Centre, Technology Park Malaysia Corp S/B, Lebuhraya Puchong Sg. Besi, Bukit Jalil, 57000 Kuala Lumpur, Malaysia: Independence-X Aerospace Sdn Bhd.

Zero2Infinity. (2015a). *Bloostar: The shortcut to orbit* (Tech. Rep.). Ronda de Can Fatjó s/n 08290, Cerdanyola del Vallès, Barcelona, Spain: Author.

Zero2Infinity. (2015b). *zero2infinity will launch nanosatellites from the stratosphere.* http://www.01l00.com/2014/10/zero2infinity-will-launch-nanosatellites-from-the-stratosphere. (Accessed: 2015-10-05)

Zimmerman, R. (2015). Stratolaunch shifts to the small sat market. *Be-*

hindTheBlack. http://behindtheblack.com/behind-the-black/points-of-information/stratolaunch-shifts-to-the-small-sat-market/. (Accessed: 2015-10-04)

11 Ground Data Systems and Mission Operations

11.1 Introduction

A ground data system consists of a network of ground stations and control centers, such as the Spacecraft Operations Control Center (SOCC), the Payload Operations Control Center (POCC) and the Mission Control Center (MCC). These networks may be located at the same geographical location depending on the type, size and complexity of the mission. However for small spacecraft missions, there is often no distinction between MCC, SOCC and POCC as these different networks support the overall objective of the spacecraft and the users of the data generated by the mission.

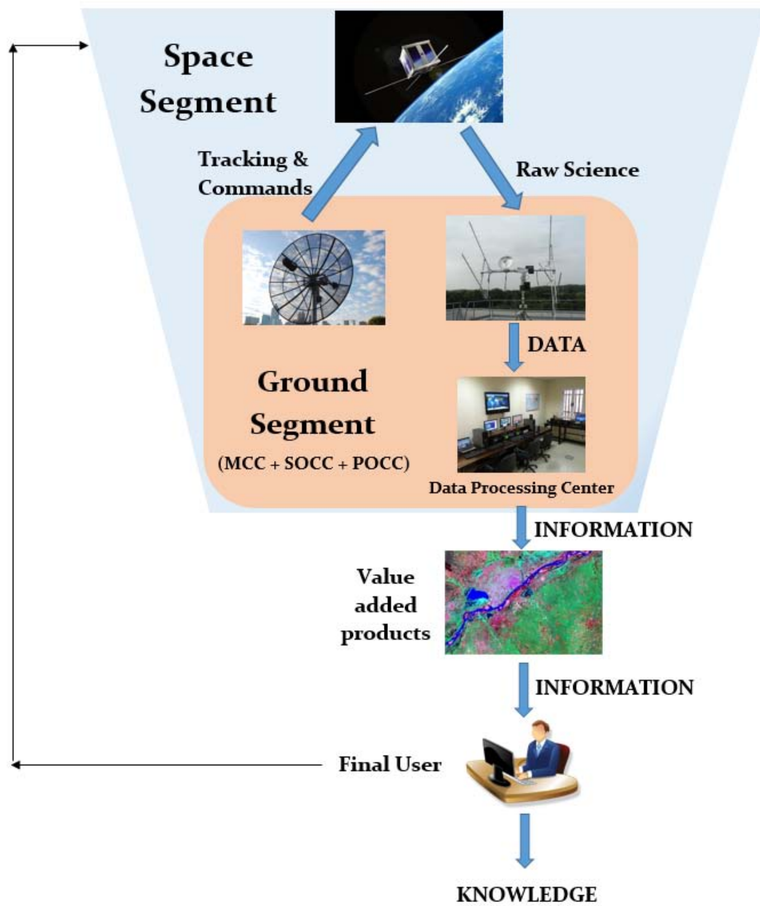


Figure 11.1. Functional relationship between space segment, ground segment and final user in a cubesat mission.

Figure 11.1 shows the functional relationship between the space segment and the ground segment of a space mission.

The ground segment supports the space segment (spacecraft and payload), relaying the mission data to the final users. To support the spacecraft mission, the ground data system must command and control the bus and payload, monitor their health, track the spacecraft's position and use ADCS sensor information to report the spacecraft's attitude (Larson & Wertz, 2004).

11.1.1 Small spacecraft ground data systems

The ground data systems architecture for small spacecraft missions will often take a different form than the classical architectures used for larger spacecraft missions. The low-cost paradigm shift and the accessibility of commercial-off-the-shelf (COTS) technology for the space sector have not only changed how designers think about spacecraft, but also the ground data systems architecture. To lower the costs of a small spacecraft ground data system, the entire small spacecraft mission is frequently managed from a single modified lab room. The ground station is either a fixed or mobile COTS antenna connected to mission control using standard cabling. Tracking, Telemetry and Command (TT&C) for both platform and payload is managed by a single computer.

Figure 11.2 illustrates the variety in ground data system architectures that can be used for small spacecraft missions. Figure 11.2a shows the Air Force Satellite Control Network (AFSCN) as an example of a classical ground data system setup. The topology of the AFSCN is hierarchical, with twelve nodes organized around a central master node at Schriever AFB, CO. Figure 11.2b depicts the distributed network of ground stations used for the PhoneSat project as it was supported by 1,343 volunteer nodes organized in a distributed topology. Figure 11.2c illustrates the common small spacecraft ground segment topology, where a single node consists of a university ground station and control room.

