NASA/TP–2014–216648/REV1

Small Spacecraft Technology State of the Art

Mission Design Division Staff
Ames Research Center, Moffett Field, California

July 2014

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–2014–216648/REV1

Small Spacecraft Technology State of the Art

Mission Design Division Staff
Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

July 2014

Acknowledgments

This report has been based largely on desk research and published documents on small spacecraft technology. Helpful suggestions and comments were also received from numerous people at NASA Ames Research Center, and in particular the authors wish to acknowledge the contributions from Aaron Cohen, Cyrus Foster, Brian Lewis, David Mauro, Matthew Nehrenz, Matthew Sorgenfrei, and Michael Soulage.

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

http://www.nasa.gov/sites/default/files/files/Small_Spacecraft_Technology_State_of_the_Art_2014.pdf

Abstract

This report provides an overview of the current state of the art of small spacecraft technology. It was 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 many types of missions in Earth orbit and beyond. 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, Attitude Determination and Control, Structures, Materials and Mechanisms, Thermal Control, Command and Data Handling, Communications, Integration, Launch and Deployment, and Ground Data Systems and Operations. Due to the high popularity of cubesats, particular emphasis is placed on the state-of-the-art of cubesat-related technology.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704–0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-07-2014	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)
Mission Design Division Staff

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Ames Research Center
Moffett Field, California 94035

8. PERFORMING ORGANIZATION REPORT NUMBER
A–

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TP–2014–216648/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 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 many types of missions in Earth orbit and beyond. 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, Attitude Determination and Control, Structures, Materials and Mechanisms, Thermal Control, Command and Data Handling, Communications, Integration, Launch and Deployment, and Ground Data Systems and Operations. Due to the high popularity 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: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
U	U	U	UU		STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER ***(Include area code)*** (443) 757-5802

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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.

NASA Ames Research Center, Mission Design Division

September, 2013

Division Chief: Chad Frost

Project Manager: Elwood Agasid

Contributing Authors:

David Biggs, John Conley, Andres Dono Perez, Nicolas Faber, Anthony Genova, Andrew Gonzales, Alessandro Grasso, James Harpur, Steven Hu, Luke Idziak, Sarah Jolitz, Jonas Jonsson, John Love, Yosuke Nakamura, Andrew Nuttall, Robin Reil, Vibha Srivastava, Travis Swenson, and Sasha Weston

Table of Contents

EXECUTIVE SUMMARY

This report was commissioned by NASA's Small Spacecraft Technology Program (SSTP) in mid-2013 in response to growing interest in using small spacecraft with a mass less than 180 kg for missions beyond Low Earth Orbit (LEO). This report summarizes the current state of the art (SoA) in small spacecraft technology for each of the following technology domains: complete spacecraft, power, propulsion, attitude determination and control, structures, materials and mechanisms, thermal control, command and data handling, communications, integration, launch and deployment, and ground data systems and operations. Due to the high popularity of CubeSats, particular emphasis is placed on CubeSat-related technology.

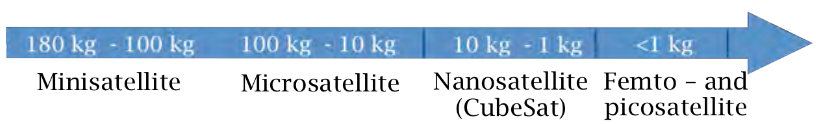


Figure 1A: Small spacecraft classifications.

This report will be regularly updated as emerging technologies mature and become the state of the art (SoA). Any current technologies that were inadvertently missed will be identified and included in subsequent versions. The authors are soliciting reader input in the comprehensive assessment of small spacecraft technology; please email arc-smallsats@mail.nasa.gov and include “state of the art report” in the subject line.

Spacecraft

State of the Art: In recent years small spacecraft have become more attractive due to lower development costs and shorter lead times. There is a natural trade-off to be made between spacecraft size and functionality, but advances in both miniaturization and integration technologies have diminished the scope of that trade-off. An example of the SoA in miniaturization technology is micro-electromechanical systems (MEMS), i.e. components with microscale (μm) features. In addition to their small size, in some cases MEMS-based devices can provide higher accuracy and lower power consumption compared to conventional spacecraft systems. Some small spacecraft are assembled and integrated with the same rigor as their larger counterparts, while others are integrated within a university laboratory. Effectively integrating individual components can substantially increase the system's functionality and density, thereby reducing unnecessary mass and volume. As such the SoA in small spacecraft integration techniques is as advanced, if not more, than those used for larger spacecraft. It is also worth mentioning that commercial off the shelf (COTS) components and consumer electronics are commonly used to build small spacecraft at the lower end of the cost range.

On the Horizon: There is a trend towards further miniaturization and higher levels of integration (such as observed in pico- and femtosats). Fractionated mission architectures are also a promising field of investigation.

Power

State of the Art: Small spacecraft are currently using advanced power generation and energy storage technology, with 29% efficient triple-junction, lightweight solar cells (weighing about 85 mg/cm^2) and high specific energy lithium ion batteries (averaging 200 W·hr/kg). The early adoption of flat lithium polymer battery packs is unique within the space industry because of the higher risk tolerance of mission designers and more stringent mass and volume requirements. Power distribution systems are reliable and robust, even to single event upsets. All spacecraft systems can benefit from technology advances and component miniaturization in the consumer electronics market.

On the Horizon: There are flexible solar cells under development allowing new concepts for solar panel deployment. Another technology on the horizon is the CubeSat-scale Radioisotope Thermal Generator (RTG).

Propulsion

State of the Art: Small spacecraft propulsion is a rapidly growing, albeit immature technology domain. The SoA in this field consists of cold gas thrusters (specific impulse, Isp, of 70 sec), solid rocket motors (Isp of 270 sec), and pulsed plasma thrusters (Isp of 830 sec). Green monopropellant systems (Isp of 300 sec) will soon be demonstrated.

On the Horizon: Both chemical and electric propulsion options are on track to mature within the next five years. Hydrolytic systems using water are also under development, along with integrated primary thrusters and reaction control systems.

Attitude Determination and Control Systems

State of the Art: The SoA of Attitude Determination and Control (ADCS) for small spacecraft relies on miniaturizing technology without significant performance degradation. Miniaturizations are achieved with advanced technologies such as new imaging devices, materials, peripheral circuits, and algorithms. Overall attitude pointing accuracy of typical mini- and microsatellite Earth observation missions is on the order of 0.1°. Higher accuracy below 0.1° can be achieved using a mission related sensor (i.e., a payload instrument) in the attitude control loop. Pointing accuracy of nano and picosatellites (including CubeSats) is an order of magnitude larger and around 2°, but has improved rapidly thanks to miniaturized ADCS components. The limiting factor for CubeSat pointing is attitude control; current control accuracy is around 1.8°. Systematically decreasing the development cost of ADCS software will contribute to the low cost and rapid development benefits of using small spacecraft.

On the Horizon: Pointing accuracy for CubeSats may go below 1° due to miniaturized star trackers.

Technology Gaps: There is a need for ADCS thruster technology for spacecraft below 100 kg, especially if interplanetary missions are planned with this type of spacecraft.

Structures, Materials and Mechanisms

State of the Art: Commercial companies fabricate structures for a large variety of small satellite missions. Pumpkin, ISIS and SSTL lead the market. Most structures built in-house pertain to mini- or microsatellites. However in-house built structures are becoming rarer and today nanosat developers tend to buy their structures off-the-shelf. CubeSat structures follow determined guidelines regarding their size and materials.

Due to their reliability and strength, aluminum alloys (with an average density of 2.8 g/cm^3) are the material most used for small satellite structures. Composites have been used more frequently in the last few years, but their high cost is still a disadvantage.

Mechanisms and actuators for small spacecraft have proven their reliability in space. Commercial companies such as SSTL or Honeybee Robotics offer deployment and antenna pointing mechanisms with a high Technology Readiness Level (TRL). A large number of missions develop their own mechanical designs.

On the Horizon: 3D-printed structures (additive manufacturing) is one mass production technique currently under investigation for small spacecraft platforms.

Thermal Control Systems

State of the Art: Passive thermal control systems for small spacecraft use thermal insulation such as multi-layer insulation (MLI) and beta cloth, or thermal coating with white and black polyurethane paint and tape. Thermal transfer is guaranteed through heat pipes (flat plate heat pipes, or loop heat pipes), bolts, washers, fillers, and spacers. Passive thermal control is inexpensive and low risk, and has been shown to be reliable and basic. Active thermal control systems have more demanding design requirements (in terms of mass and power) making these techniques more difficult to use on small spacecraft. Engineers are able to equip temperature sensitive devices such as batteries and cameras with electric heaters and coolers to maintain operational temperatures. Until it is possible to miniaturize current active thermal methods, small satellites will not be able to use that technology efficiently.

On the Horizon: There is a trend to miniaturize active thermal control systems of larger spacecraft so they can be applied to small spacecraft using MEMS or other nano-devices.

Technology Gaps: Nanosats are approaching a scale (6U) at which more power can be generated than can be passively dissipated with current technology. Active systems at CubeSat scale or novel passive systems are needed.

Command and Data Handling

State of the Art: Command and Data Handling (C&DH) technologies have benefited from advances in commercial industries. Today, C&DH systems have greater processing capability with lower mass, power and volume requirements. This general trend is enabling small spacecraft to tackle a broader range of missions.

Power and reliability, traditionally the primary limiting factors, have seen significant advances due to the infusion of commercial technology and higher risk tolerance of small spacecraft. Many small spacecraft platforms use COTS C&DH components for quicker advances and shorter qualification timelines. While the current high rate of progress will likely level off as the reliance on small spacecraft becomes routine for more critical missions, the general evolution of C&DH technology for small spacecraft remains promising.

Communications

State of the Art: Current satellite communication transmission strategies use VHF, UHF, microwave, and infrared/visible frequency spectra. Selecting a frequency spectrum depends on a number of factors including expected data throughput, available power and mass, and licensing issues. Due to these reasons, technology development is still underway on all of these frequency spectra.

Current SoA technology shows a trend of increasing carrier signal frequency and increasing data transfer speeds. There is also a trend to increase carrier signal frequency and the power and mass requirements of the transmitter. Using transmitter technology appropriate for small satellites in LEO, UHF/VHF transmitters have a maximum data transfer rate of around 38 kbps, S-band transmitters have a maximum data transfer rate around 10 Mbps, X-band transmitters around 500 Mbps, and K/Ku/Ka band transmitters around 1.2 Gbps. The Infrared communication system used on NASA Ames' LADEE mission has a maximum data transfer rate of 2.88 Gbps. Developments have been made in deployable high gain antennae to facilitate high volume data transfers. There are currently a number of deployable high gain antennae for CubeSats and larger applications. They offer maximum gains around 15-20 dBi. Uplink to the spacecraft via the Iridium constellation has also been demonstrated.

On the Horizon: CubeSat scale laser communications is a field of current interest. The use of Iridium or Globestar for bi-directional communications is also under investigation.

Technology Gaps: There is a need for deep space communication technology for small spacecraft.

Integration, Launch and Deployment

State of the Art: Small satellite integration, launch, and deployment systems have largely leveraged existing launch vehicles used for much larger payloads. Many heritage vehicles are available with excess mass capacity for secondary spacecraft, and a wide variety of integration and deployment systems have been developed to provide rideshare opportunities. These rideshares help reduce costs but are often allocated only after the primary mission defines most launch criteria. Integration and deployment mechanisms are thus designed for minimal interference to the primary mission, usually by providing electromagnetic shielding and shock absorption. Adapters exist to both secure and deploy secondary payloads of various sizes. Adapters like the Poly Picosatellite Orbital Deployer (P-POD) carry up to 6U CubeSats and integration systems like Naval Postgraduate School's CubeSat Launcher (NPSCul) are available to host up to 24 CubeSats. Nanosatellites also have options of deploying from the ISS via the Japanese Experiment Module, or riding as hosted payloads, operating independently but sharing the power supply and transponders of a commercial satellite. Adapters such as the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) also exist to serve secondary payloads up to 180 kg. SoA technologies in these areas are also responding to increased demand and capability for small satellite missions. EELV rockets (United Launch Alliance's Atlas V and Delta IV) are currently the most frequent launchers, especially after the development of the ESPA ring. However current launch vehicles are often unable to meet demands for missions that need very specific science orbits, interplanetary trajectories, precisely timed rendezvous, or special environmental considerations. Launching as a secondary payload also limits advantages of small satellites such as quick iteration time and low total capital costs.

On the Horizon: Several promising small launch vehicles, orbital maneuvering systems (space tugs), and large CubeSat deployers are currently under development.

Technology Gaps: Dedicated launch vehicles are needed to take full advantage of rapid iteration and mission design flexibility.

Ground Systems and Operations

State of the Art: Small spacecraft use a variety of ground system architectures, including legacy systems with a hierarchical node topology, distributed systems with peer-to-peer nodes participating on a voluntary basis, and low-cost single node ground stations. The principal driver for small spacecraft ground systems is cost of infrastructure and personnel. To reduce cost, it is common for small spacecraft ground systems to merge the conventional control centers and ground stations in a single unit at a single geographical location. Many developers provide single-node, turn-key ground system solutions for purchase. Satellite phone/data networks are being tested by some small spacecraft operators as a communication alternative to ground stations. These ground systems command and communicate with the spacecraft using mostly amateur radio frequency bands. Increasing mission complexity has, however, resulted in the increased use of higher data rate and non-amateur frequencies.

On the Horizon: Open source software packages under development are enabling distributed operations of small spacecraft through peer-to-peer ground station networks.

Technology Gaps: To make operational costs affordable for multi-spacecraft missions (swarms of dozens of units etc.), operations need to be conducted autonomously in orbit or at least in a more automated way from ground.

1. INTRODUCTION

1.1 Objective

The objective of this report is to assess and give an overview of the SoA in small spacecraft technology. It was 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. In addition to reporting on what is currently available, we also look ahead towards technologies on the horizon.

Information in this report has been collected essentially through desk research and is not meant to be exhaustive—no such assessment can be comprehensive, especially in its first release. New technology is developed continuously, and emerging technologies will mature to become the SoA. 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.

1.2 Scope

A spacecraft is herein called a "small spacecraft" when its dry mass is below 180 kg. This definition adopts the terminology set out by NASA's Small Spacecraft Technology Program (SSTP)[1]. Figure 1 gives an impression 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 weight slightly below 180 kg. On the lower mass end, there are future projects such as KickSat, with a mere size of a large postage stamp and with a mass well below 1 kg. Spacecraft are generally grouped according to their mass, where small spacecraft include minisatellites with a mass of 100-500 kg,

[1] See http://www.nasa.gov/offices/oct/crosscutting_capability/edison/Smallsat_tech.html

microsatellites with a mass of 10-100 kg, nanosatellites with a mass of 1-10 kg, and picosatellites with a mass below 1 kg.

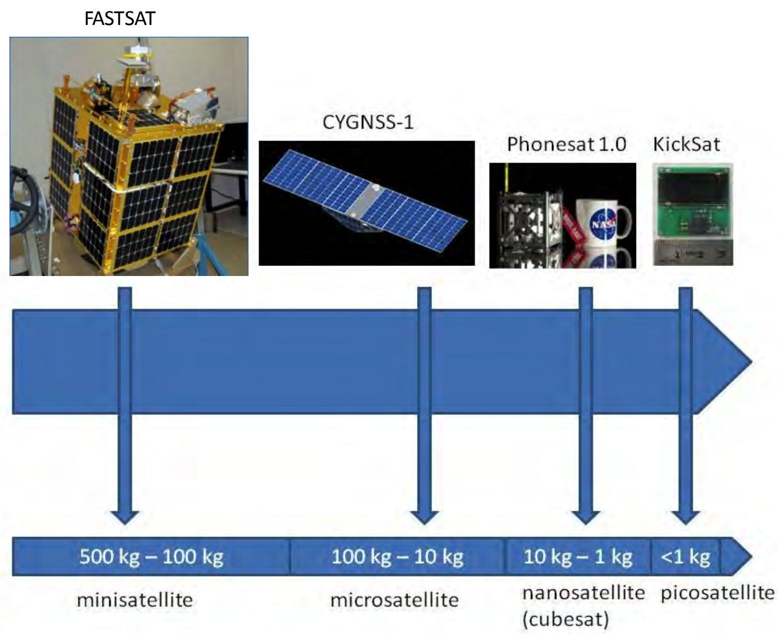


Figure 1: Overview of the variety of spacecraft that fall into the small spacecraft category.

CubeSats are a type of small spacecraft that weigh only a few kilograms and are built using a standard form factor relying on a 10 cm^3 cube. CubeSats can be composed of a single cube (nicknamed a '1U' unit) or several cubes combined forming, for instance, 3U or 6U units (see Figure 2). Due to their high popularity and their increased usage in recent times, particular emphasis is put on the SoA of CubeSat technology in this report (see also Figure 2).

A table of the small spacecraft missions that have been studied to assess the state of the art of small spacecraft technology is provided in Appendix I. Although the list gives a good overview of current endeavors it is not meant to be exhaustive. Along the same line of thought the technology tables shown in subsequent Sections are not meant to be comprehensive. Their goal is to illustrate the current SoA based on what could be found through desk research in a limited amount of time.