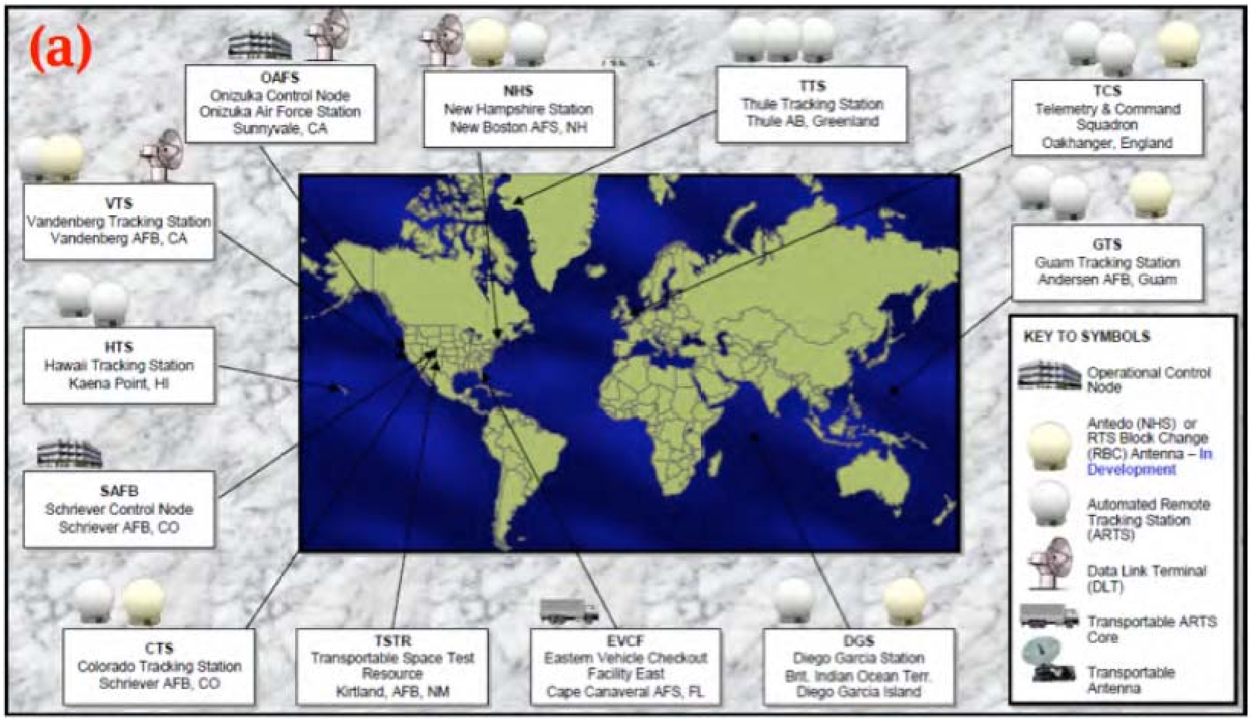
Under stringent power and volume budget constraints, small spacecraft (primarily cubesat platforms) missions typically use academic or amateur ground data systems with only one antenna, limiting the ability to communicate with more than one spacecraft simultaneously. This impact restricts cubesats to orbits below Geosynchronous (GEO) altitudes, as they are unable to carry far-ranging radio dishes or utilize a more powerful antenna. Other disadvantages include less bandwidth, lower data rate and less throughput capability for the entire mission.

Peer-to-peer topologies are also possible with a large number of ad-hoc nodes participating on a voluntary basis and, despite overcrowding of the frequency bands (typically UHF, VHF and S-band), the individual nodes in the topology can be interchangeable. For an exhaustive treatise on the characteristics of small spacecraft ground data systems, refer to Schmidt (2011). Additionally, the services provided by cubesats ground stations generally do not provide the same security, reliability and latency as classical ground data stations. Larger and more complex spacecraft usually use Consultative Committee for Space Data Systems (CCSDS) standards based long-haul communication protocols. On the contrary, cubesats primarily use TCP/IP based communication protocols, which provides lower data communication reliability and performance (de Cola, Ernst, & Marchese, 2007).

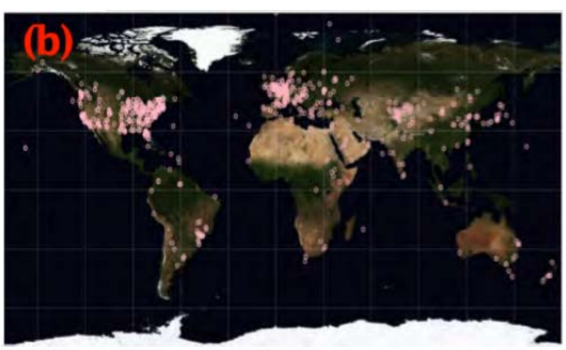
11.1.2 Amateur and Non-Amateur communications bands

Traditionally, amateur radio bands have been the preferred means for cubesats to communicate with the ground for many different reasons. However, cubesats are increasingly shifting from low-performance missions to higher-complexity science or technology missions. The larger amount of data produced by these higher-complexity missions necessitates higher communication data rates than amateur bands can provide.

From a regulatory point of view, small spacecraft missions must adhere to the same radio spectrum regulations that apply to larger spacecraft. In the U.S. for example, these regulations are governed by the Federal Communications Commission (FCC). Amateur radio frequencies for communications have licenses that are simple and quick to obtain. Since this kind of license is not available to government entities, whose missions are regulated by the National Telecommunications and Information Administration (NTIA), a number of partnerships have emerged between govern-



(a) The US Air Force Satellite Control Network (AFSCN) is an example of a conventional hierarchical ground data system setup. Image courtesy of USAF.



(b) The 1343 nodes that participated on a voluntary basis in the distributed ground data system architecture of Phonesat. Image courtesy of `http://www.phonesat.org`.

(c) An example of a smallsat mission managed and operated using a single ground station only. Image courtesy of Petr Dlouhý, Wikimedia Commons, Public Domain.

Figure 11.2. Various ground data system architectures encountered in small spacecraft missions.

ment entities and academia. For instance, a number of cubesat missions developed by NASA Ames Research Center are operated from the MOC at Santa Clara University. Similar radio frequency regulations exist in other countries, and these regulatory issues can make small spacecraft partnerships increasingly difficult. It is the responsibility of the developers to ensure they follow the proper regulations as they build and operate their spacecraft.

In most administrations, unlike other RF spectrum users, radio amateurs may build or modify transmitting equipment for their own use within the amateur spectrum without the need to obtain government certification of the equipment, and this can be a big advantage in designing telecommunication systems for cubesats. Licensed amateurs can also use any frequency in their bands (rather than being allocated fixed frequencies or channels) and can operate medium to high-powered equipment on a wide range of frequencies as long as they meet certain technical parameters including occupied bandwidth, power and maintenance of spurious emission. For example, the International Amateur Radio Union has allocated cubesats in the spectrum between 437.100 and 437.575 MHz, with a maximum single satellite bandwidth allocation of 20 kHz. This was done to protect the existing and future amateur radio voice satellites (van de Groenendaal, 2012).

While available bands at 2.4 GHz and 5.8 GHz for amateur spacecraft communication are increasingly crowded, higher frequency amateur bands require uncommon microwave parts to implement transceivers, and working with 10 GHz or higher require electric power typically not available in cubesats. Moreover, encryption is not generally permitted in the amateur radio service, except for the special purpose of spacecraft control uplinks. For these reasons, cubesat missions are moving to higher, non-amateur frequency bands to support their data requirements. For instance, the 1.5U cubesat Dynamic Ionosphere Cubesat Experiment (DICE), launched in 2011, used the 460-470 MHz meteorological-satellite band with L3 Cadet radios to produce a 1.5 Mbps downlink data rate to support its science mission (Klofas & Leveque, 2012). As cubesat missions abandon amateur radio bands for higher-speed frequencies, the radios and ground stations get difficult and expensive to build. Non-amateur radio licenses, on the other hand, prohibit autonomous beaconing of satellite data. This is a big disadvantage because the cubesat teams can no longer rely on the existing network of amateur radio operators to downlink beacon data. Non-amateur satellite licenses are usually point-to-point, so all ground stations commanding and receiving satellite data must be on the same territory and must be licensed, which is an expensive and time-consuming process (Klofas & Leveque, 2012).