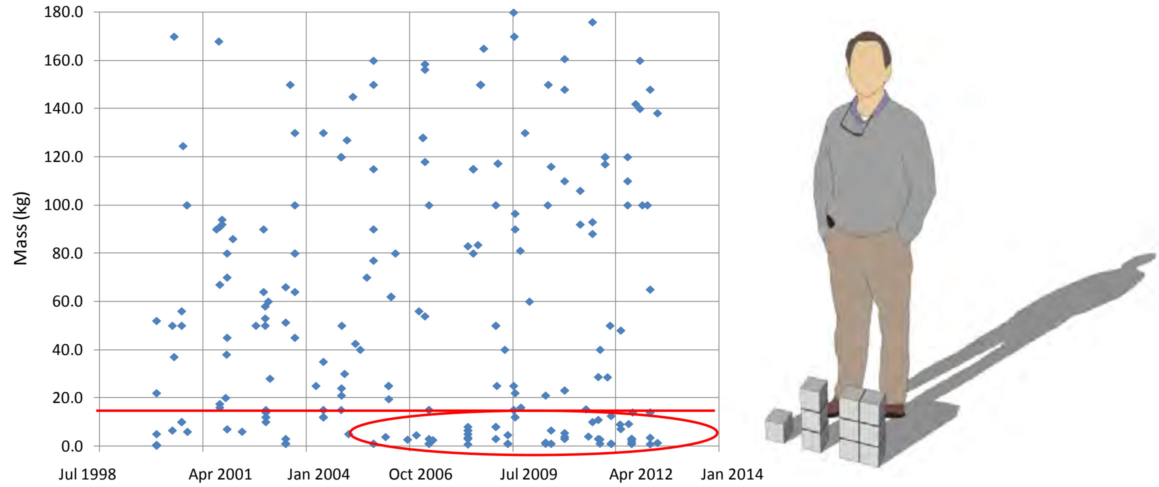


Figure 2: (Left) Launch dates vs mass of the small spacecraft studied in this report (see Appendix I for more detail). Spacecraft below the red line are essentially CubeSats with 15 kg or less. The recent trend in the increased use of CubeSats is visible (along with a depletion of launches in the 15 kg-100 kg). (Right) CubeSats with a form factor of 1U, 3U, and 6U, respectively. The volume of the 1U base unit is 10 cm^3.

1.3 Assessment

The SoA assessment of a technology is performed using NASA's TRL scale (http://www.nasa.gov/content/technology-readiness-level; see Figure 3). A technology is deemed SoA 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[2]. A technology is considered not SoA whenever its TRL is lower than or equal to 5. In this category, the technology is considered to be 'on the horizon'[3].

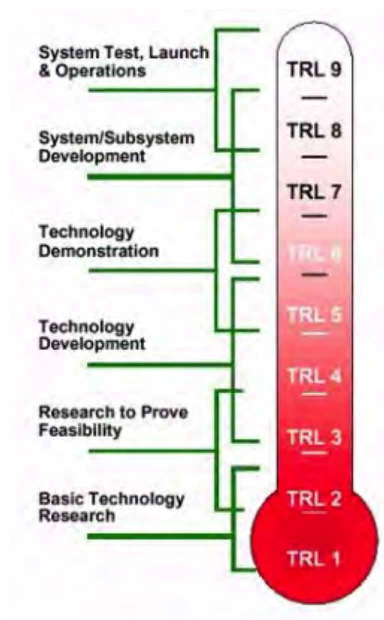


Figure 3: NASA Technology Readiness Levels (TRLs).

[2] A relevant environment is either a high fidelity laboratory environment or a simulated operational environment. See http://www.nasa.gov/content/technology-readiness-level

[3] The above definition of 'state of the art' has essentially 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.

1.4 Overview

This report is laid out as follows: in Section II the SoA 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 Sections 3-11, the SoA of the spacecraft subsystems are presented in turn:

- Power
- Propulsion
- Attitude Determination and Control System (ADCS)
- Structures, Materials and Mechanisms
- Thermal Systems
- Command and Data Handling (C&DH)
- Communications
- Integration, Launch and Deployment
- Ground System and Operations

Conclusions on the overall SoA of small spacecraft are given in Section 12. Appendix 1 shows a number of tables that have not been inserted earlier for the sake of readability.

2. SPACECRAFT

2.1 Introduction

In recent years, increasing attention has been paid to smaller spacecraft enabling low-cost missions through the utilization of COTS technology, consumer technology, rapid prototyping, and ride shares. In order to drastically reduce mission costs, the objective is to have one or more small spacecraft complete the same tasks as their larger counterparts.

2.2 State of the Art

Small spacecraft missions are made possible through miniaturization technologies. Miniaturization is the act of creating systems of ever-smaller scales and thereby increasing the functional density of the product. Devices have a comparable capability, but are of smaller size than their predecessors. Perhaps the most famous example of this trend is Moore's law, which roughly states that the number of transistors on integrated circuits doubles every two years (Moore, 1998): this trend has remained valid since the invention of the integrated circuit in the late 1950's. Although Moore's two-year law cannot be applied directly to small spacecraft, a significant amount of miniaturization has been achieved for spacecraft subsystems and components. Figure 4 illustrates this trend.

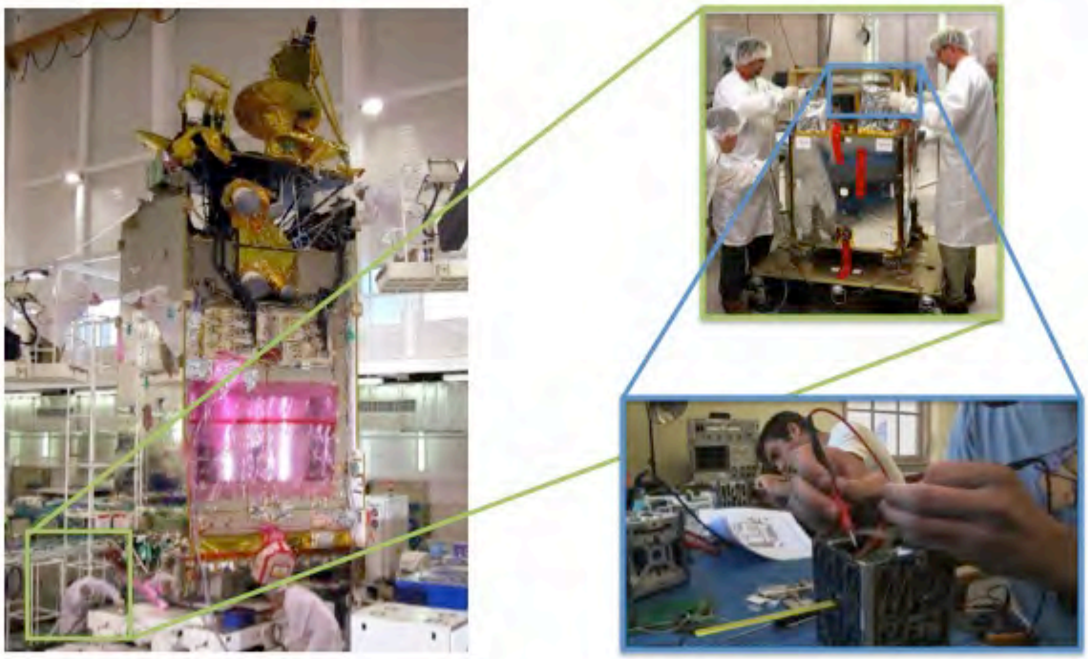


Figure 4: Integration of various spacecraft. (Left) large spacecraft clean room (Intelsat 10-02, image credit: EADS Astrium); (Right) Integration environments for small spacecraft FASTSAT (Top) and Phonesat (Bottom). The blue and green rectangles highlight the differences in size compared to Intelsat 10-02.

An example of a miniaturizing technology is the use of micro-electro-mechanical systems (MEMS). In this field of research, cleanroom processes inherited from the semiconductor industry are used to bridge the disciplines of electronics and mechanics (as well as areas such as optics and fluidics) to produce devices with feature-sizes on the microscale (μm). This not only enables devices with a higher functionality density, but also with potential performance improvements such as higher sensitivity and lower power consumption. MEMS devices are mostly used on spacecraft as sensors (see Figure 5) and, to a lesser extent, as actuators. Sensors convert signals from one energy form to another (for example a movement or a temperature change into an electrical signal). Actuators perform the opposite transformation, converting electrical signals into a mechanical action or motion.

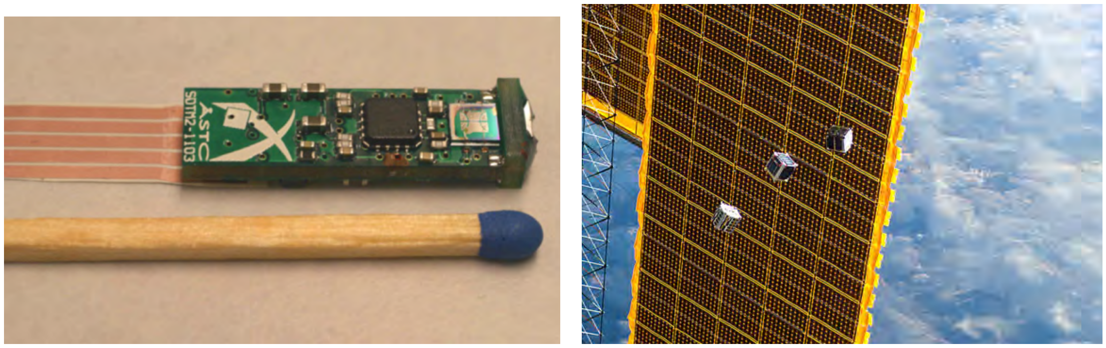


Figure 5: A miniaturized 3-dimensional magnetometer with MEMS sensors and electronics (left, credit ASTC), which was flown on the Vietnamese CubeSat F-1 (right), one of three CubeSats deployed from the ISS in 2012.

The highest level of integration is achieved when individual components are integrated all onto the same substrate to form the subsystems of the spacecraft. The closest example to this is the previously mentioned picosatellite KickSat. The dead mass and space are decreased as a function of the density at which different components are assembled. The functionality density of the system increases and tends to lower the associated power requirements. The speed and stability of the system increase as well. The SoA of the level of integration is driven by consumer electronics.

Some small spacecraft are assembled and integrated with the same rigor as their larger counterparts, while other small spacecraft never see the inside of a cleanroom and are built in a normal laboratory environment. In the realm of CubeSats, it is easy to build or buy the subsystems and integrate them into a complete spacecraft on a normal workbench; the spacecraft performance achieved may not be exactly the same, but the total mission cost is drastically reduced.

2.3 On the Horizon

Current research focuses on further reducing the time and cost of building and integrating a satellite. This may be enabled through a number of approaches, such as reinforced usage of COTS and consumer electronics for which highly miniaturized and integrated components are readily available. Plug-and-play technology will allow rapid assembly of a specific satellite using a collection of general subsystems. Rapid prototyping and 3-D printing of structures, components, and even complex subsystems will enable faster and much more flexible manufacturing processes.

On the lower mass limit, the future may see the arrival of standardized ChipSats, built out of highly integrated components fulfilling all the needs of a satellite on a single chip (Johnson & Peck, 2012).

2.4 Conclusion

Small spacecraft missions are a low-cost alternative to large spacecraft missions. There is a trade-off to be made between the size of a spacecraft and its functionality. Advances in both miniaturization and integration technologies have diminished the scope of that tradeoff. Small spacecraft technology is made possible through miniaturization, COTS products and consumer products.

Some small spacecraft are assembled and integrated with the same rigor as their larger counterparts. Others have never seen the inside of a clean-room and have been integrated within a university laboratory.

The SOA of small spacecraft integration methods is as advanced as the one relating to larger spacecraft. COTS components are commonly used to build small spacecraft at the lower end of the cost range.

2.5 References

Johnson, M. I., Peck, M. A.: *KickSat, an Open Source ChipSat Dispenser and Citizen Space Exploration Proof of Concept Mission.* 4th European CubeSat Symposium. Bussels, Belgium, 2012.

Moore, G. E.: *Cramming more components onto integrated circuits.* Proceedings of the IEEE, 86(1), p. 4, 1998.

3. POWER

3.1 Introduction

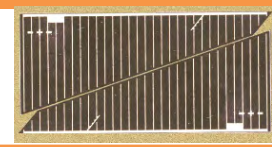
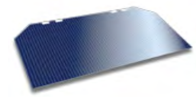
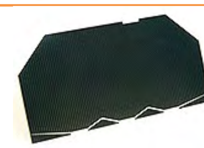
Spacecraft function relies on electrical power. The power system typically accounts for 20-30% of the total spacecraft mass. The three subsystems are power generation, storage, and distribution (Lyons, 2012). Each subsystem is approximately one third the total power system mass. Mission requirements for average and peak power, solar intensity, and duration of eclipses dictate the system architecture. While long missions require power generation, shorter missions can solely rely on energy stored in batteries. The NASA Technology Roadmap aims to improve power systems for all spacecraft weight classes, however not all of these technologies are applicable to small satellites.

3.2 State of the Art

3.2.1 Power Generation

Solar cells generate electricity by harvesting Sunlight using the photovoltaic effect. Solar intensity varies as the inverse square of the distance from the Sun. The amount of energy converted varies as a cosine function of the angle between the cell and the Sun. Solar cells degrade during their mission lifetime. This is characterized by the End of Life/Beginning of Life (EOL/BOL) ratio, which can be as high as 96% and low as 60%. The solar cell output at EOL will determine size requirements for the particular mission. A protective coverglass material over the cell resists light-reflection, darkening, and ultraviolet radiation damage. Triple junction solar conversion efficiency is about 29% in production while research cells approach 38%. The cells usually include protective diodes to stop reverse current flow when the cells are in partial shadow while in space. Solar panels are assembled from individual cells. State of the art panels suitable for CubeSats can provide more than 50 W according to kit manufacturers. Spectrolab Inc., produces a Triangular Advanced Solar Cell (TASC), which has the advantage of fitting odd form factors on small satellites without the need to custom cut individual solar cells. Other issues with turning cells into panel arrays involve matching individual cells in terms of current and voltage (Kalman, 2012).

Table 1: Power generation with solar cells for small satellites.

Technology Name	Description	Developer	TRL Status	Figures
Solar cell	Triangular shape, Improved Triple Junction (ITJ), Efficiency 27%	SpectroLab (USA)	**9** On orbit	
Solar cell	NeXt Triple Junction (XTJ), Efficiency 29.5%	SpectroLab (USA)	**9** On orbit	
Solar cell	BTJ / ZTJ Space Solar Cell, Efficiency 27-29.5%	Emcore (USA)	**9** On orbit	
Solar cell	Triple Juction Solar Cell, 3G28 / 3G30 Efficiency 28 -30%	AzurSpace Solar (Germany)	**9** On orbit	
Solar panel	Panel of SpectorLab or AzurSpace cells	Clyde (UK)	**9** On orbit	
Solar panel	PMDSAS for 1/2/3U CubeSats	Pumpkin (USA)	**9** On orbit	

3.2.2 Energy Storage

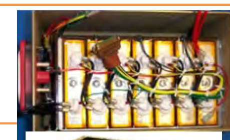
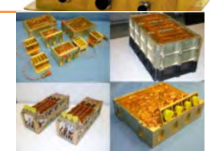
During eclipse periods or peak power needs, batteries use chemically stored energy as the source of power. Primary one-time-use batteries can have a long mission life; however their chemistry differs from that of rechargeable batteries. Battery technology is at TRL 9 and includes 3.7 V Lithium Ion batteries, usually in cylindrical form factor of 18.4 x 65.1 mm, and the latest lithium polymer batteries in a flat form factor such as used in modern mobile phones. Table 2 and Table 3 illustrate the general characteristics of different battery types for small spacecraft.

Table 2: General characteristics of battery technology (Lyons 2012).

Battery	Chemistry	Mission	Specific Energy (Wh/kg)	Energy Density (Wh/l)	Operting Temp. Range (˚C)	Cycle Life	Mission Life (yrs)	Issues
Primary	Ag-Zn Li-SO2 Li-SOCl2	Launch vehicles, Cassini, MER lander, Sojourner Rover	90-250	130-500	-20 to 60	1	1-9	Limited temp. range & voltage decay
Rechargable	Ni-Cd Ni-H2	ToPex, HST, Space Station	24-35	10-80	-5 to 30	>50,000 @ 25% DOD	>10	Heavy/bulky & temp. range
Advanced	Li-Ion Li-Polymer	MER rovers, Cubesat	100	250	-20 to 30	>400 @ 50% DOD	>2	Cycle life

Batteries are a commodity item available from a variety of manufacturers in raw form; "raw" meaning unprotected from thermal runaway. Batteries can have protection circuits built into the individual cell, and without protection circuits they are referred to as raw batteries. Li-Ion batteries have one-time thermal protection that opens the circuit to prevent thermal runaway conditions. Small satellite engineers perform acceptance testing on individual COTS battery cells and assemble them into battery packs according to mission needs. As an alternative to buying COTS batteries, there are also companies that make their own space-qualified batteries.

Table 3: Battery options for small satellites.

Technology Name	Description	Developer	TRL Status	Figures
Primary battery	Ag-Zn, SZHR50, 0.76kg, 1.5 V, 50 AHr	Eagle Picher (USA)	**6** Not flown on small satellite	
Primary battery	Ag-Zn, Silvercels, 1.5 V, 0.1-20k AH	Yardney (USA)	**6** Not flown on small satellite	
Rechargable battery	$Ni\text{-}H_2$, SAR10097, 28kg, 10 V, 75 AHr	Eagle Picher (USA)	**6** Not flown on small satellite	
Advanced battery	Li-Ion, custom from space qualified COTS	ABSL Space Products (UK / USA)	**6** Not flown on small satellite	
Advanced battery	Li-Polymer, 8.2 V, 1.24 Ahr	Clyde Space Ltd. (UK)	**6** Not flown on small satellite	
Advanced battery	Li-Ion #VEL / #VL, 3.6 V, 4.5 - 50 Ahr	Saft SA (France/ USA)	**6** Not flown on small satellite	
Advanced battery	Li-Ion #18650HC raw #19670 protected	Sony (Japan)	**6** Not flown on small satellite	
Advanced battery	Li-Ion Lithion 3.6V 7-350 AHr	Yardney (USA)	**6** Not flown on small satellite	

3.2.3 Power Management and Distribution

Satellite power distribution architectures include voltages regulated centrally or distributed along with Direct Energy Transfer (DET) or Peak Power Tracking (PPT); small satellites follow the same power distribution architectures as well. A study of 33 CubeSat power systems where data was available revealed 20 centralized and five distributed with 13 DET and 15 PPT, with DET favored in the newer designs (Burt, 2011). In a DET architecture, the regulation mechanism matches the solar power voltage to the load(s) and there are no intermediate components to dissipate excess power, thus making it the most efficient power regulation of the two available methods. A PPT design has a series regulation device between the solar arrays and loads, which regulates how much current is extracted from the array (Burt, 2011). Nanosatellite Electrical Power Systems (EPS) 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. The main commercial CubeSat EPS suppliers are Pumpkin Inc., GomSpace ApS., Stras Space, and Clyde Space Ltd. The manufacturer's datasheets generally mention quality and acceptance component testing as well as flight qualified heritage. SpaceMicro Inc., lists commercially-available radiation-hardened systems and testing methods for qualifying systems for space applications. Improvements in the electronic components for the power management and distribution systems are due to trends in consumer electronics rather than manufacturers being responsive to the needs of the space industry.

3.3 On the Horizon

3.3.1 Power Generation

There are new technologies for power generation that are currently being assessed for smaller spacecraft applications. The areas include improved solar efficiencies, regenerative fuel cells, space tethers, and numerous methods to harvest the heat from radioactive decay. Four-junction solar cells are on a roadmap to reach 50% efficiency, but currently research laboratory cells are at 43% under concentrated solar conditions. Specification sheets are not available so it is unknown if the addition of another layer on the solar cell ("the fourth junction") results in an equivalent power–to-weight-ratio.

Fuel cells might be a more effective technology to generate power during long eclipse periods when compared to photovoltaics and battery power; however, no fuel cell has advanced beyond laboratory tests. In addition to system lifetime, the obstacles to overcome include minimizing mass, volume, and the parasitic power requirement. One development program by Boeing/Saint Louis University called BillikenSat-II was a CubeSat that was powered by beer, but the status of the program is unknown (Pais, et al., 2007). Figure 6 shows the relative energy densities of fuel cells (Pais et al., 2007). It should be noted that fuel cells cannot be recharged on orbit hundreds of times like advanced batteries, but regenerative fuel cells are also being researched. Another program is the 2011 JPL/USC 300 W suitcase-sized prototype Direct Methanol Fuel Cell developed for DARPA at TRL 3 (Vega, 2011).

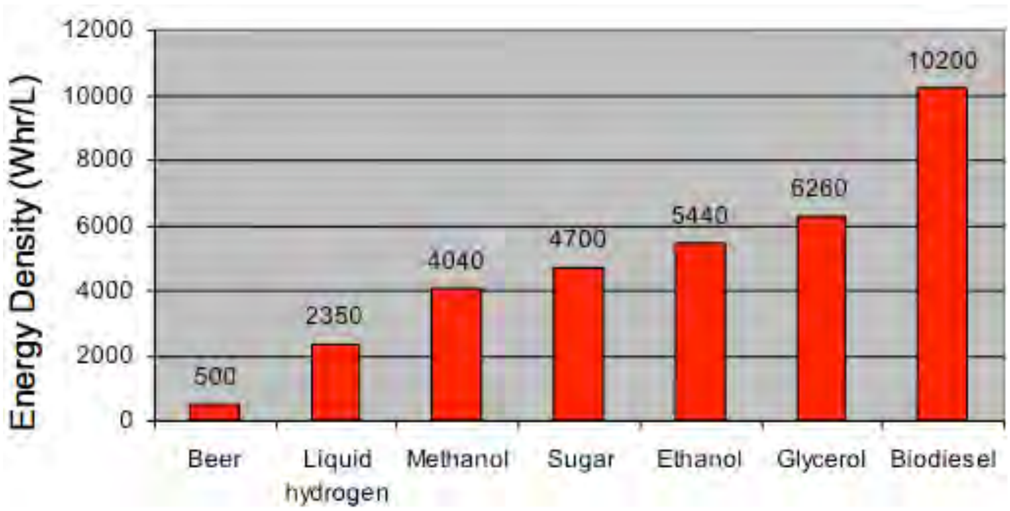


Figure 6: Relative stored energy for candidate fuel cells (Pais, et al., 2007).

Although electrodynamic power generation is possible using conductive space tethers, as shown with the Tethered Satellite System aboard STS-75, no tests are planned on small satellites. Electric tethers require the magnetic field of the Earth to harvest electrons at the cost of reducing the orbital kinetic energy. The satellite must be launched to a sufficiently high altitude to prevent reentry due to drag before the mission ends, but the output can be several hundred volts per kilometer of tether.

Another method in power generation is utilization of radioactive decay. Small nuclear devices have the potential to be an enabling technology for small satellites and landers if solar energy is unavailable. Figure 7 shows that radioisotope thermoelectric generators (RTG) have been used for primary power supply since the beginning of the space program. The smaller Multi-Mission RTG (MMRTG) used on the Mars Science Lab Curiosity has a mass of 44 kg and generates 125 W, which could be utilized on small satellites. There are also lightweight Radioisotope Heating Units (RHU), shown in, used to keep components like circuits and rechargeable batteries above 0°C.

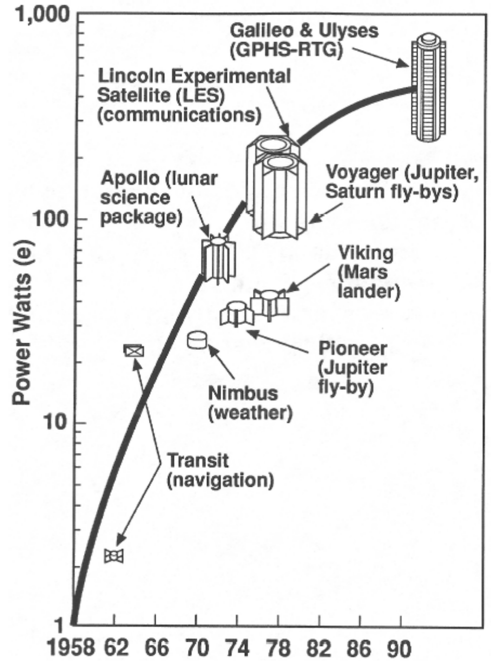


Figure 7: Evolution of RTG technology (Rockwell, 1992).

A full size RTG, such as on New Horizons mission to Pluto (Radioisotope Power Systems, New Horizons 2012), has a mass of 56 kg and can supply 300W (6.3% efficiency) at the beginning of its life. Future developments on Advanced Stirling Radioisotope Generators (ASRG) are looking to increase efficiency to 28% with a mass of 20 kg to generate 143 W, but are only at TRL 5 (Vining & Bennett, 2010).

Radioactive heat sources are mainly Plutonium-238 in the form of Plutonium Oxide, PuO_2, with a half-life of about 87 years. Other candidates are Curium-242 and Americium-241. Generally, power density roughly scales inversely with half-life. Americium's power density is less than a quarter of Plutonium with a half-life of 432 years. Compared to

Figure 8: Light Weight Radioisotope Heater Unit compared to the size of a U.S. one cent penny (Image credit: LANL, found in Cataldo, et al., 2011).

Plutonium, both require more radiation shielding, with Curium requiring significantly more due to gamma particle emission. Americium's lower output results in a higher mass system for the same electrical output.

At a lower TRL, beta- and alpha-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.

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. Thermophotovoltaics are technically challenging because they require the radioisotope fuel to have a temperature of >1273 K for high infrared emission, whilst maintaining temperature suitable for photovoltaic cells (<323 K) for efficient electrical conversion. These devices are predicted to produce tens of watts of power at specific powers of 6 W/kg. The radioisotope fuel of choice is Plutonium-238 in the form of PuO_2, which, however, requires Congressional authorization to use. Other options are Curium and Americium.

Piezoelectric power converters are miniature electromechanical devices that utilize a cantilever beam system to convert vibrational energy into electrical

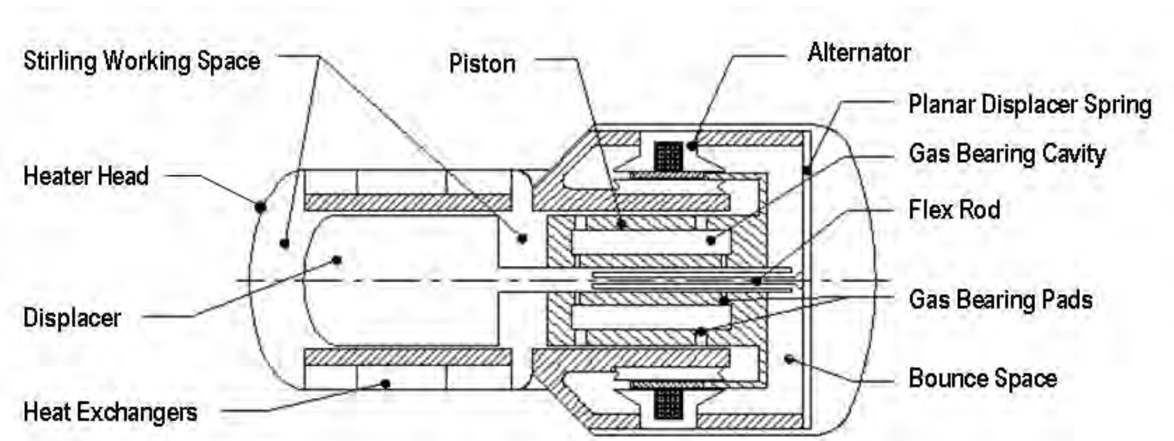
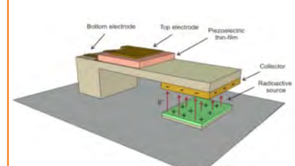
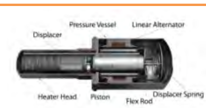


Figure 9: Advanced Stirling Convertor (Image credit: Sunpower, Inc.).

energy via a piezoelectric thin-film. A miniature cell has been tested to produce 15 µW with dimensions 4.5 mm × 2 mm × 1 µm.

NASA Glenn is developing both the Small Radioisotope Power System (SRPS). An example of the ASRG convertor developed by Sunpower, Inc. is shown in Figure 9. These utilize linear Stirling actuators and a 30% efficient thermodynamic cycle using a piston to convert thermal and mechanical energy to electrical energy. A single SRPS device is aimed at producing 80 W of power with a specific power of 7 W/kg. Table 4 shows future technologies in power generation for small satellites. The table is heavily weighted to using radioisotope heat sources and advanced mechanical or photovoltaic harvesting methods. NASA Glenn is the lead center in space power generation research.

Table 4: Future technologies in power generation for small satellites.

Technology Name	Description	Developer	TRL Status	Figures
Thermoelectric power conversion	Thermal energy from a radioisotope is converted via a thermocouple to produce a voltage difference	NASA Glenn (USA)	**6** Flown on larger satellites and Mars rovers	
Beta-voltaic power conversion	β particles emitted from a radioisotope are absorbed with a p/n junction diode to produce electron-hole pairs	NASA Glenn (USA)	**5** Non-satellite applications	
Alpha-voltaic power conversion	α particles emitted from a radioisotope are absorbed with a p/n junction diode to produce electron-hole pairs	NASA Glenn (USA)	**2** Analysis and laboratory testing	N/A
Thermophoto-voltaic power conversion	Infrared radiation emited from a hot radioisotope is absorbed with an infared photovoltaic cell	University of Toronto (Canada)	**2** Analysis and laboratory testing	
Piezoelectric power conversion	A miniature cantilever beam is bombarded with radiation from a radioisotope source, and the vibrational energy is converted via piezoelectrics	University of Toronto (Canada)	**2** Analysis and laboratory testing	
Small radioisotope power system	Stirling thermodynamic cycle power conversion from a radioisotope	NASA Glenn (USA)	**2** Analysis and laboratory testing	

3.3.2 Energy Storage

There is nothing to indicate new battery technology developments for small satellite systems. One issue may be that large firms are not actively marketing to the small satellite manufacturers. COTS batteries are put through quality assurance testing and then custom integrated into products intended for the small satellite market.

3.3.3 Power Management and Distribution

There is a general need to miniaturize and radiation-harden electronic components for single event upsets. No evidence of progress in that direction (focused on small satellite technology) could be found during the limited amount of time assigned to this study.

3.4 Conclusion

Small spacecraft are using advanced power generation and energy storage technology, namely 29% efficient triple-junction solar cells and lithium ion batteries. Today's small spacecraft mission designers are faced with stringent mass and volume restrictions and requirements and have a higher risk tolerance—which has led to the industry's early adoption of flat lithium polymer battery packs. All the power subsystems benefit from technology advances and component miniaturization in the consumer electronics market. Figure 10: Advances in solar cell efficiency by cell type (National Renewable Energy Laboratory, 2013). shows the general trend of solar cell efficiency over the last three decades. Figure 11 shows energy storage density by volume and mass versus battery chemistry.

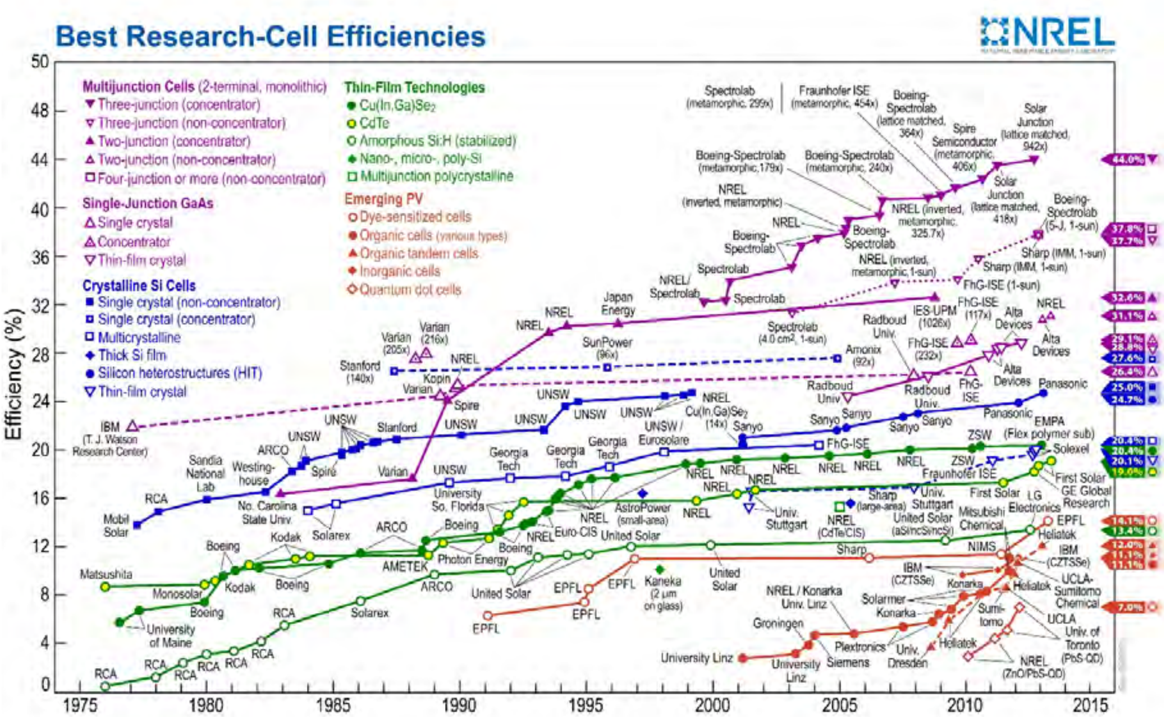


Figure 10: Advances in solar cell efficiency by cell type (National Renewable Energy Laboratory, 2013).

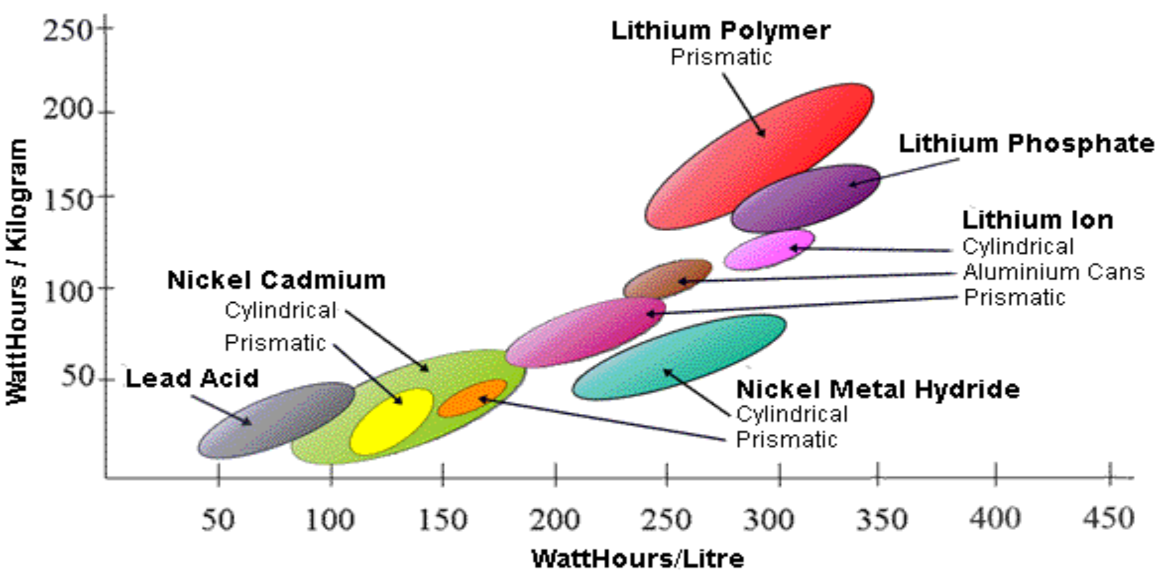


Figure 11: Comparison of energy storage density by volume and mass versus battery chemistry (Wagner, 2006 ©Woodbank Communications, Ltd).