Cubesat programs could use higher frequencies in either the C-band or X-band to reduce the volume and mass of both the transceiver and antenna. This will also increase the bandwidth to support payloads that have a significant data downlink requirement. However, designers need to consider the utility of additional bandwidth with decreased size and mass against increased required power to close the link with the ground station since the energy-per-bit is lowered for the same power consumption (Schroer, June, 2009). As cubesat power generation systems become more effective and three axis stability is achieved, higher operating frequencies become increasingly feasible while permitting smaller components and increased antenna gain. The user must carefully evaluate all the pros and cons that Amateur and Non-Amateur bands provide in order to select and define the most appropriate telecommunication solution to meet the mission requirements.

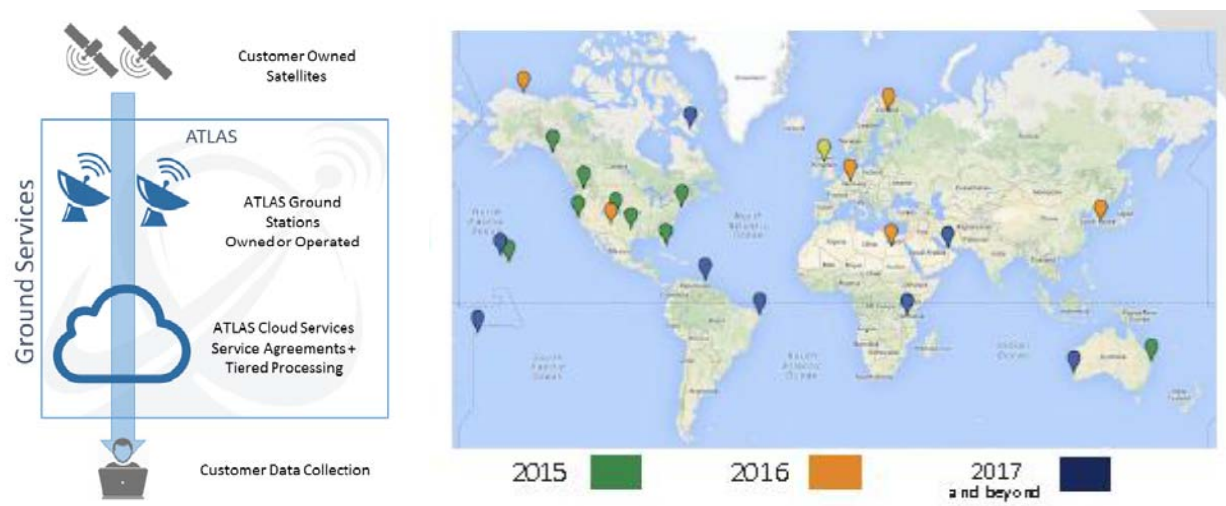
11.2 State of the art

The ultimate goal for small spacecraft network ground stations is to relay all its downklinked data as soon as it has commenced operations and continue until all the intended data has been downlinked. Theoretically, data is downlinked to the different active ground stations during its entire pass, however active ground stations are not always available for every pass as there are a number of other spacecraft transmitting data to them. Ground station networks for small spacecraft utilization have greatly improved in the last few years as many companies are producing and developing the new state of the art systems. Some companies focus more on single products that have yet to be validated in space, others consolidate and extend their current services with turnkey solutions which add more capability and availability to their already well developed ground data systems.

11.2.1 Turnkey solutions

Turnkey solutions can be a good option for designers who want to focus more on the payload and the system engineering of the spacecraft. The ground operations can be commissioned to companies which provide full capability and support for the spacecraft ground communications. Table 11.1 lists some companies or organizations that develop and provide turnkey solutions for small spacecraft ground data systems.

Assured Space Access Technologies (ASAT) is an affiliated corporation formed to develop the ATLAS global network of commercially available spacecraft ground stations, aimed at providing affordable cloud based solutions for space access. It provides global TT&C operations systems using the Amazon Virtual Cloud, which interfaces connectivity for the user to the ground stations. The supported frequency bands in which ATLAS operates are mainly S, X and UHF, however an extension of the capability to the Ka-band is planned for 2017 (Assured Space Access Technologies, 2014). Figure 11.3 shows how the ATLAS ground service works with the cloud service (on the left) and the locations of the antennas around the globe (on the right).



(a) Functional diagram

(b) Locations of the owned and operated antennas

Figure 11.3. ATLAS ground system. Image courtesy of Assured Space Access Technologies (2014).

KSAT Lite is a low-cost ground station antenna network designed to support different phases of small spacecraft missions. It retains all the major advantages of the existing and highly successful KSAT network, including the implementation of more flexible options and procedures in terms of priority allocation, availability and pass selection. The KSAT network has a long legacy of ground data systems operations with unique located polar stations in the arctic and antarctic regions (see Figure 11.4), providing from 85% to 100% availability on passes for polar orbit spacecraft. The network also operates mid-latitude ground stations, providing access for many other orbits. The baseline for KSAT antennas is the 3.7 m platform, which provides X-band and S-band for the

Table 11.1. Turnkey solutions for ground systems

Product	Manufacturer	Status	Supported bands
ATLAS Global Network	ASAT	TRL 9 for ground infrastructure, TRL 8 for software integration	S, X, UHF bands (Ka-band from 2017)
KSAT Lite	Kongsberg Satellite Services AS	TRL 9	X-band and S-band downlink and S-band uplink. VHF, UHF. Ka-band support from 2016
Surrey Ground Segment	Surrey Satellite Technology Ltd	TRL 9	S-band for uplink and downlink and X-band downlink
ISIS Small Satellite Ground Station	Innovative Solutions In Space B.V.	TRL 9	Amateur and non-Amateur protocols for VHF, UHF, S-band
Endeavor TT&C	TYVAK Inc.	TRL 8+	VHF, UHF and 2.2-2.29 GHz (S-band)
Open System of Agile Ground Systems (OSAGS)	Espace, Inc.	TRL 8	S-band for U/L and D/L Additional HF/VHF/UHF receive capability
GAMALINK Ground Station Network	GAMALINK	TRL 7+	Provides VHF/UHF pack and S-band pack. Additional Ranging and GPS support available.
Satellite Tracking and Control Station (STAC)	Clyde Space	TRL 8	VHF, UHF, L-band and 2.4 GHz

Figure 11.4. KSAT ground stations in the polar region (Svalbard, Norway). Image courtesy of Kongsberg Satellite Services AS (2015).

downlink and S-band for the uplink. In addition, KSAT Lite offers VHF and UHF capacities that support a variety of system configurations. Ka-band support for the small spacecraft market is planned to be integrated in 2016 (Kongsberg Satellite Services AS, 2015).

Innovative Solutions in Space B.V. (ISIS) also offers turnkey ground station solutions, supporting cubesats and small spacecraft in the UHF, VHF and S-band for amateur and non-amateur radio bands.

The Open System of Agile Ground Stations (OSAGS) supports high-frequency communications for small spacecrafts. Owned by Espace, Inc., OSAGS is a low-cost network of three equatorial S-band ground stations located in Kwajalein, Cayenne, and Singapore, based on software defined radio (Cahoy, 2012). The stations operate in S-band with a 2.025-2.0120 GHz uplink and 2.20-2.30 GHz downlink frequency. The agile system can support different spacecraft missions simultaneously and is readily available for any small spacecraft mission in need of ground segment support for little cost. Satellites are required to use dedicated software provided by Espace, Inc., and they must have the proper S-band capabilities to communicate with the system.