3.5 References

Anonymous: *Datasheet* [Online], 2002. Available at: http://www.spectrolab.com/DataSheets/PV/PV_NM_TASC_ITJ.pdf [Accessed August 2013].

Banks, J.: *Technology Thrusts* [Online], 2012. Available at: https://rt.grc.nasa.gov/power-in-space-propulsion/photovoltaics-power-technologies/technology-thrusts/ [Accessed August 2013].

Burt, R.: *Distributed Electrical Power System in CubeSat Applications.* s.l.: All Graduate Theses and Dissertations. School of DigitalCommons@USU, 2011.

Cataldo, R., Bennett, G.: *US Space Radioisotope Power Systems and Applications: Past, Present and Future.* Cleveland: s.n., 2011.

Dimroth, F.: *43.6 % Four-Junction Solar Cell under Concentrated Sunlight New Manufacturing Technologies allow for Higher Efficiencies* [Online], 2013. Available at: http://www.ise.fraunhofer.de/en/press-and-media/press-releases/presseinformationen-2013/43.6-four-junction-solar-cell-under-concentrated-Sunlight [Accessed August 2013].

Dow, A., Schmid, U., Kherani, N. P.: *Analysis and Modeling of a Piezoelectric Energy Harvester Stimulated by β-emitting Radioisotopes.* Smart Materials and Structures Journal, 20(1), pp. 1-9, 2011.

Dyches, P.: *Radioisotope Power Systems, New Horizons* [Online], 2012. Available at: http://solarsystem.nasa.gov/rps/newhorizons.cfm [Accessed August 2013].

Fraeman, M. et al.: *Small Radioisotope Power System at NASA Glenn Research Center.* s.l.:s.n., 2011.

Furano, G.: *Review of Rad Hard electronics activities at European Space Agency.* Topical Workshop on Electronics for Particle Physics (TWEPP). Oxford, UK, 2012.

Kalman, A.: *Enhanced Power Systems for CubeSats.* San Luis Obispo, s.n., 2012.

Landis, G. et al.: *Non-solar photovoltaics for small space missions.* Austin, s.n., p. 2819 – 2824, 2012.

Lange, R., Carroll, W.: *Review of Recent Advances of Radioisotope Power Systems. Energy* Conversion and Management Journal, 49(3), pp. 393-401, 2008.

Lyons, V. J., Gonzalez, G. A., Houts, M. G., Iannello, C. J.: *Space Power and Energy Storage Roadmap, Technology Area 03.* s.l., NASA, 2012.

Otting, W., Gard, L., Hammel, T. E., Bennett, R.: *Preparation of the MMRTG for the Mars Science Laboratory Mission.* Atlanta, s.n., 2012.

Reinhard, W.: *Electropaedia.* [Online], 2006.
Available at: http://www.maximintegrated.com/app-notes/index.mvp/id/3958

Rockwell International. Dynamic Isotope Power Systems (DIPS) for Space Exploration – Technical Information, BC92-68, Rocketdyne Division, Canoga Park, California, 1992.

Sunpower, Inc. [Online], 2013. Available at:
http://sunpowerinc.com/services/applications/asc.php [Accesses October 2013].

Vega, P.: *JPL-Developed Clean Energy Technology Moves Forward* [Online], 2011.
Available at: http://www.jpl.nasa.gov/news/news.php?release=2011-163
[Accessed August 2013].

Vining, C., Bennett & Gary, L.: *Power for Science and Exploration: Upgrading the General Purpose Heat Source Radioisotope Thermoelectric Generator.* Nashville, s.n., pp. 1-15, 2010.

Woodbank Communications, Ltd [Online] 2013 Available at: www.mpoweruk.com.. [Accessed October 2013].

4. PROPULSION

4.1 Introduction

Miniaturized propulsion systems for small spacecraft are advancing rapidly in ability and are the subject of great attention. Small spacecraft have numerous proposed objectives that can be attained by using propulsion systems: responsive space systems and communication platforms; distributed and fractionated satellite architectures that rely on precise formation flying; and scientific research and remote sensing of Earth and beyond.

Although numerous systems such as ion electrospray and miniaturized Hall thrusters are currently in development and show great promise for high specific impulse and efficiency, the SoA in small satellite propulsion is limited to cold gas thrusters, solid rocket motors, and pulsed plasma thrusters. However, serious challenges exist for such systems to achieve a mature level of adoption and flight heritage. Associated technology requirements for the full utilization and realization of small spacecraft propulsion are deployable solar arrays, thermal management systems, and miniaturized power processing units (PPUs) sufficient for high voltage requirements. The increase in mission capabilities provided by small satellite propulsion is also proving to be a driver for development by numerous institutions.

As a secondary payload, small spacecraft cannot interfere with the primary mission, which has led to the development of relatively benign thruster technologies such as cold gas and electric propulsion. While some small satellites can be custom built and launched as a higher priority or primary mission, the CubeSat Design Specification (CDS) agreed upon between CubeSat builders and launch vehicle providers require a waiver to deviate from general requirements (CDS Rev 13, 2013). These requirements limit potential propulsion systems in addition to CubeSat dimensions: less than 1.33 kg mass for 1U, up to 4.0 kg mass for 3U, pressurization less than 1.2 standard atmospheres, less than 100 W-Hr of stored chemical energy, and no hazardous materials.

4.2 State of the Art

4.2.1 Cold Gas Thrusters

The simplest propulsion system available to small spacecraft vents a cold, pressurized gas through a nozzle. The specific impulse of a cold nitrogen gas system is less than 75 sec and thrust levels are less than 5 N. The system does not have a pump and is referred to as a blow down system, where the pressure of the system decreases with time. It is possible to have a high-pressure tank with a regulator to vent the gas at a lower pressure for a longer amount of time, but the total impulse delivered is the same since it is a function of the pressure force over time. Many cold gas systems used on larger satellites are theoretically usable on small satellites, however their use on CubeSats may be limited due to valve power requirements even if sufficiently low in mass and volume. While no CubeSat has yet flown a cold gas thruster, Surrey Space flew SNAP-1, a 6.5 kg small satellite with a 450 g butane cold gas system from Polyflex Aerospace, Ltd, which performed proximity operations on orbit.

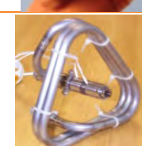
Different gases are available as propellants; nitrogen and helium are popular for pressurization because they do not chemically react, but they may require a pressure regulator to function with an on/off valve. Propellants with a critical temperature above the ambient exist only in the gas phase, while those below the critical temperature are liquid. Propellants below the critical temperature such as propane, sulfur hexafluoride, and butane are self-pressurizing, negating the need for a pump, and they have a higher storage density in liquid form. Because operational safety is of primary importance in CubeSats, there is active development of cold gas systems for small satellites. Butane has the lowest vapor pressure at room temperature, as shown in Table 5. Because butane's low pressure allows for non-spherical or flat-wall tank designs, 3D-printers can manufacture conforming tanks.

Table 5: Comparison of propellants used in cold gas systems.

Propellants	Vapor Pressure, 40°C	Vapor Pressure, critical point	Temperature, critical point
Helium, He	Gas	2.3 bar	-268°C
Nitrogen, N_2	Gas	34 bar	-147°C
Nitrous oxide, N_2O	Gas	72 bar	36°C
Sulfur hexafluoride,	30 bar	35 bar	47°C
n-Butane, C_4H_{10}	3.8 bar	37 bar	151°C

Table 6 shows the SoA in cold gas systems. Currently, several nitrogen cold gas systems are available, yet many systems may prove to be ineffective on a small satellite due to limitations of valve power, volume, and mass requirements.

Table 6: List of a few small satellite cold gas propulsion systems.

Technology Name	Description	Developer	TRL Status	Figures
Cold gas thruster	n-Butane, 0.025 N Isp 70 sec	VACCO Space (USA)	**7** Tested, not flown	
Cold gas thruster	MPS, n-Butane, 0.01N Isp 69 sec	Polyflex Aerospace LTD (UK)	**9** Flown on SNAP-1	
Cold gas thruster	SF_6, 0.05 N, Isp 45 sec	VACCO Space (USA)	**9** Flown on Can X-2	
Cold gas thruster	58E143/144/145/146 Nitrogen, 0.016-0.04 N Isp 65 sec	Moog (USA)	**9** NASA CHAMP	

4.2.2 Chemical Propulsion

Chemical propulsion systems use a chemical reaction to produce a high-pressure, high-temperature gas that accelerates out of a nozzle. Chemical propellant can be liquid, solid or a hybrid of both. Liquid propellants can be a monopropellant passed through a catalyst. A more conventional bipropellant is a mix of oxidizer and fuel. A solid rocket motor contains both an oxidizer and a fuel that are molded into various grain patterns.

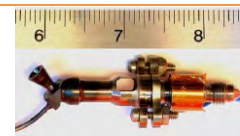
The benefits of monopropellants and solid systems include relatively low-complexity/high-thrust output, low power requirements, and high reliability. Liquid and hybrid systems can be stopped and re-started, and in some cases throttled, whereas solid motors can only be used once. The highest thrust and highest specific impulse systems are bipropellant but they are more complex, not miniaturized, and are not meant for low thrust applications. Table 7 shows a variety of propellants from different systems, including cold gas for comparison.

Table 7: Comparison table of propellant options, efficiency, and thrust for small satellites.

Propellants	Specific Impulse (sec)	Thrust (N)
Nitrogen (Cold Gas)	65	0.1-5
Butane (Cold Gas)	70	0.055
Hydrazine (Monoprop.)	160-230	10-Jan
AND (Green Monoprop.)	220	1
HAN (Green Monoprop.)	250	1
Hydrogen Peroxide (Monoprop.)	100-135	0.2 – 1
MMH N2O4 (Bi-prop)	275-300	1 – 13
ATK STAR 4G (Solid)	269	58
ATK STAR 5A (Solid)	250	169

Table 8 show monopropellant and solid systems available for use on small spacecraft. It is important to note that, at the time of this study, virtually no bipropellant systems were suitable for small spacecraft.

Table 8: List of select small satellite chemical propulsion options.

Technology Name	Description	Developer	TRL Status	Figures
Monopropellant thruster	GPIM, HAN (AFM315E), 1N - 22 N, Isp 250 sec	NASA Glenn, Ball Aerospace (USA)	**6** GPIM datasheet, Falcon Heavy launch 2015	
Monopropellant thruster	HPGP, ADN (FLP106), 1 N, Isp 220 sec	ECAPS, SSC Group, (Sweden)	**6** PRISMA satellite demonstration	
Monopropellant thruster	MR-140, Hydrazine, 1 N, Isp 202 sec	Aerojet (USA)	**7** Champs system	
Solid rocket motor	STAR 4G, Solid, 257 N, Isp 269 sec	ATK (USA)	**7** Two test, 0 flights	 
Solid rocket motor	STAR 5A, Solid, 169 N, Isp 250 sec	ATK (USA)	**9** Six tests, 3 flights	

In recent years, there has been more of a push to move from toxic propellants (hydrazine and nitrogen tetroxide) to "greener," less-toxic propellants such as hydrogen peroxide (H_2O_2) or nitrous oxide fuel blend (NOFB), and ionic liquids such as hydroxyl ammonium nitrate (HAN), hydrazinium nitroformate (HNF) and ammonium di-nitramide (ADN). One such program for small satellites is NASA Glenn's Green Propellant Infusion Mission (GPIM) using HAN, which plans to fly on a SpaceX Falcon Heavy launch in 2015. OHB-Sweden's PRISMA project has a high-performance green propellant ADN 150 kg satellite demonstration called Tango.

4.2.3 Electric Propulsion

Electric propulsion systems produce thrust generally by producing plasma and accelerating it electromagnetically out of the thruster. The plasma can be produced through various discharge mechanisms such as with electrodes or antennas, and can use a variety of propellants ranging from solids to gasses. The advantage of an electrical propulsion system over chemical propulsion systems is that the propellant is separated from the power source (typically solar photovoltaic arrays) and as such the thruster is not limited by the energy of a chemical reaction. Plasma thrusters are capable of high specific impulse and long burn durations, thus allowing for high delta-V maneuvers.

Electric propulsion systems have a long flight heritage on satellites, with hundreds of ion thrusters and Hall effect thrusters being flown since the 1970s. Similarly to chemical thrusters, miniaturized plasma thrusters for small satellites are a relatively new technology and development is currently underway. Nevertheless, there are pulsed plasma thrusters (PPT) that have flown on missions, and should be considered SoA.

Pulsed plasma thrusters produce plasma by ablating solid Teflon with an arc discharge across electrodes. The plasma is then accelerated electromagnetically to produce thrust. Busek Company, Inc., has developed the Micro Propulsion Attitude Control System (MPACS, see Figure 12), which has flown on the Air Force Academy CubeSat FalconSat-3. MPACS provided attitude control for the CubeSat with 80 μNs impulse bits at 830 sec Isp. Aerojet also has a similar EO-1 PPT that flew on NM EO-1, and the thruster has similar specifications (650-1400 sec Isp, 90-860 μNs impulse bit, at 5 kg thruster mass).

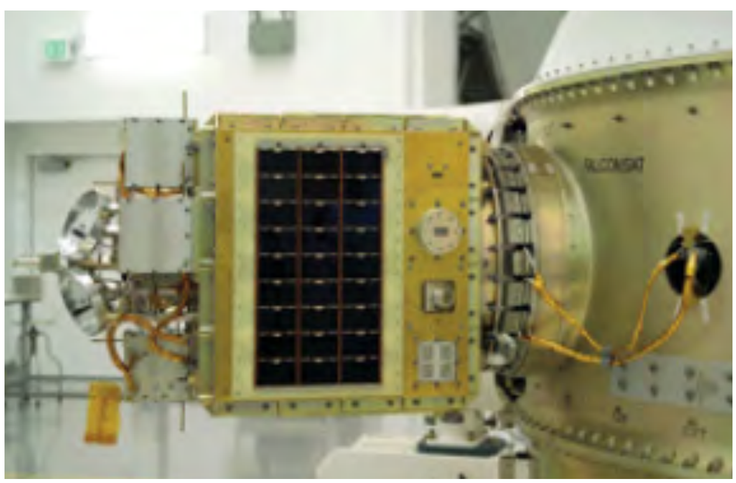


Figure 12: Busek MPACS (Busek datasheet).

4.3 On the Horizon

4.3.1 Chemical Propulsion

Monopropellant hydrazine thrusters have a long heritage as ADCS thrusters since as early as 1966 (Mueller, et al., 2008). Recently JPL has developed a CubeSat scale hydrazine thruster, the Hydrazine Milli-Newton Thruster shown below in Figure 13, capable of 150 sec Isp and 129 mN thrust at 40 g of thruster mass and 8 cm^3 volume. The power requirements of the thruster are low at an instantaneous 8 W for valve opening and a continuous 1 W during the burn.

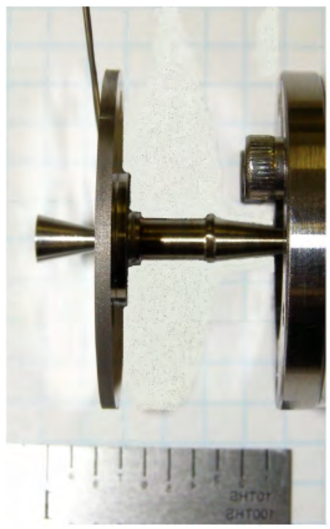


Figure 13: JPL hydrazine Milli-Newton thrusters (Mueller, et al., 2008).

Another group researching green propellants at Austrian Research Centres Seibersdoorf (ARCS) is using hydrogen peroxide as their monopropellant, a fuel which has an equivalently long flight heritage (1960's) as hydrazine. Scharlemann, et al., 2011. at ARCS have demonstrated their Miniature Hydrogen Peroxide Thruster (Figure 14) as capable of 100-800 mN at 153 sec Isp. The power requirement is higher for heating the catalyst bed, around a continuous 10 W.

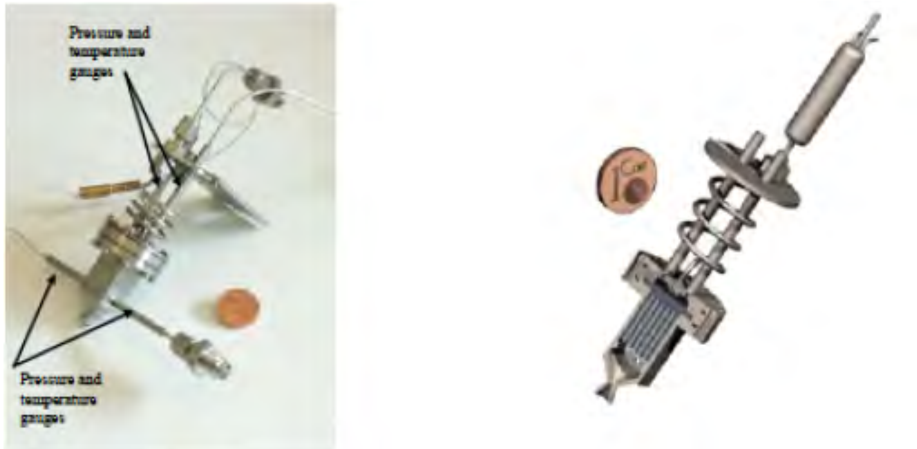


Figure 14: Miniature hydrogen peroxide thruster (Scharlemann, et al., 2011.).

Bipropellants offer the capability of higher specific impulse than monopropellants, with the disadvantage of requiring separate storage tanks for oxidizer and fuel. Tethers Unlimited overcomes this challenge with their Hydros thruster (Figure 15) by storing the hydrogen and oxygen propellants as water, and then generates them into gaseous form through electrolysis. They have so far demonstrated 0.8 N of thrust at 300 sec Isp. Bipropellant thrusters, as with previously mentioned chemical propulsion technologies, have a long flight heritage on large satellites and are in development for small satellites.

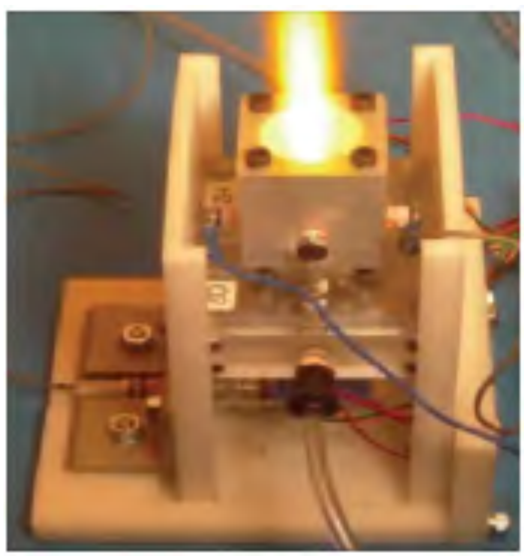


Figure 15: Hydros thruster (Tethers Unlimited datasheet).

4.3.2 Electric Propulsion

As there currently are numerous electric propulsion technologies being developed for small satellites, this section will be limited to a selection of several different candidates. These include vacuum arc, hall effect, gridded ion, electrospray, and helicon thrusters—all of which are at various TRL designations of 5 or below.

NASA JPL is developing a vacuum arc thruster (see Figure 16) that creates plasma from an arc discharge between two solid electrodes. The plasma then expands and accelerates out of a magnetic nozzle, creating thrust. The laboratory demonstrated specifications are 125 μN thrust and 1500 sec Isp at 40 g mass and 10 W power. The plasma emitted from the thruster is quasi-neutral and thus does not require a neutralizer to prevent spacecraft charging.

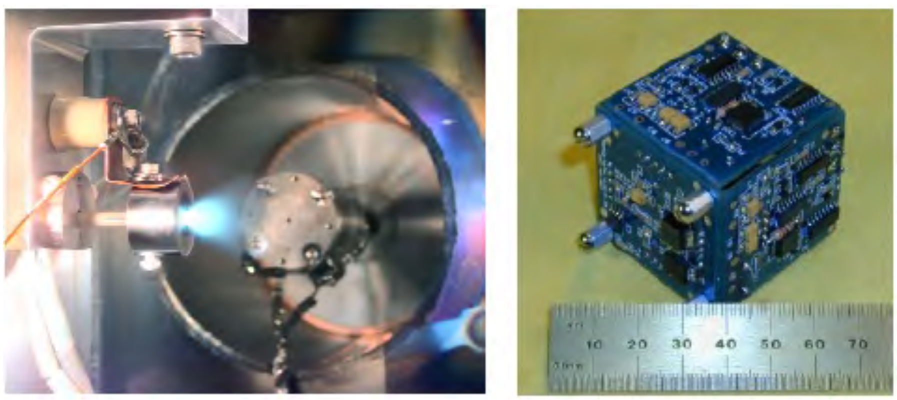


Figure 16: JPL vacuum arc thrusters (Mueller, et al., 2008).

Princeton Plasma Physics Laboratory is developing a cylindrical Hall thruster (Figure 17) capable of 3-6 mN and 1200-2000 sec Isp at 50-170 W power and < 1 kg mass. The Hall thruster forms plasma by electron bombardment of a neutral gas, and the resulting ions are accelerated out of the chamber due to an electrostatic potential difference. A neutralizer in the form of an electron-emitting cathode is required in order to prevent spacecraft charging, and the miniaturization of thermionic cathodes has been a challenge facing developers.

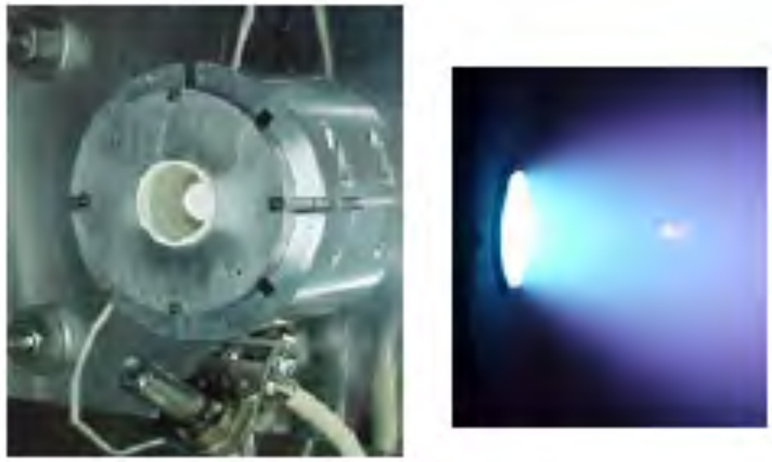


Figure 17: PPPL cylindrical Hall thruster (Mueller et al., 2008).

JPL is also producing a RF plasma discharge gridded ion thruster called the Miniature Xenon Ion Thruster (MiXI, shown in Figure 18). MiXI is capable of 1.5 mN thrust and 3200 sec Isp, uses 50 W of power and has a mass of 200 g. The plasma in RF discharge is formed by accelerating electrons in an oscillating electromagnetic field and causing ionization upon neutral particle bombardment. The ions are then accelerated out of the thruster via electrostatic potential grids, and thus a neutralizer is also required.

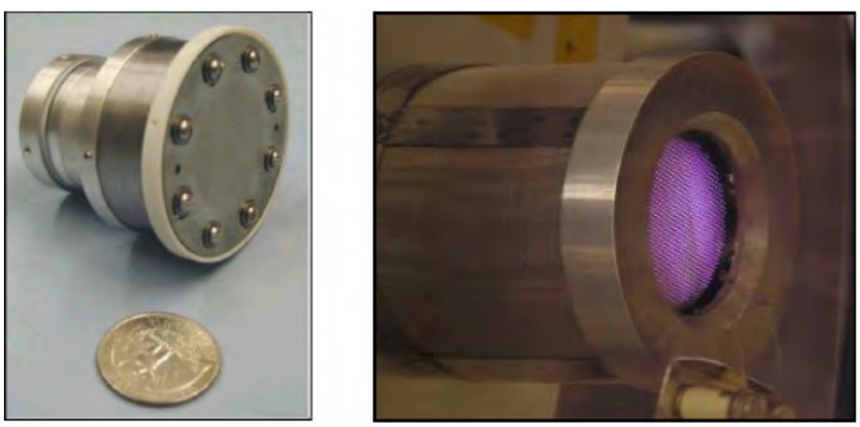


Figure 18: JPL Miniature Xenon Ion thruster (Mueller, et al., 2008).

Electrospray thrusters function by electrostatically accelerating charged liquid particles, usually from a volatile ionic liquid, and thus do not require any mechanism to form a plasma discharge. These are beneficial and much more efficient than miniature plasma thrusters. Busek Corporation has also developed an electrospray thruster (Figure 19) with specifications of 1 mN thrust and 400 –

1300 sec Isp, while consuming 8.5 x 8.5 x 6 cm and 10 W power. The electrospray thruster also requires a neutralizer to prevent spacecraft charging and spacecraft contamination.

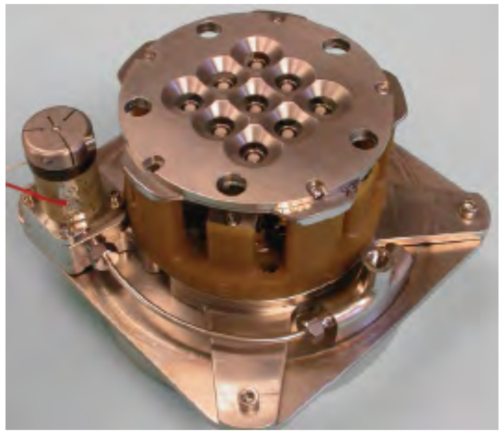


Figure 19: Busek PUC electrospray thruster.

Two new plasma thrusters being developed are the CubeSat Ambipolar Thruster (CAT, Figure 20) at University of Michigan and the mini Heated Helicon Thruster (mH2T) at Stanford University. Both thrusters form plasma with a radiofrequency discharge in an axial magnetic field specifically to develop a helicon wave within the plasma—this has been shown to efficiently produce high-density, low-pressure plasma. CAT then accelerates the plasma out of a magnetic nozzle via an ambipolar electric field. CAT is predicted to produce 1 mN thrust at 2000 sec Isp while consuming 10 W of power. mH2T further heats the electrons after ionization before accelerating the plasma similarly out of a magnetic nozzle. This is predicted to produce 1.5 mN thrust at 3000 sec Isp while consuming 50 W power.

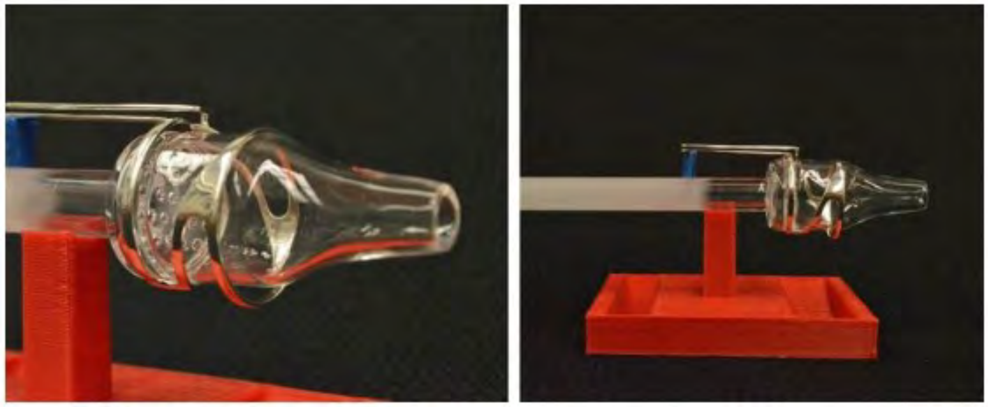


Figure 20: CubeSat Ambipolar Thruster (Longmier, 2013).

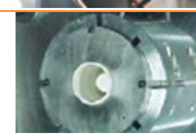
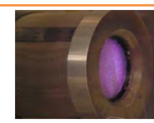
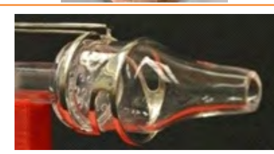
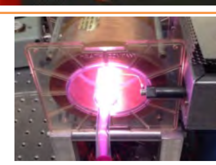
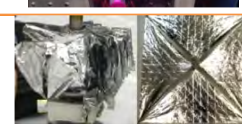
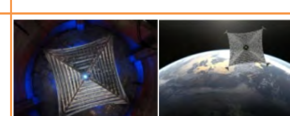
4.3.3 Solar Sails

Solar sails offer a propellant-less option for satellites by harnessing momentum of the solar flux with reflective sails. This is an attractive alternative that also complies with the CubeSat standard prohibiting the use of high pressure storage tanks. University of Surrey in the United Kingdom is developing a 3 kg solar sail CubeSat called CubeSail (Figure 21), with a sail surface area of 5 x 5 m.

Figure 21: Engineering and CAD models of CubeSail (Lappas, et al., 2011).

Table 9 shows a summary of the small satellite propulsion technologies listed above. Although this subsection has focused primarily on CubeSat technologies, similar technologies are being developed globally for 50-180 kg class small spacecraft. One such mission is NASA's Sunjammer solar sail. The 180 kg sail module is scheduled for launch in 2015. This mission builds on the NanoSail-D2 demonstration on a 3U CubeSat.

Table 9: List of small satellite propulsion technologies.

Technology Name	Description	Developer	TRL Status	Figures
MPACS	Pulsed plasma thruster flown on FalconSat-3	Busek Corp (USA)	**9** Flight tested	
Miniature hydrogen peroxide thruster	Green monopropellant thruster using hydrogen peroxide	ARCS (Austria)	**4** Component laboratory testing	
Hydros thruster	Oxygen and hydrogen bipropellant chemical thruster, propellant stored as water	Tethers Unlimited (USA)	**4** Component laboratory testing	
JPL hydrazine milli-newton thruster	Hydrazine monopropellant thruster	JPL (USA)	**3** Proof of concept, laboratory development	
Vacuum arc thruster	Pulsed plasma thruster that erodes its cathode via an arc to produce propellant	JPL (USA)	**4** Component laboratory testing	
Cylindrical hall thruster	Miniature Hall effect thruster using a cylindrical (instead of anular) geometry	Princeton (USA)	**4** Component laboratory testing	
Miniature xenon ion thruster	RF discharge gridded ion thruster	JPL (USA)	**3** Proof of concept, laboratory development	
PUC electrospray thruster	Electrostatically accelerates charged liquid particles from an ionic liquid	Busek Corp. (USA)	**5** Subsystem laboratory testing	
CAT	Thruster with a helicon plasma discharge accelerated out of a magnetic nozzle	University of Michigan (USA)	**3** Proof of concept, laboratory development	
mH2T	Thruster with a helicon plasma discharge with electron heating stage and magnetic nozzle	Stanford University (USA)	**2** Technology concept and application formulated	
CubeSail	25 square meter CubeSat solar sail	University of Surrey (UK)	**3** Proof of concept, laboratory development	
Sunjammer	1200 square meter Kapton solar sail module	NASA L'Garde (USA)	**5** Schedule for launch 2015	

4.4 Conclusion

Small spacecraft propulsion is a slightly primitive, but rapidly growing technology field. The SoA in this field consists of cold gas thrusters, solid rocket motors, and pulsed plasma thrusters. There are upcoming demonstrations in green monopropellant systems. The future of propulsion technology is diverse with both chemical and electric propulsion options on track to mature within the next five years. A summary of the performance of these technologies is detailed graphically below in Figure 22.

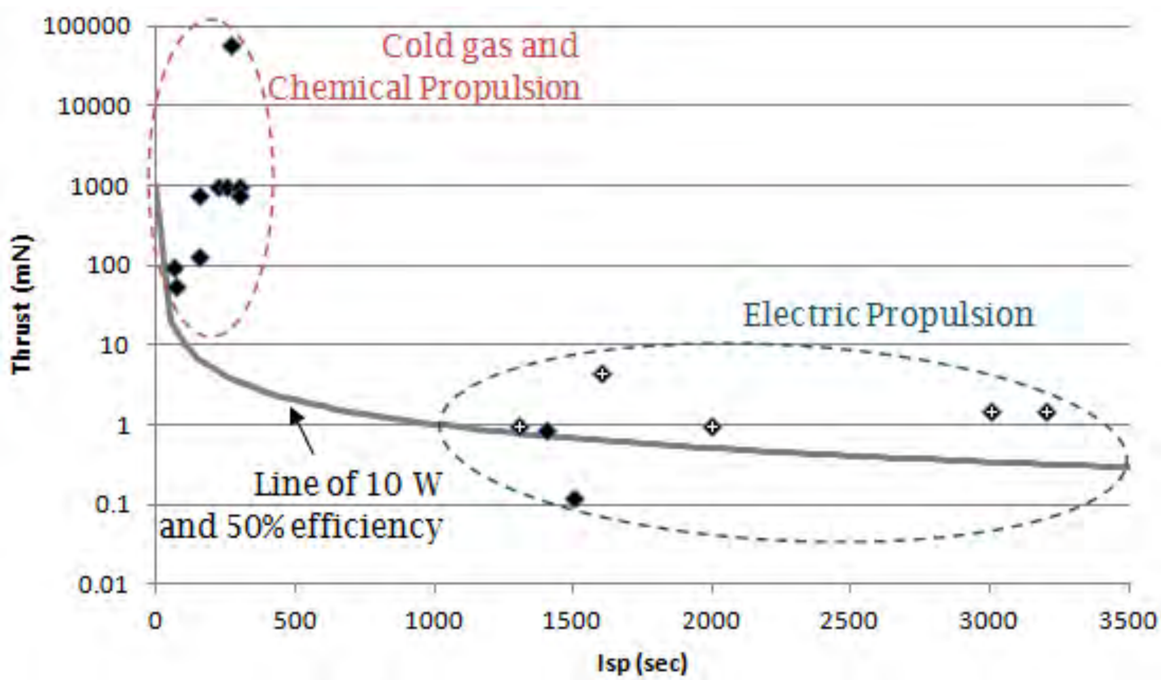


Figure 22: Plot detailing the spectrum of small satellite propulsion options.

4.5 References

B. W. Longmier: *PEPL Thrusters: CubeSat Ambipolar Thruster*. May 2013.

Busek Co, Inc.: *Busek Electrospray*. [Online], 2013. Available at: http://www.busek.com/technologies__espray.htm [Accessed August 2013].

CubeSat Design Specification (CDS). Revision 13, California Polytechnic State University, San Luis Obispo, CA, April 2013.

CubeSat Technology*: Current SoA and Future Needs*. Jet Propulsion Laboratory

Hruby, Vlad, Busek Corp.: *High Isp CubeSat Propulsion.* iCubeSat Conference at MIT, 2012.

Lappas, Vaios, et al.: *CubeSail: A low cost CubeSat based solar sail demonstration mission.* Advances in Space Research 48.11, 1890-1901, 2011.

Mueller, J. et al.: *A survey of micro-thrust propulsion options for microspacecraft and formation flying missions.* 5th Annual CubeSat Developers Workshop. San Luis Obispo, CA, 2008.

Mueller, J., Hofer, R. and Ziemer, J. *Survey of propulsion technologies applicable to CubeSats.* 2010.

Tethers Unlimited, Inc.: *Hydros, Powerful Propulsion and Precision Pointing for CubeSats.* [Online] 2013. Available at: http://www.tethers.com
http://pepl.engin.umich.edu/thrusters/CAT.html

Tajmar1, M. and Scharlemann, C. A. *Development of Electric and Chemical Microthrusters.* International Journal of Aerospace Engineering, Hindawi Publishing Corporation, Volume 2011, Article ID 361215, 1-10. 2011.