Government sponsored missions often use the turnkey solutions offered by the Space Network (SN) (National Aeronautics and Space Administration, 2007), Near Earth Network (NEN) (National Aeronautics and Space Administration, 2010) and Deep Space Network (DSN) (National Aeronautics and Space Administration, 2015), collectively known as Space Communications and Navigation (SCaN). The DSN offers the only existing solution for spacecraft tracking and communications beyond Earth orbit. The Air Force Satellite Control Network (AFSCN) is even more tightly controlled. The Air Force does make the services of the Joint Space Operations Center (JSpOC) available to the public, in particular space situational awareness in the form of two-lined element sets (TLE) for tracking satellites, and conjunction alerts (potential collisions). AGI has developed a similar system in the commercial sector called the Commercial Space Operations Center (ComSpOC).

Some companies can also provide specific individual components to users that want to assemble their own customized ground stations. For example, Helical Communication Technologies specializes in quadrifilar helical antennas, made of four helical filars or windings that support right and left hand circularly polarized signals. These antennas receive and transmit signals from the ground station to Low Earth Orbit (LEO) amateur radio satellites at frequency between 300 and 3000 MHz, and are particularly useful to receive small spacecraft signals shortly after launch without the need for antenna tracking positioning equipment and associated tracking software. Due to the nearly omni-directional pattern, the quadrifilar helical antenna provides good gain at low elevation.

KSAT and ISIS are also able to provide single antenna components that can interface with many different ground data systems. For example, Bring Your Own Device (BYOD) is a solution from KSAT which provides KSAT rugged antennas to be implemented and interfaced with customers own back end equipment.

11.2.2 Ground Data Systems Hardware and Software

Every ground station needs hardware and software components to operate and support spacecraft missions. There are a number of conceptual systems for tracking and commanding hundreds or thousands of small spacecraft and emulation tools also play an important role for these types of missions and systems. Table 11.2 lists some companies that provide front end and back end hardware and software for ground stations.

QuantumGND is a turnkey ground data system solution offered by Kratos/RT Logic designed specifically for small spacecraft applications. It is a complete C2-to-RF (Command and Control communication to Radio Frequency signal processing) turnkey small spacecraft ground data system package that includes everything from the C2 system through the ground network to the ground modem, giving a pre-integrated and easy-to-use solution. QuantumGND is comprised of quantum-CMD for a small spacecraft C2, qFEP for front-end processing, encryption and decryption, and qRADIO for network transport and RF signal processing. All these components are also available separately and independently for users who need only particular components for their customized ground data system. A block diagram on how quantumGND works is shown in Figure 11.5.

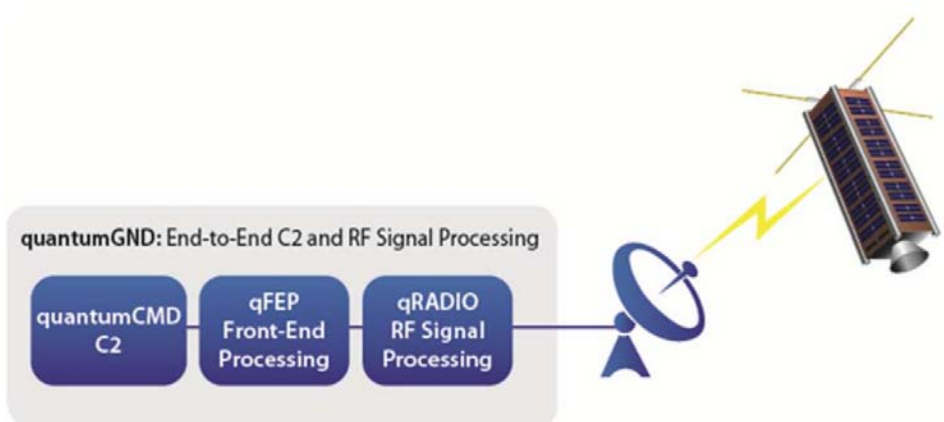


Figure 11.5. QuantumGND block diagram. Image courtesy of *RT Logic* (2015).

For system engineering and testing of a spacecraft constellation, SoftFEP can emulate thousands of spacecraft in a constellation and their ground networks. It dynamically exercises the constellation management, ground payload and TT&C software and simulates the entire end-to-end multi-node communication system. It has been used to model complex space to ground communication systems and also to emulate thousands of data channels to test the software applications that process that data.

Table 11.2. Hardware and software for ground systems

Product	Manufacturer	Status	Type of product
quantumGND	RT Logic	TRL 9	quantumCMD: Command and Control (C2) software; qFEP: Front-End Processors for encryption of commands and decryption of telemetry; qRadio: digital IF front-ends and IP-Modem; T4: software framework
ISIS GSKit Ground Station	Innovative Solutions In Space	TRL 9	UVTransceiver: contains the modem and the gain blocks; Rotator Controller: used to control the azimuth and elevation rotator
Soft FEP	AMERGINT	TRL 8+	Emulation ground systems software
Distributed Simulation & Test Environment (DSTE)	SSBV	TRL 9	Hardware and software elements all operating within a single reference platform and environment.

The Distributed Simulation & Test Environment (DSTE) is a family of standard products designed and developed by SSBV Space and Ground Systems to support simulation, assembly, integration and testing of spacecraft, subsystems and payloads. All the elements of DSTE are based on modular hardware and software architecture that utilizes the latest technology to enable multi-purpose modules and components in a common and reconfigurable spacecraft and instrument simulation and test environment.

11.3 Alternative Solutions

A possible alternative to using mission-specific ground stations altogether is to communicate with satellite phone data networks such as Iridium, Orbcomm and Globalstar.

TechEdSat-1, a 1U cubesat launched in October 2012, had a mission goal to investigate this alternative inter-satellite communication method. The spacecraft had Quake Global Q1000 and Q9602 modems onboard to test communications with both the Iridium and Orbcomm constellations (Löfgren, 2013). Unfortunately, the spacecraft was forced to disable its modems before communications could occur due to a delay of the FCC license. In April 2013, another experiment including an Iridium modem flew as an additional payload attached to the outside of the Bell PhoneSat's frame (Green, 2013). This experiment successfully communicated the spacecraft location to the Iridium constellation, which then sent the information to the mission team via email. The team saw improvements in data rate and signal quality as compared to communications with amateur radio ground stations. The experiment was also able to transmit ten hours of data to the Iridium constellation over a 24 hour period, which is a significant improvement over typical spacecraft-to-ground transmission durations for cubesats (Green, 2013). Inter-satellite communication was tested again using TechEdSat-3p, a 3U cubesat launched in August 3, 2013 (Harding, 2013). After deployment, TechEdSat-3p sucessfully communicated with the Iridium satellite network using two redundant Quake Global Q9602 modems.