5. ATTITUDE DETERMINATION AND CONTROL SYSTEM

5.1 Introduction

The SoA of ADCS for small spacecraft relies on miniaturizing technology without significant degradation of performance. Despite the fact that ADCS algorithms used on small spacecraft are essentially the same as those flown on conventional spacecraft, small spacecraft are good platforms to test new algorithms and advanced software. Benefits of using small spacecraft include low cost and rapid development; research to decrease the development cost of ADCS software is addressed below.

5.2 State of the Art

5.2.1 Reaction Wheels

The performance of reaction wheels is described by maximum angular momentum, maximum output torque, electrical power, and the level of micro-vibrations produced by the wheels. Current research focuses on increasing angular momentum and maximum output torque, and decreasing electrical power and micro-vibrations. For CubeSats, which may not have sufficient volume to accommodate three independent wheels, integrated three-axis wheel systems are considered a SoA option[4].

Wheel performance, in terms of maximum angular momentum and output torque, is proportional to wheel volume (Larson & Wertz, 2004). One convenient way of describing the SoA of wheels is by mapping the ratio of maximum angular momentum to volume against the mass of the wheel, as depicted in Figure 23. The Figure gives an overview of the current SoA techniques by comparing a number of benchmark wheels presented in detail in Table 10.

[4] Traditionally CubeSats did not require precise attitude stability and micro-vibrations have not been considered problematic for these spacecraft, but recent CubeSat missions require more precise observations, and thus recent miniature wheel research focuses both on improved pointing, and on being able to deal with micro-vibrations.

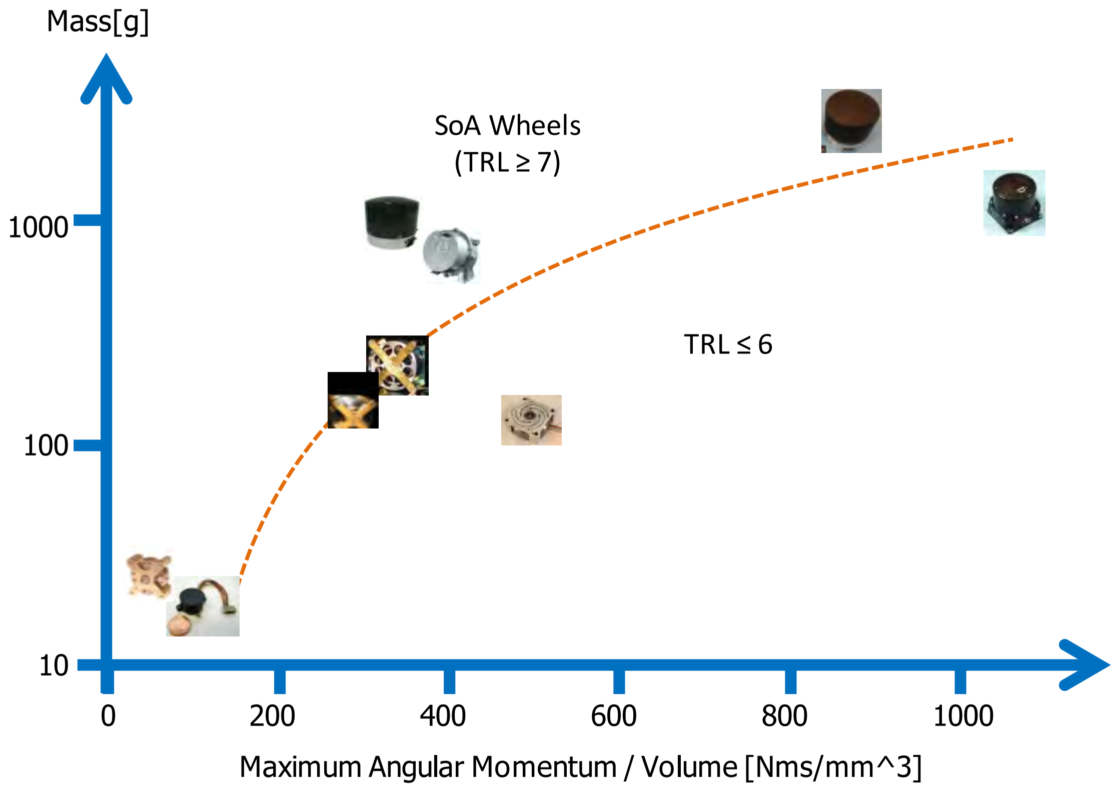
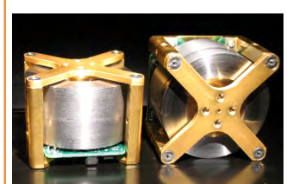
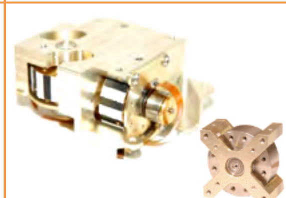


Figure 23: SoA for small spacecraft ADCS wheels. The performance of nine wheels, expressed through the ratio of maximum angular momentum to volume, is plotted against mass. The orange dashed line separates SoA technologies from those still under development. The data used to draw the graph is given in Table 10.

Table10: Examples of SoA wheel technology for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
100SP-O	SoA single axis wheel for minisatellite (Max AM = 1500 mNms, Max torque =110 mNm)	SSTL (UK)	**9** TechDemoSat-1 Kazakhstan	
10SP-M	SoA single axis wheel for microsatellite (Max AM = 420 mNms, Max torque =11 mNm)	SSTL (UK)	**9** UK-DMC-2, Deimos-1, NigeriaSat-2, & ExactView-1	
RW90	SoA single axis wheel for microsatellite (Max AM = 340 mNms, Max torque =15 mNm)	Astro- und Feinwerktechnik (Germany)	**8** BIRD, TET-1	
RW-0.03-4	SoA single axis wheel for nanosatellite (Max AM = 30 mNms, Max torque =2 mNm)	Sinclair Interplanetary	**8** UniBRITE BRITE-Austria	
MAI-200	SoA three axis integrated miniature wheel for cubesat (Max AM = 10.8 mNms, Max torque =0.63 mNm)	Maryland Aerospace	**7** QbX1, QbX2	
RW1	SoA single axis miniature wheel for cubesat (Max AM = 0.6 mNms, Max torque =0.02 mNm)	Astro- und Feinwerktechnik (Germany)	**7** BEESAT	

5.2.2 Magnetorquer

The purpose of magnetorquers is to develop a magnetic field that interfaces with Earth's magnetic field so that the counter-forces produced provide useful torque. Whereas large spacecraft usually do not rely on magnetorquers (their size would be prohibitive), magnetorquers for small spacecraft are built around two types of technology: air core coils and metal core coils (also known as 'torque rods'). The performance of metal core coil magnetorquers depends on the material used: materials with high magnetic permeability allow higher magnetic moment; mini- and micro satellites are adapted to having a redundant coil inside their magnetorquer in case of contingency. Table 11 gives an overview of some SoA technology for magnetorquers.

Table 11: Examples of the SoA of magnetorquer technology for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
Magnetorquer	The most popular magnetorquer for micro satellites to mini satellites (with/without redundancy)	ZARM (Germany)	**9** Numerous flight demonstrations	
Magnetorquer	The most popular magnetorquer for pico satellites to nano satellites (with/without redundancy)	ZARM (Germany)	**9** Numerous flight demonstrations	
Magnetorquer rod	Magnetorquer with redundancy	SSBV Aerospace & Technology Group (UK)	**9** Flight heritage on the BADR B, Fedsat and MicroLabSat	

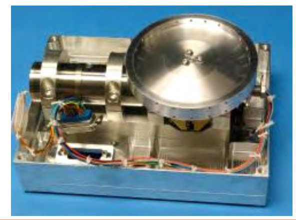
5.2.3 Other Actuators

For active, high-agility missions such as side-looking slew maneuvers in Earth observation, gamma ray burst observation, or observation of asteroid fly-by's, higher output torque actuators are required. In these cases, Control Moment Gyros (CMGs) are usually the technology of choice.

Technologies for passive attitude stabilization using the ambient space environment include aerodynamic wing technologies (taking advantage of atmospheric drag), gravity gradient stabilization, and permanent magnets for magnetic field aligned control.

These technologies are mostly used with active control actuators or rate dampers (see Table 12).

Table 12: Examples of the SoA of other actuators for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
CMG	CMG used in SSTL's satellites	SSTL (UK)	**8** Flown on BILSAT-1	
Aerodynamic wing	Pumpkin's Colony I CubeSat Bus	Pumpkin (USA)	**7** Flown on QbX	

5.2.4 Star Trackers

Currently, star trackers are the most important attitude sensor for small spacecraft. The performance of star trackers is measured by accuracy, data output rate, first tracking time, and maximum allowable slew rate (attitude maneuver rate). The accuracy of a star tracker is proportional to the size of its field of view. Figure 24 maps the in-plane accuracy of a number of benchmark star trackers against their mass and power requirements. A subset of the data used is given in Table 13.

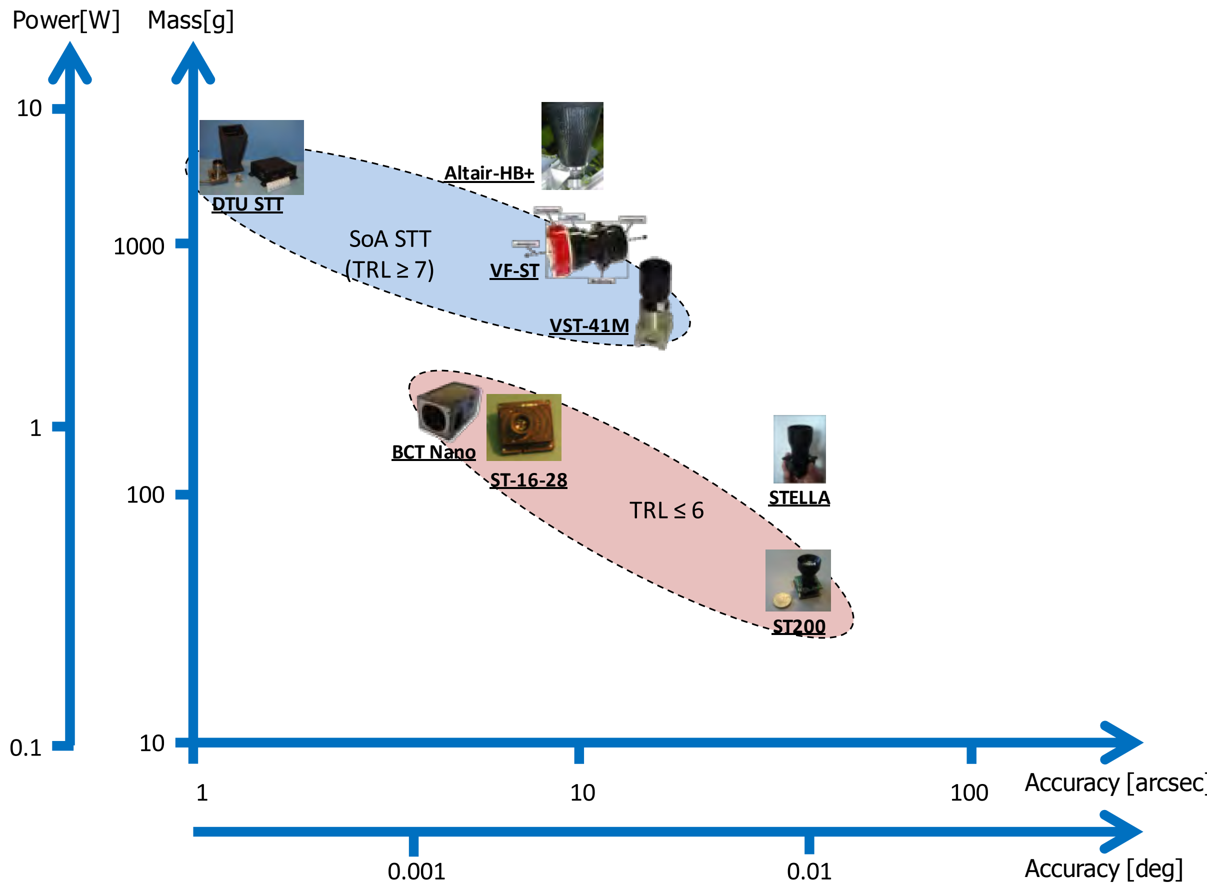


Figure 24: SoA of small spacecraft star trackers. The performance of eight star trackers, expressed through the accuracy achievable, is plotted against mass and power requirements. The blue surface highlights the SoA technology at TRL higher than 7, and the red surface highlights technology at TRL lower or equal to 6. A subset of the data used to draw the graph is given in Table 13.

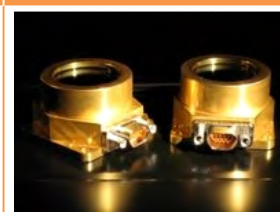
Table 13: Examples of SoA star trackers for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
μASC (Micro Advanced Stellar Compass)	World's highest accuracy star tracker for mini satellites (accuracy=1 arcsec)	Technical University of Denmark (DTU)	**9** Proba series, Myriade series	
VST-41M	Miniature star tracker for micro satellites (accuracy=18 arcsec)	VECTRONIC Aerospace (Germany)	**9** TUBSAT series, SDS series	

5.2.5 Sun Sensors

There are two types of Sun sensors for small spacecraft: fine- or medium-precision Sun sensors and coarse Sun sensors. Traditionally, fine-precision Sun sensors have combined two orthogonally arranged solar cells with narrow slits over the cells, and measured the analog current from the cells to detect the direction of the Sun. More recently, fine-precision sensors use two line array sensors or an area sensor to obtain a digital value for the Sun's direction. Coarse Sun sensors basically consist of a solar cell or a photo diode. Currently the most advanced Sun sensor technology for small spacecraft is the SS-411 from Sinclair Interplanetary, as shown in Table 14.

Table 14: Examples of SoA fine-precision Sun sensors.

Technology Name	Description	Developer	TRL Status	Figures
SS-411 Digital Sun Sensor	World's best seller micro DSS (accuracy=0.1°)	Sinclair Interplanetary (Canada)	**9**	
µDSS	2-D APS (Active Pixel Sensor) detector array DSS (accuracy=0.1°)	TNO (Netherlands)	**7** PROBA-2, Delfi-n3Xt(2013)	

5.2.6 Earth Sensors

Most recent miniature Earth sensors use thermopile sensors or photodiodes to locate the curve of the Earth without the use of scanning mechanisms. Since the temperature of the Earth's contour differs significantly between polar regions and the equator, a set of thermopile arrays measures both the temperature of the limb of the Earth and space, and a CPU calculates the difference to determine the displacement from nadir. The process is illustrated in Figure 25, with an example of current TRL in Table 15.

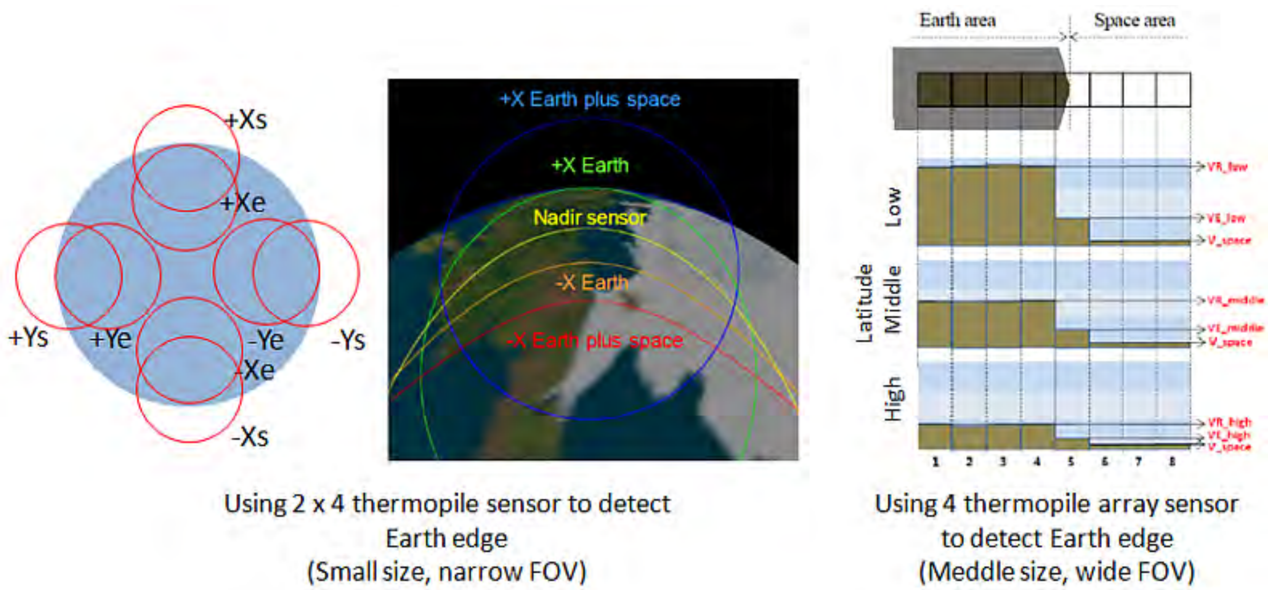
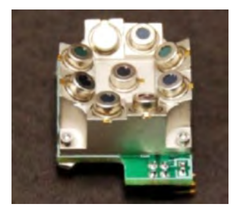


Figure 25: The use of thermopiles to detect the limb of the Earth has enabled Earth sensors to be miniaturized.