The Transformational Satellite Communications System (TSAT) funded by the USAF successfully tested a simplex Globalstar modem from NearSpaceLaunch. This test was repeated by the Globalstar Experiment and Risk Reduction Satellite (GEARRS) and GEARRS2 flights also successfully tested a duplex Globalstar modem (Voss & Dailey, 2015). A NASA suborbital flight, Sub-Orbital Aerodynamic Re-entry EXperiments (SOAREX-VI), tested a Tracking and Data Relay Satellite (TDRS) modem from LJT & Associates called the LCT-2b in August 2008 (White, Morgan, & Murbach, 2007). However, as the TDRS system is administered by NASA, there might be regulatory complications for consumer spacecraft wishing to use it.

These missions are actively proving the value of inter-satellite communications to relay data to the ground, with potential for saved costs and improved quality that can result from small spacecraft exchanging ground stations with existing satellite phone constellations.

11.4 On the horizon

As the ground data systems and communication options for small spacecraft, particularly cubesats, expand, engineers must consider the trade-off between data quality, data volume and cost. In the past, several missions depended entirely on amateur radio ground stations to support spacecraft operation and communication, and the amateur radio community has proved to be invaluable to the cubesat community. As mission complexity and data requirements increase, more projects are looking to non-amateur ground stations and other options like inter-satellite communications or laser optical communications. These options, however, tend to present higher costs due to the need for associated radio frequency licenses and bespoke software specific to a given service provider.

Further, the service itself may be priced based on data size or communication duration. Many factors can affect the cost, data quality and size of each communication method, and for some of these methods the factors are either only beginning to be understood in the context of small spacecraft operations, or they have yet to be encountered. The relationship between data quality, data size and cost for these communication methods must be studied over the coming years as the various methods are analyzed by current and future small spacecraft missions.

With the need to speed up transmission of high-rate science data and due to increasing demand for S-band and X-band telecommunications, the Ka-band, at 26 GHz, is now considered the spectrum of the future for NASA small spacecraft missions. At the same time, NASA is also exploring laser communication technology for its future missions and investing in lasercom terminal development. Optical systems that transmit information using laser beams, rather than a radio signal, offer the potential to greatly increase the volume of information that can be transmitted by a spacecraft per unit power required. This cutting edge technology has already been successfully demonstrated from lunar orbit to Earth by the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission, which was operated and managed by NASA Ames Research Center. The Optical Communications and Sensor Demonstration (OCSD) mission led by the Aerospace Corporation, and funded by NASA's Small Spacecraft Technology Program, will address two crosscutting capabilities of interest to NASA: optical communications systems and low-cost sensors for proximity operations for cubesats and other spacecraft. This will demonstrate space-to-ground optical communications links that will be performed with a ground based optical tracking system using a commercial 300 mm telescope, controlled by custom-built high accuracy pointing systems.

In light of the distributed and highly dynamic ground data system topology for small spacecraft missions, there is a need for coordination between the ground stations involved. This coordination can be achieved through common, openly available software for the management of a ground data system. The Global Educational Network for Satellite Operations (GENSO) system, by the European Space Agency (ESA), is a software networking standard for universities which allows a remote operator to communicate with their small spacecraft using participating amateur radio ground stations around the globe (Leveque, Puig-Suari, & Turner, 2007). Data collection for a given spacecraft could increase from minutes per day via one ground station to several hours per day via this type of network. Other independent ground station networks include the now-defunct Mercury Ground Station Network and the Japanese Ground Station Network (Bryan Klofas, 2006).

Planning & scheduling and data management are two areas of ongoing research within the field of small spacecraft ground data systems software. The future will see an increasing number of small spacecraft missions involving not only single spacecraft but swarms, constellations and formations of spacecraft (Raymond, Bristow, & Schoeberl, 2000). A distributed infrastructure of small spacecraft made up of dozens, if not hundreds, of units would allow low-cost high-resolution Earth observation and science missions. However, the scalability of mission operations without significant automation is limited. Siewert and McClure (1995) recalls that the number of operators typically scales linearly with the number of telemetry nodes required to monitor the spacecraft. The authors propose that, assuming a best case scenario in which a single small spacecraft requires roughly ten operators to ensure mission success (not including payload operators), a constellation of hundreds of spacecraft would require thousands of operators and thus an inordinate operations budget. In the cubesat realm, where operations budgets are generally scarce, conventional operations would require an unrealistic commitment from the academic and amateur community. To keep costs low and allow for the emergence of next-generation distributed small spacecraft platforms, it will therefore become necessary for the spacecraft to perform certain operations autonomously in orbit or automatically from the ground. The challenges related to partially or fully autonomous operations and multi-mission operations centers for small spacecraft clusters are ongoing fields of research.

11.5 Conclusion

From the moment of launch, the only connection between the spacecraft and Earth is through the communication system. This, together with the ground segment, is responsible for sending scientific data back to Earth in the specified quality and quantity together with engineering data reporting the condition of the spacecraft. The communications system also provides the capability of tracking the spacecraft and commanding it to take certain actions.

Depending on the requirements and priorities of the user, different types of solutions to build and assemble a ground station are available in the market. If the user wants to focus more on the payload and the system engineering of the spacecraft, some companies have pre-defined turnkey solutions, which provide full capability and support for the spacecraft ground communications. Other possible solutions are customizing the ground station with specific components (such as antennas, transceivers, modems and software) that can be provided by different manufacturers. The user can choose all the different pieces of hardware and software needed for this purpose and have a customized ground station assembled. Finally, another valuable solution for small spacecraft to communicate with Earth is using inter-satellite communications relays. Some cubesat missions have already demonstrated these capabilities.

Whichever solution turns out to be the most reasonable and appropriate, it must be ensured that the chosen ground system can provide cost-effective, accurate and on-time space communication during the whole mission.

References

Assured Space Access Technologies. (2014). *Atlas.* (Accessed: 2015-11-02)

Bryan Klofas. (2006). Amateur Radio and the CubeSat Community. In *AMSAT Space Symposium.*

Cahoy, K. e. a. (2012). S-Band cubesat communications with the Open System of Agile Ground Stations (OSAGS). In *CalPoly Cubesat Developers' Workshop.* San Luis Obispo.

de Cola, T., Ernst, H., & Marchese, M. (2007). Performance analysis of CCSDS File Delivery Protocol and erasure coding techniques in deep space environments. CNIT - Italian National Consortium for Telecommunications.

Green, M. (2013). *Phonesat flight demonstrations: Successful phonesat mission completed.* `http://www.nasa.gov/directorates/spacetech/small_spacecraft/phonesat.html`. (Accessed 23 August 2013)

Harding, P. (2013). *Japan's HTV-4 launches supplies and science to the ISS.* `http://www.nasaspaceflight.com/2013/08/japans-htv-4-launches-supplies-scienceiss/`. (Accessed 23 August 2013)

Klofas, B., & Leveque, K. (2012). The future of cubesat communications: Transitioning away from amateur radio frequencies for high-speed downlinks. In *AMSAT Symposium.* Orlando, FL.

Kongsberg Satellite Services AS. (2015). *KSAT - Kongsberg Satellite Services.* (Accessed: 2015-11-02)

Larson, W. J., & Wertz, J. R. (2004). *Space mission analysis and design* (3rd ed.). El Segundo, CA: Microcosm Press.

Leveque, K., Puig-Suari, J., & Turner, C. (2007). Global Educational Network for Satellite Operations (GENSO). In *21st Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Löfgren, H. e. a. (2013). Techedsat: a minimal and robust 1u cubesat architecture using plug-and-play avionics. In *9th IAA Symposium on Small Satellites for Earth Observation.* Berlin, Germany.

National Aeronautics and Space Administration. (2007). *Space Network Users' Guide (SNUG)* (Tech. Rep. No. 450-SNUG). Goddard Space Flight Center, Greenbelt, Maryland: Author. http://esc.gsfc.nasa.gov/assets/files/SN_UserGuide.pdf. (Accessed: 2015-11-02)

National Aeronautics and Space Administration. (2010). *Near Earth Network (NEN) Users' Guide* (Tech. Rep. No. 453-NENUG). Goddard Space Flight Center, Greenbelt, Maryland: Author. http://esc.gsfc.nasa.gov/assets/files/453-UG-002905%282%29.pdf. (Accessed: 2015-11-02)

National Aeronautics and Space Administration. (2015). *DSN Telecommunications Link Design Handbook* (Tech. Rep. No. 810-005). Deep Space Network Project Office, Organization 920, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California: Author. http://deepspace.jpl.nasa.gov/dsndocs/810-005/. (Accessed: 2015-11-02)

Raymond, C. A., Bristow, J. O., & Schoeberl, M. R. (2000). Needs for an intelligent distributed spacecraft infrastructure. In *NASA Earth Science Technology Workshop.* Arlington, VA.

RT Logic. (2015). (Accessed: 2015-11-02)

Schmidt, M. (2011). Ground station networks for efficient operation of distributed small satellite systems. In *Universitaet Wuerzburg: Schriftenreihe Wuerzburger Forschungsberichte in Robotik und Telematik.* Wuerzburg.

Schroer, M. P. (June, 2009). Nps-scat: A cubesat communications system design, test, and integration. Monterey, CA.

Siewert, S., & McClure, L. H. (1995). A system architecture to advance small satellite mission operations. In *9th AIAA/Utah State University Conference on Small Satellites.* Logan, UT.

van de Groenendaal, H. (2012). Personal communication..

Voss, H., & Dailey, J. (2015). Technology, Service, Education: Globalstar 24/7 for LEO. In *12th Annual CubeSat Developers' Workshop.* CalPoly, San Luis Obispo, California.

White, B., Morgan, H., & Murbach, M. (2007). ELECTRONIC SYSTEMS OF THE SLOTTED COMPRESSION RAMP (SCRAMP) PROBE. In *Fifth Annual International Planetary Probe Workshop.* Bordeaux, France.

12 Passive Deorbit Systems

12.1 Introduction

There has been rapid growth in space flight in the past decade as the price for building and launching a small spacecraft has become relatively inexpensive for commercial space programs, government space agencies and universities. It has been estimated that as a result of space flight, there has been an accumulation of space debris consisting more than 700,000 particles with a diameter 1-10 cm and over 20,000 pieces with diameters >10 cm in orbit between Geostationary (GEO) and Low Earth Orbit (LEO) altitudes. Figure 12.1 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 and they have mandated either a lifetime requirement for all spacecraft or storage in a graveyard orbit. The lifetime requirement is 25 year post-mission or 30 year after launch if unable to be stored in a graveyard orbit.

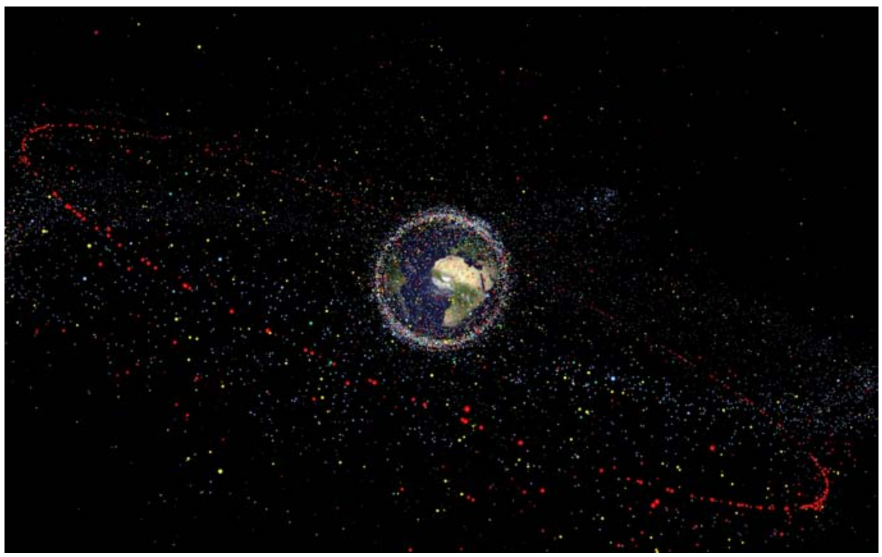


Figure 12.1. Distribution of space debris. Image courtesy of European Space Agency (2015).

Small spacecraft are typically launched into LEO as it is a more accessible and less expensive orbit to obtain: there is high availability to LEO through all commercial launch providers; the close proximity to Earth reduces mass and power requirements the communication system; it can employ a relatively small propulsion system; and the radiation environment is relatively benign. Small spacecraft that are launched at or around ISS altitude (400 km) naturally decay in well under 25 years. However at orbit altitudes beyond 600 km, it can no longer be guaranteed that a small spacecraft will naturally decay in 25 years due to uncertainty of atmospheric density, as seen in Figure 12.2. As the majority of those spacecraft are unable to be parked in a graveyard orbit due to required excess propellant to increase their altitude, the only option for small spacecraft in lower orbits is to deorbit.