Table 15: An Example of a SoA Earth sensor for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
Earth nadir sensor	SoA miniature European Space Agency for cubesat	Aerospace (USA)	7 PSSCT-2	

5.2.7 Angular Rate Sensors

Gyroscopes can be ranked as follows, in decreasing order of precision and system resource requirements: mechanical and ring laser gyroscopes, fiber optical gyroscopes, and MEMS vibrating structure gyroscopes. Microsatellites tend to use fiber optical gyroscopes, while nano- and picosatellites generally use MEMS-based gyroscopes. The precision of gyroscopes is measured by bias instability and angle random walk. Figure 26 shows an overview of the SoA gyroscopic technology available to small spacecraft by mapping system resource requirements against precision. Note that the values for power and mass need to be multiplied by three if the angular rate is required to be measured along the three axes of the spacecraft. Some of the raw data used in Figure 26 is specified in Table 16.

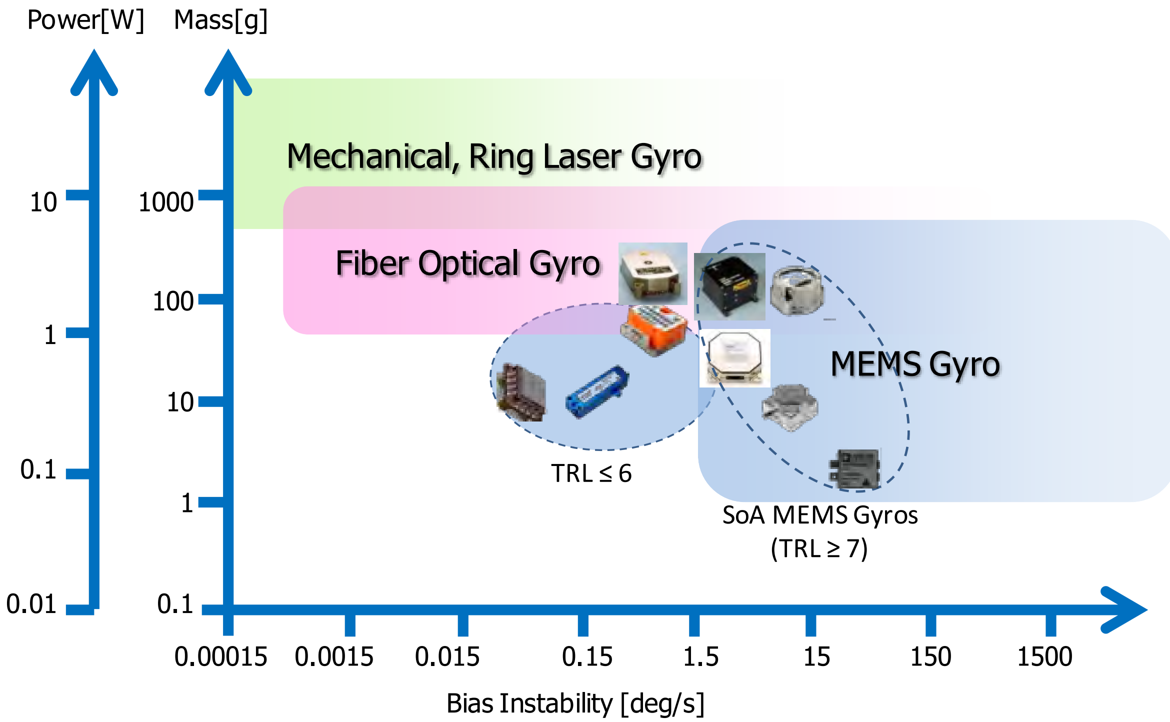
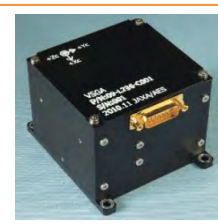


Figure 26: SoA of gyroscopic technology for small spacecraft. System resource requirements are mapped against precision.

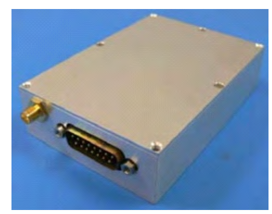
Table 16: Examples of SoA gyroscopes for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
μFORCE-1	Single axis fiber optical gyro for mini satellites (BI=1deg/h)	Northrop Grumman LITEF GmbH (USA/ Germany)	**9**	
VSGA	3-axis MEMS gyro using CRS09 for mincrosatellites (BI=3deg/h)	AES (Japan)	**7** Flown on SDS-4	
ADIS16405BLM	Triaxial inertial sensor with magnetometer for nano and pico satellites (BI=25.2deg/h)	Analog Devices (USA)	**8**	

5.2.8 GPS Receivers and Antennas

GPS receivers are used not only for orbit control but also for ADCS purposes, in particular to determine of the direction of a ground target. The best way to make GPS receivers smaller is to develop high-end Application Specific Integrated Circuits (ASIC). Examples of these current technologies are listed in Table 17. In order to use COTS GPS receivers in space, the Doppler frequency range and the ionospheric delay correction must be modified accordingly. To do so, developers must have access to the firmware of the receiver.

Table 17: Example SoA GPS receivers for small spacecraft.

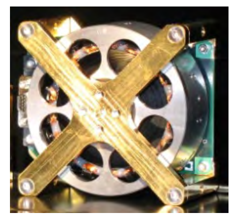
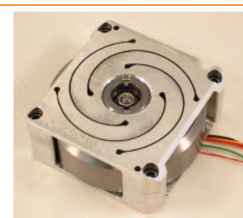
Technology Name	Description	Developer	TRL Status	Figures
SGR-10	Higher-end GPS receiver (L1, 2 antennas,24ch, 10m)	SSTL (UK)	**9** Flown on NigeriaSat-2	
GPS-12-V1	GPS receiver (L1, 1 antenna,12ch, 10m)	SpaceQuest (USA)	**9** Flown on AprizeSat-1,-2	
SGR-05P	Miniature GPS receiver (L1, 1 antenna,12ch, 10m)	SSTL (UK)	**8** Flown on UKDMC	
Phoenix-S	Miniature and higher performance GPSR with Kalman filter inside (L1,1antenna,12ch, 10m)	DLR (Germany)	**9** Flown onPROBA-2, X-Sat, PRISMA, FLP, & ARGO	
OEM4-G2L	Dual frequency GPSR (L1/L2,1antenna,12+12ch, 1.5m)	NOVATEL (Canada)	**7** Flown on CanX-2 & CASSIOPE	

5.3 On the Horizon

5.3.1 Reaction Wheels

Table 18 presents a number of wheel technologies currently under development.

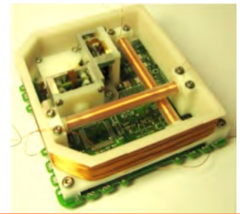
Table 18: On the horizon technologies for small spacecraft wheels.

Technology Name	Description	Developer	TRL Status	Figures
Type SSS	Single axis wheel for microsatellite (Max AM=400mNms, Max AM/V = 1102 Nms/m^3)	Mitubishi Precision (Japan)	**6** Not flown yet	
RW-0.060	Single axis wheel for nanosatellite (Max AM=60mNms, Max AM/V = 324 Nms/m^3)	Sinclair Interplanetary (Canada)	**6** Not flown yet	
Micro reaction wheel	Single axis miniature wheel for cubesat (Max AM=18mNms, Max AM/V = 541 Nms/m^3)	Blue Canyon Technologies (USA)	**6** Not flown yet	

5.3.2 Magnetorquer

Three-axis integrated magnetorquer systems for nano- and picosatellites are in development, as shown in Table 19.

Table 19: Examples of future magnetorquer technology for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
TU Delft μMTQ Sytem	Three axis integrated magnetorquer system	Delft University (Netherlands)	**5** DELFI-N3XT	
ISIS Magnetorquer	The ISIS MagneTorQuer (iMTQ) is a PCB based 3-axis magnetorquer system	ISIS (Netherlands)	**5** Not flown yet	

5.3.3 Other Actuators

Research focuses on CMGs and aerodynamic wings for CubeSats. For missions beyond-GEO and near-Earth environment, magnetorquers such as thrusters and electrochromic vanes for solar pressure control cannot be used. However, all are promising technologies as shown in Table 20.

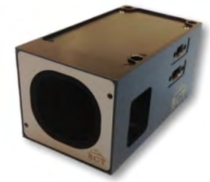
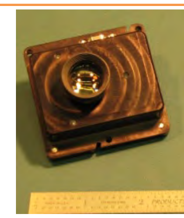
Table 20: Examples of future technologies for other actuators for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
CMG	CMG for microsatellite	Tamagawa Seiki (Japan)	**6** Demonstrated on TSUBAME	
Electrochromic vanes for solar pressure control	Electrochromic vanes for solar pressure control	JPL (USA)	**4**	

5.3.4 Star Trackers

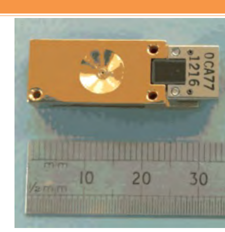
Areas of research include fast and effective star identification algorithms, and low-reflection small (or deployable) baffles, as shown in Table 21.

Table 21: On the horizon technologies of star trackers for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
BCT Nano Tracker	CubeSat compatible star tracker with digital interface drive electronics (accuracy=6 arcsec)	Blue Canyon Technologies (BCT) (USA)	**6** To be flown on JPL's INSPIRE 3U CubeSat, planned for launch 2014-2016	
ST-16 Star Tracker	Miniature star tracker (accuracy=7 arcsec)	Sinclair Interplanetary (Canada)	**6** 17 Flight units delivered. First launch Q4 2013	
Star Tracker ST-200	The ST-200 is one of the world's smallest autonomous star trackers for CubeSats and other nano satellite missions (accuracy=30 arcsec)	Berlin Space Technologies (BST) (Germany)	**5** Not flown yet	
Star Tracker ST-100	The ST-100 is a low-cost star tracker for micro and nano satellites which allows tracking of magnitude 6 stars with an update rate of 5Hz (accuracy=30 arcsec)	Berlin Space Technologies (BST) (Germany)	**6** Flying on LAPAN-A2 and LAPAN-ORARI microsatellites, launching mid-2013	

5.3.5 Sun Sensors

Research is ongoing as can be noted from Table 22.

Technology Name	Description	Developer	TRL Status	Figures
Miniature CubeSat Sun Sensor	Fine sun sensor for cubesats	SSBV Aerospace & Technology Group (Netherlands/ UK)	**6** To be flown on Ukube-1 and TechDemoSat-1 (a.k.a. TDS-1), both of which are launching in Sep. 2013	

5.3.6 Earth Sensors

Table 23 shows an example of an Earth sensor for small spacecraft currently under development.

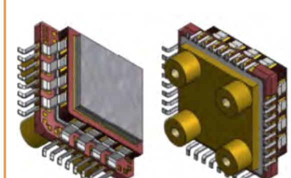
Table 23: Example of an Earth sensor for small spacecraft under development.

Technology Name	Description	Developer	TRL Status	Figures
MESA	Wide FOV ESA for nanosatellite	Meisei Electric (Japan)	**6** Not flown yet (planned in 2013 on SOCRATES)	

5.3.7 Angular Rate Sensors

Recent R&D has enabled MEMS gyros to be on par with fiber optic solutions in terms of precision. As shown in Table 24, a number of microsatellites have already adopted MEMS gyros. MEMS gyros are small, lightweight, low power, and fit the needs of small spacecraft.

Table 24: Examples of gyroscopes under development for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
STIM300	3-axis MEMS gyro (BI=0.5°/h)	Sensonor (Norway)	**5** Not flown yet	
CRS39	Single axis MEMS gyro (BI=0.2°/h)	Silicon sensing (UK)	**5** Not flown yet	
SAR500	Single axis MEMS gyro (BI=0.02°/h)	Sensonor (Norway)	**5** Not flown yet	

5.3.8 GPS Receivers

Current research areas that look to be advantageous are: multi-antenna inputs, multi-Global Navigation Spacecraft Systems (GNSS) decoders, L1/L2 dual-frequencies, internal Kalman filtering (only very few GPS receivers for small spacecraft currently have an internal Kalman filter), GPS constellation spacecraft initial acquisition & search algorithms, precise positioning using carrier-wave phase information, and open source software GPS receivers. An example of this is the FOTON subsystem under development by University of Texas, Austin (as shown in Table 25).

Table 25: Example of a GPS receiver under development for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
FOTON	Dual frequency, open source GPSR with Kalman filter inside (L1/L2,2 antennas,12+12ch, 1.5m)	University of Texas Austin (USA)	**6**	

Table 25A: ADCS accuracies achievable for mini-, micro-, nano- and picosatellites. The overall accuracy is the root mean squared value of the three preceding values.

	Attitude Determination	Ground Target Position	Attitude Control	Overall Accuracy
Mini/Microsatellites	~0.1	~0.8	~1.8	~2
Nano/Picosatellites	~0.01	~0.01	~0.04	~0.1

5.3.9 Reaction Control System Thrusters

No small spacecraft in LEO have used RCS thrusters in past missions. Currently, there are only limited efforts going in this direction. An example of a current project is the STRaND-2 mission by SSTL developing a cold gas thruster based RCS for nanosatellite rendezvous and docking. A large number of thrusters have been developed for small spacecraft but all of these systems have been built for the purpose of orbit correction and not for attitude control. The reasons for this lack of development are the limitations in size, mass and power of small spacecraft. In LEO, magnetorquers are typically used to unload angular momentum and no RCS thrusters are necessary.

The situation changes for interplanetary missions beyond Earth orbit. Magnetorquers cannot be used any more since Earth's magnetic field is not available to provide the torque. There is a need to develop RCS thrusters for interplanetary missions. Cold gas thrusters are the most likely candidate technology since chemical thrusters are too complex to mount on small platforms. Electric thrusters are not a likely option either since the net thrust force of such systems is not sufficient for RCS purposes. Electric systems also require significant power that is usually not available for typical small spacecraft.

5.4 Conclusion

Pointing accuracy depends on attitude determination error, ground target error, and attitude control error. Errors can furthermore be categorized into random errors, bias (offset) errors, and transitional errors. Figure 27 gives an overview of the SoA of pointing accuracy technology for small spacecraft. Most mini- and microsatellites are Earth orbiting spacecraft and the attitude control requirement is typically 0.1° (see Table 26).

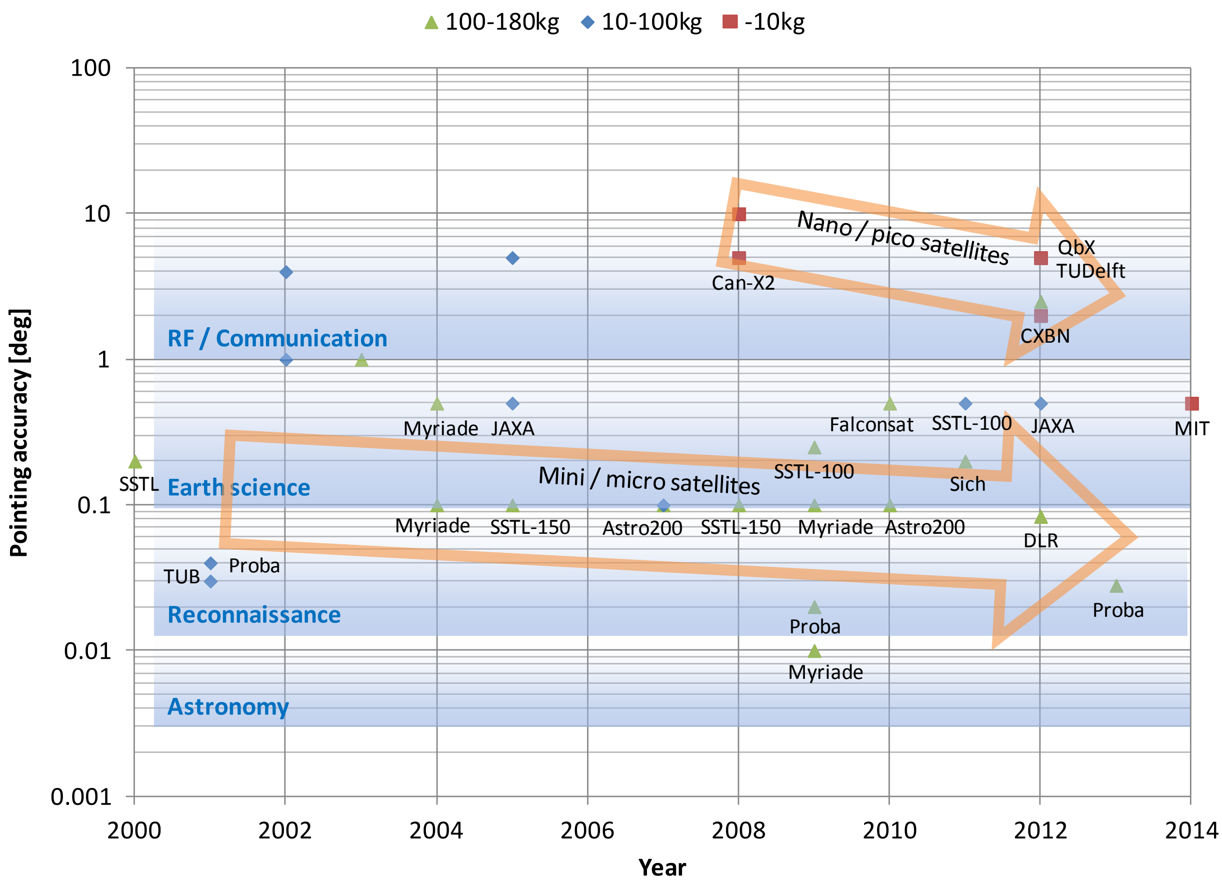


Figure 27: Pointing accuracy of spacecraft below 180 kg as a function of time. The two arrows depict the trend through the last decade for mini/microsatellites and nano/picosatellites. The SoA is 0.1° for mini/micro and 2° for nano/pico, respectively. The requirement for typical small spacecraft EO missions is on the order of 0.1°. Higher accuracy below 0.1° can be achieved using a mission related sensor (i.e., a payload instrument) in the attitude control loop. CubeSats are part of the nano- and picosat category. Their pointing accuracy has improved rapidly thanks to miniaturized ADCS components. The data used to plot the graph is shown in Table 26.