12.2 State of the Art

Since deorbit systems are still in their infancy, there are few high TRL devices guaranteed to satisfy the 25 year requirement. Deorbit techniques can be either passive or active, although the primary focus has been in the design of passive methods. Active deorbiting requires attitude control and

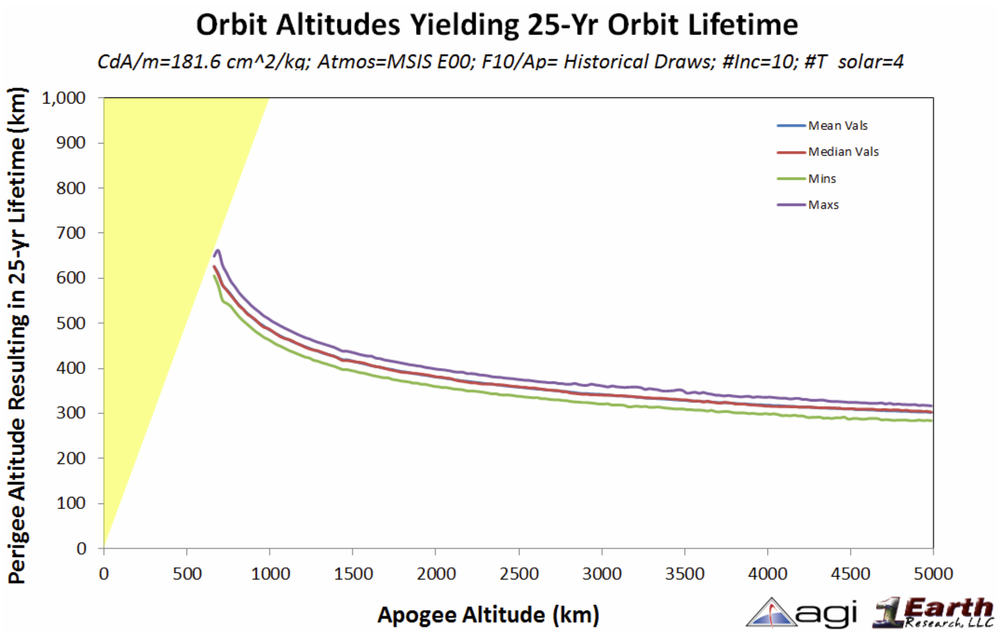


Figure 12.2. Orbit altitudes yielding 25 year lifetime. Used with permission from Analytical Graphics Inc. (2015).

surplus propellant post mission. For example, a steered drag sail relies on a functioning attitude system post mission for control. This can be challenging for small spacecraft, as this demand "increases complexity and cannibalizes precious mass and volume" (Bonin, Hiemstra, Sears, & Zee, 2013). Even if enough excess propellant was carried for an active decay approach and adequate attitude control capability post mission was assured, this method requires continuous operation until reentry is met, making it inconvenient and costly for a small spacecraft mission (Bonin et al., 2013). In contrast, passive deorbit methods require no further active control after deployment. Therefore, the state of the art section will focus on passive deorbit mechanisms. Table 12.1 displays current state of the arttechnology for passive deorbit systems.

Table 12.1. Passive deorbit systems

Product	Manufacturer	Status
RODEO	Composite Technology Development, Inc.	TRL 7
AEOLDOS	Clyde Space	TRL 7/8
Terminator Tape	Tethers Unlimited	TRL 8/9

12.2.1 Passive Deorbit Systems

Several small spacecraft missions have been developed and launched to demonstrate passive deorbit technologies using a drag sail or boom, such as NanoSail-D2 and CanX-7. NanoSail-D2, deployed from FASTSAT in late January 2011 into a 650 km altitude 72° inclination orbit, demonstrated

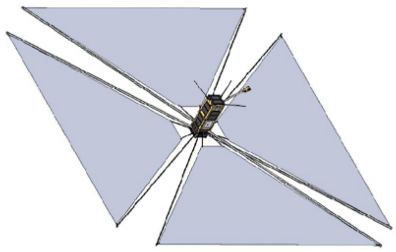


Figure 12.3. CanX-7 deployed drag sail representation. Image courtesy of Bonin et al. (2013).

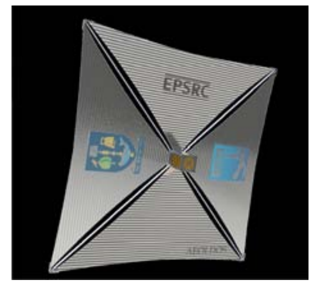


Figure 12.4. AEOLDOS can multiply the average frontal area of a typical cubesat mission almost 100-fold. Image courtesy of Clyde Space (2014).

deorbit capability of a large low mass high surface area sail (Bonin et al., 2013). The 3U spacecraft, developed at NASA Marshall Space Flight Center, reentered Earth's atmosphere in September 2011. CanX-7, still in orbit at an initial 800 km SSO, plans to deployed a drag sail developed and tested at University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS-SFL) (shown in Figure 12.3).

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 and successfully deployed on suborbital RocketSat-8 13 August 2013 (Turse et al., 2014). Clyde Space collaborated with the University of Glasglow to construct the Aerodynamic End-of-Life Deorbit system for cubesats (AEOLDOS), where a lightweight, foldable "aerobrake" made from a membrane supported by boom-springs that open the sail to generate aerodynamic drag against the upper atmosphere (Harkness et al., 2014). Figure 12.4 is a representation of the AEOLDOS membrane after deployment.

In addition to drag sails, an electromagnetic tether has also been shown to be an effective deorbit method. An electromagnetic tether 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 30 m long conductive tape (electromagnetic tether) at the conclusion of the small spacecraft mission (Hoyt, Barnes, Voronka, & Slostad, 2009). Currently on orbit with Aerocube-V cubesats, the terminator tape module is expected to activate at the end of 2015 and three more cubesat Terminator Tape modules are manifested for flight in 2016 (Tethers Unlimited, Inc., 2014).

12.3 Conclusion

Small spacecraft deorbit systems are relatively immature but are necessary to meet space debris mitigation requirements. As most small spacecraft are unable to relocate to a graveyard orbit due to propulsion limitations, deorbit system development has focused on passive devices. NanoSail-D2, DeorbitSail and CanX-7 are all cubesat platforms that have successfully demonstrated the utilization of drag sails for deorbiting in Low Earth Orbit within the 25 year post mission requirement. Terminator Tape is another deorbit option that uses electromagnetic tethers that is currently being flown on Aerocube-V cubesat.

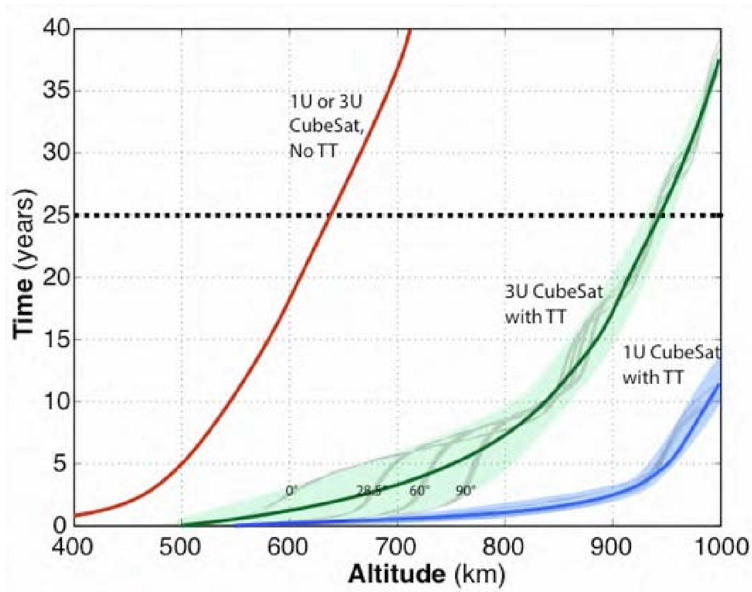


Figure 12.5. Performance curve of Terminator Tape for 1U cubesats in orbits up to 1200 km and for 3U cubesats up to 950 km. Image courtesy of Tethers Unlimited, Inc. (2014).

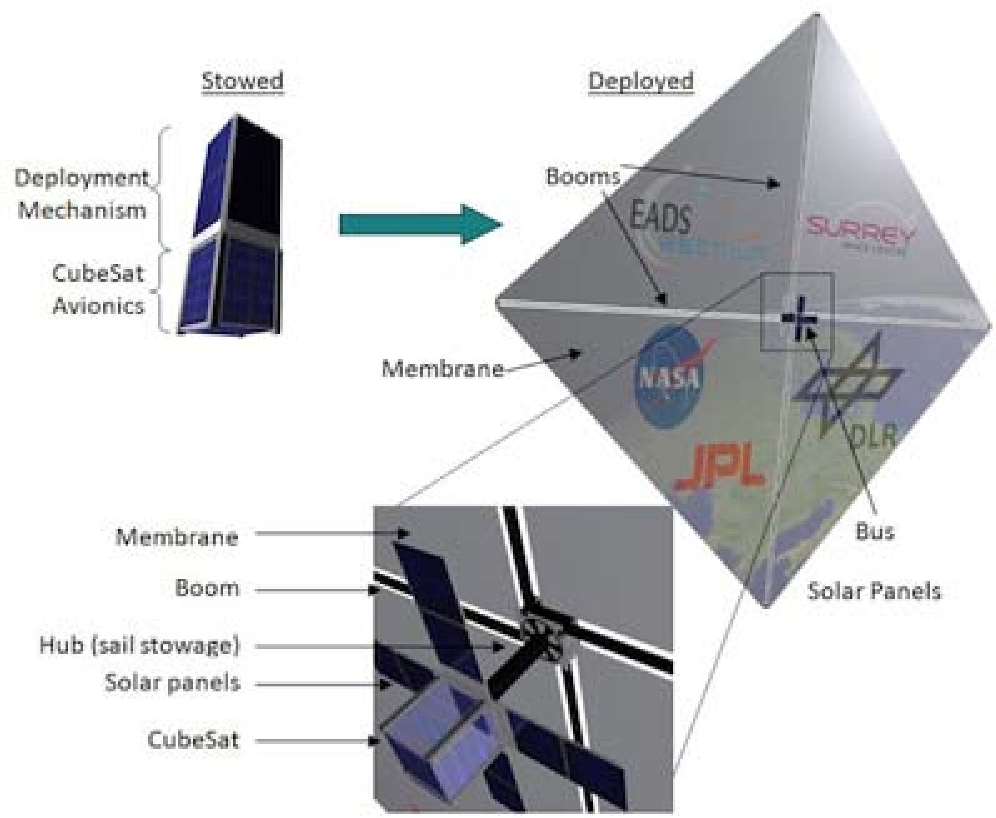


Figure 12.6. Labeled diagram of the Deorbitsail concept. Image courtesy of University of Surrey (2015).

References

Analytical Graphics Inc. (2015). *An Evaluation of CubeSat Orbital Decay.* http://www.agi.com/. (Accessed: 2015-10-29)

Bonin, G., Hiemstra, J., Sears, T., & Zee, R. E. (2013). The CanX-7 Drag Sail Demonstration Mission: Enabling Environmental Stewarship for Nano- and Microsatellites. In *27th Annual AIAA/USU Conference on Small Satellites.*

Clyde Space. (2014). *CUBESAT DISPOSAL - AEOLDOS: Aerodynamic End-Of-Life DeOrbit System.* http://www.clyde-space.com/cubesat_shop/de-orbit_devices/349_aeoldos. (Accessed: 2015-07-29)

European Space Agency. (2015). *Space debris.* http://www.esa.int/Our_Activities/Operations/Space_Debris. (Accessed: 2015-10-23)

Harkness, P., McRobb, M., Lutzkendorf, P., Milligan, R., Feeney, A., & Clark, C. (2014). Development status of AEOLDOS: A deorbit module for small satellites. *Advances in Space Research*.

Hoyt, R. P., Barnes, I. M., Voronka, N. R., & Slostad, J. T. (2009). The Terminator Tape: A Cost-Effective De-Orbit Module for End-of-Life Disposal of LEO Satellites. In *AIAA Space 2009 Conference.*

Tethers Unlimited, Inc. (2014). *The Terminator Tape and Terminator Tether Satellite Deorbit Systems: Low-Cost, Low-Mass End-of-Mission Disposal for Space Debris Mitigation.* http://www.tethers.com/TT.html. (Accessed: 2015-08-01)

Turse, D., Keller, P., Taylor, R., Reavis, M., Tupper, M., & Koehler, C. (2014). Flight testing of a low cost de-orbiting device for small satellites. In *Proceedings of the 42nd Aerospace Mechanisms Symposium.* NASA Goddard Space Flight Center.

University of Surrey. (2015). *DeOrbitSail Mission Overview.* http://www.surrey.ac.uk/ssc/research/space_vehicle_control/deorbitsail/mission/index.htm. (Accessed: 2015-10-7)

13 Conclusion

This report has provided an overview and assessment of the state of the art for small spacecraft technology. Since the last report many small spacecraft technologies have matured to the extent that every subsystem now offers a selection of previously flown (TRL 9) hardware. Over the next decade this selection is expected to increase dramatically as new technologies are matured and the cost of designing, building and launching a small spacecraft continues to fall.

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. Reader input is welcome; please email arc-smallsats@mail.nasa.gov and include "state of the art report" in the subject line.

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704–0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-12-2015	Technical Publication	

4. TITLE AND SUBTITLE	
Small Spacecraft Technology State of the Art	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Mission Design Division	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
NASA Ames Research Center Moffett Field, California 94035-1000	A–
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
National Aeronautics and Space Administration Washington, DC 20546-0001	NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	NASA/TP–2015–216648/REV1

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified-Unlimited
Subject Category
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES

An electronic version can be found at http://ntrs.nasa.gov.

14. ABSTRACT

This report provides an overview of the current state of the art of small spacecraft technology. It was first commissioned by NASA's Small Spaceraft Technology Program (SSTP) in mid-2013 in response to the rapid growth in interest in using small spacecraft for many types of missions in Earth orbit and beyond, and revised in mid-2015. For the sake of this assessment, small spacecraft are defined to be spacecraft with a mass less than 180 kg. This report provides a summary of the state of the art for each of the following small spacecraft technology domains: Complete Spacecraft, Power, Propulsion, Guidance Navigation and Control, Structures, Materials and Mechanisms, Thermal Control, Command and Data Handling, Communications, Integration, Launch and Deployment, Ground Data Systems and Operations, and Passive Deorbit Devices. Due to the high market penetration of cubesats, particular emphasis is placed on the state of the art of cubesat-related technology.

15. SUBJECT TERMS

spacecraft, technology, nanosat, smallsat

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
U	U	U	UU		**19b. TELEPHONE NUMBER** ***(Include area code)*** (443) 757-5802