Table 26: Examples of the SoAs for small spacecraft with improved pointing accuracy

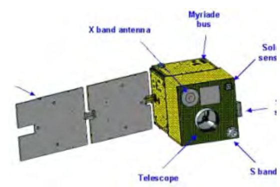
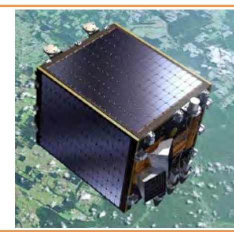
Technology Name	Description	Developer	TRL Status	Figures
SSTL150 bus	ADCS system level SoA for 150-180 kg satellites (Pointing accuracy = 0.1°)	SSTL (UK)	**9** Flown on Beijing-1 & RapidEye	
Astro200 bus	ADCS system level SoA for 150-180 kg satellites (Pointing accuracy = 0.1°)	Comtech AeroAstro (USA)	**9** Flown on STPSat-1 & STPSat-2	
Myriade bus (Astrosat-100)	ADCS system level SoA for 150-180 kg satellites (Pointing accuracy = 0.1°)	CNES / Astrium (France)	**9** Flown on Parasol, Demeter & Picard	
Proba bus	ADCS system level SoA for 100-150 kg satellites (pointing accuracy = 0.02°)	ESA / QinetiQ (UK)	**9** Flown on PROBA-2 & PROBA-V	
SSTL100 bus	ADCS system level SoA for 50-100 kg satellites (pointing accuracy = 0.5°)	SSTL (UK)	**9** Flown on Alsat & NigeriaSat-X	
SDS bus	ADCS system level SoA for 10-50 kg satellites (pointing accuracy = 0.5°)	JAXA (Japan)	**8** Flown on SDS-4	
Cubesat bus	ADCS system level SoA for less than 10kg satellites (pointing accuracy = 2.0°)	Morehead State University (USA)	**7** Flown on CXBN	

Table 27 shows design approaches for achieving higher pointing accuracy. Most of the current research in ADCS can be related to the steps denoted. The SoA design level for nano- and picosatellites deals mostly with Steps 1 to 3 and is highlighted in italics. The development of miniature star trackers and miniature wheels is especially important. For micro- and minisatellites, the design level can go up to Step 14. End-to-end in-orbit calibrations and systematic micro-vibration management are an area of importance here.

Table 27: Design strategies and approaches in order to achieve higher pointing accuracy for small spacecraft. The steps highlighted in italics show the current SoA for nano- and picosatellites (including CubeSats). The ADCS of mini- and microsatellites can be refined to include all the design steps presented.

Basic	1. *Apply 3-axis control architecture.* 2. *Use high accuracy sensors like star trackers.* 3. *Apply filtering (e.g. Kalman filter) to eliminate random errors and to estimate bias errors in the attitude determination software.* 4. Apply transitional error calibration e.g., temperature compensation. 5. Use a mission related sensor (a payload instrument) in the control loop for end-to-end feedback. 6. Conduct an alignment test on ground to calibrate misalignments between ADCS and mission related sensors. 7. Apply 3-axis zero momentum control architecture.
Advanced	8. Use low micro-vibration wheels, and apply dumping materials to the structure. 9. Design structure and components layout for higher moment of inertia for the same size and mass. 10. Use actuators with a better input frequency response. 11. Use higher performance onboard computer to increase control frequency. 12. Flexible structure analysis and design. 13. Apply in-orbit calibration and parameter modification in the attitude control software. 14. Apply highly autonomous fault detection, isolation and reconfiguration software for operational safety.

There are two main ways to address ADCS software development: model-based development and open-architecture development.

In the case of model-based development the ADCS flight software uses an overarching model from conceptual design to system level test. At conceptual design level, the Matlab and Simulink tools are usually used to model the ADCS. The same model, with partial refinements, is then used in the preliminary and critical design phases (where C++ flight code can be generated from Matlab). Even during final ADCS flight software testing, the model is used to simulate attitude dynamics and to create test cases. Some merits of applying model-based development are overall consistency between design phases, cost savings achieved with a decrease in labor, and rapid development cycles. Proba-V (ESA), Myriade (CNES, EADS) and LADEE (NASA ARC) ADCS are examples of current software development projects using model-based development.

Open-architecture development relies on a different philosophy to address ADCS software development. This environment enables multi-national and multi-institutional projects: anybody can join and contribute to the development of ADCS software modules. The development of proprietary code is avoided. This is often the option of choice for ADCS software developed in an academic setting. The SoA for small spacecraft ADCS subsystems is based on miniaturizing existing technology without performance degradation. Miniaturizations are achieved for many technologies. Examples include:

- new imaging devices such as the high resolution CMOS image sensor for star trackers, and thermopile sensor for Earth sensors;
- new materials to increase the moment of inertia of wheels, and new materials to decrease reflections inside the baffle of star trackers;
- new configurations to miniaturize fine-precision Sun sensors, and Earth sensors;
- new algorithms to increase the accuracy of GPS receivers, and star trackers; and
- new peripheral circuits to increase the accuracy of MEMS gyros.

5.5 References

Arnold, S., et. al.: *QbX - The CubeSat Experiment.* SSC12-XI-4.

Kyohei A., et. al.: *High-Speed Attitude Control System for Small Spacecraft with Micro-CMGs.* 27th International Symposium on Space Technology and Science (ISTS), Tsukuba, July 5-10, 2009-d-23, 2009.

Lappas, V., et. al.: *Micro CMGs for Agile Small Spacecraft: Design and In-Orbit Tests.* Proceedings of the 6th International ESA Conference on Guidance, Navigation and Control Systems. Loutraki, Greece, Oct. 17-20, 2005.

Larson, W. J., Wertz, J. R.: *Space Mission Analysis and Design.* Microcosm Press, 3rd ed. El Segundo, CA, 2004.

6. STRUCTURES, MATERIALS AND MECHANISMS

6.1 Introduction

The structure is what holds the different components of the spacecraft together and provides the necessary interfaces for each subsystem. The selection of the structure depends on the accommodation of the payload devices and circuitry, material properties, stability, and protection reliability. The structure should dually minimize the complexity of the design and minimize the cost. In addition, it must support significant loads encountered during launch while still providing an easily accessible power and data bus.

Different materials can be used for the construction of the main frame, providing desirable protection against radiation as well as taking into account the temperature gradients and the vacuum conditions in space. Mechanisms and actuators are a key component to guarantee the functionality of various subsystems (a prominent example is power and the related deployment of solar panels).

6.2 State of the Art

6.2.1 Structures

Structures have to meet various needs such as stiffness, stability, low mass, low price, ease of manufacture, and ability to support deployable mechanisms. The primary frame can be machined out of a single block of material, or it can be assembled from separate parts. There is no consensus on the typical structure mass for small spacecraft as many different configurations were represented. The assembly techniques differ greatly, however, and use screws to fasten separate pieces together still seems to be the most common technique. Computer Numerical Controller (CNC) techniques are very efficient since they minimize material losses and internal stresses during fabrication. Spacecraft developers can purchase prefabricated structures or make their own custom designs.

SSTL, Pumpkin, and Incorporated and Innovative Solutions in Space (ISIS) are the most popular commercial vendors of CubeSat structures. Pumpkin's designs range from 0.5 to 3 U and are based on precision sheet-metal fabrication. They are made of 5052-H32 aluminum sheet metal that is hard anodized and alodined in order to comply with CubeSat guidelines. An advanced version is fabricated from 7075-T6 billet aluminum and is one of the lightest and strongest structures available due to the ability to resist both compression and twist forces.

The CubeSat frame was proposed in 1999 at CalPoly and Stanford University. The typical dimensions for a 1U unit are shown in Figure 28 (CalPoly, 2013).

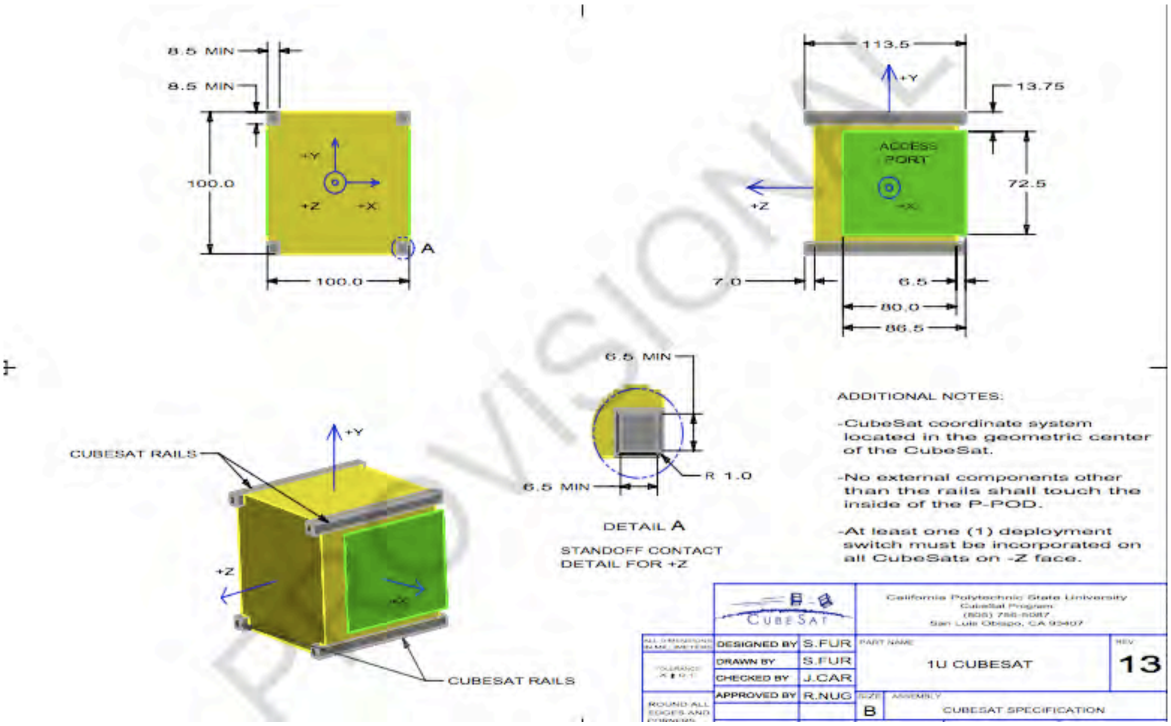


Figure 28: CubeSat specifications (CalPoly, 2013).

ISIS CubeSat structures comply with CubeSat standards. Avionics and payload modules are mounted onto the primary load-carrying components. The package includes the following components:

Primary Structure:

- 2x side frames, black hard anodised
- Ribs, blank alodined
- 2x kill-switch mechanisms
- Supplied with inserted phosphor bronze helicoils
- Fasteners

Secondary Structure:

- 6x aluminum shear panels, blank alodined
- M3 threaded rods, M3 hex nuts, M3 bus spacers
- Boards are supported using M3 washers

6.2.2 Custom Designs

Several institutions and universities have created their own spacecraft designs (NASA 3U designs). SwissCube, launched in 2009, was a project undertaken in Switzerland that machined an entire block of aluminum by adapting the wire electrical discharge machining (EDM) method. This technique consists of a fast series of single electrical discharges that make precision shapes without exceeding cutting tool pressure. As a result, SwissCube had a structure of just 95 g of mass, one of the lightest frames ever produced.

6.2.3 Materials

Materials have to be lightweight and conduct electricity, since radiation can induce potential charge accumulation in the satellite electronics. Various conductive lightweight metals are the most commonly used materials for small spacecraft structures.

The California Polytechnic State University, San Luis Obispo (CalPoly) writes a yearly report with updated basic standards for CubeSat design and integration. In their latest release (CalPoly, 2009), they establish general rules governing materials:

- No hazardous material shall be used in a CubeSat.
- All CubeSats should comply with the following requirements regarding outgassing:
    - Total mass loss shall be less than 0.1%.
    - Collected Volatile Condensable Material shall be less than 0.1%.

6.2.3.1 Aluminum

Aluminum is the most common material of choice in most recent small satellite missions. Aluminum offers reliability and lightweight support at low cost. It is thermally and electrically conductive, chemically resistant and non-sparking. In terms of strength, aluminum is equal to that of other metals if reinforced at low temperatures (University of Texas, 2003). Table 28 and

Table 29 show the characteristics of a few examples of different aluminum alloys used in previous satellite missions.

Table 28: Aluminum structures used in recent missions.

Mission	Materials	Launch Date
EST-1	Aluminum AW 6061-T6 and AW 7075	2013
PROBA V	Aluminum (AA2024-T3) and Aluminum (AA7075-T7351	2013
e-St@r	Aluminun 5005 H16	2012
Techedsat	Aluminum 6061	2012
Hermes	Aluminum 7075-T73	2011

Table 29: Properties of aluminum types.

Aluminum Type	Density (g/cm^3)	Modulus of Elasticity (Gpa)	Fatigue Strength (MPa)	Ultimate Tensile Strength (MPa)	Thermal Conductivity (W/m·K)	Electrical Resistance (ohms·cm)
2024-T3	2.78	73.1	138	483	121	5.82E-06
7075-T73xx	2.81	72	150	505	155	4.30E-06
5005 H16	2.7	69	N/A	180	205	N/A
6061	2.7	68.9	62.1	124	180	3.66E-06

6.2.3.2 *Other Metals*

Titanium has several positive traits, such as resistance to corrosion, a low thermal expansion coefficient, and high durability. However, it is very difficult to machine and is about 60% heavier than aluminum.

Steel offers a very low stiffness to density ratio and a large range of strength and ductility. It is also extremely heavy, even more than titanium.

Beryllium has appeared as a viable option due to its high stiffness to weight ratio and high thermal conductivity. It is lighter than aluminum but much more brittle, which in turn makes it very expensive and time-consuming to machine. In addition, particles are toxic, driving manufacturing costs even higher.

6.2.3.3 Composites

Composite materials are made of two or more materials with different physical and chemical properties. The main advantage of composites is that they can be designed for the necessities of the mission. Composites are usually made from a matrix material and a reinforcement material. The material used for the matrix is usually a cured resin, and it supports the reinforcement materials—usually carbon fiber. Cyanate resin exhibits very convenient performance characteristics for space applications due to low moisture absorption, low microcracking and low outgassing (Ozaki, 2008). Composites are anisotropic; hence the properties are beneficially different in each part of the material, depending on the direction of the loads. However one potential problem is that shock forces can separate the laminates between layers. Due to various potential outcomes, manufacturing is expensive and time consuming.

Small spacecraft manufacturers are employing composite structures with more frequency. For example, SSTL is developing a series of low-cost, multifunctional, high-performance, lightweight composite structures of TRL 6 or more. They are made from a cyanate-ester and epoxy based polymer resin with various fiber reinforcements (see Figure 29). Another example is the NASA ARC Common Bus that has been used for the recent LADEE mission.

Figure 29: SSTL Composite Structure.

6.2.3.4 Additive Manufacturing Materials

Additive manufacturing is a layer-by-layer process that uses CAD data to create a 3D object. Current capabilities using additive manufacturing are:

- High strength build materials of nylon/carbon fiber or titanium
- Fully fused construction, which allows for high pressure vessels
- Internal cavities

Additive manufacturing does have certain limitations:

- Inadequate material strengths
- Porous construction, which can lead to outgassing
- Non-functional parts/used for fit checks

Additive manufacturing is recently being used for prototype-building due to flexibility in 3D printing technology. Figure 30 shows a list of some of the most common materials used in additive manufacturing of small spacecraft components.

Metallic materials	Polymeric materials	Ceramic materials	Organic materials
Tool Steel	ABS	Alumina	Waxes
Aluminium	Polyamide (nylon)	Mullite	Tissue / cells
Titanium	Filled PA	Zirconia	
Inconel	PEEK	Silicon Carbide	
Cobalt Chrome	Thermosetting epoxies	Beta-Tri calcium Phosphate	
Copper	Ceramic (nano) loaded epoxies		
Stainless steel	PMMA	Silica (sand)	
Gold / platinum	Polycarbonate	Plaster	
Hastelloy	Polyphenylsulfone	Graphite	
	ULTEM		
	Aluminium loaded polyamide		

Figure 30: List of materials for additive manufacturing (SINTech, 2013).

6.2.3.5 Windform Materials

CRP Technology, an Italian-based group, is specialized in Laser Sintering (LS) technology and is well known for their additive manufacturing materials line called Windform XT. Windform XT is a carbon fiber-reinforced composite material, of which the properties are shown in

Table 30 and a visual representation can be seen in Figure 31.

Table 30: Properties of Windform XT 2.0.

Material	Density (g/cm^3)	Elongation at Break	Tensile Modulus (MPa)	Tensile Strength (MPa)	Melting Point (°C)
Windform	1.097	3.80%	8928.2	83.84	179.3

Applications of Windform:

- In October 2011, CRP Technology successfully completed construction of a CubeSat built with rapid prototyping and using Windform XT (see Figure 31).

Figure 31: Satellite skeleton prototyped using Windform material (CRP Technology).

- A 1U CubeSat called PrintSat was 3D printed by the Montana State University Space Science and Engineering Laboratory. Once in orbit, PrintSat will measure and report on the characteristics of Windform XT2.0. The goal is to validate the usefulness of additive manufacturing for satellite structures and mechanisms. It will be launched in 2014.
- RApidprototyped MEMS Propulsion and Radiation Test (RAMPART) is a tech demo satellite which will demonstrate the use of rapid prototyping using Windform XT materials to design, build and fly CubeSats (see Figure 32). 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.

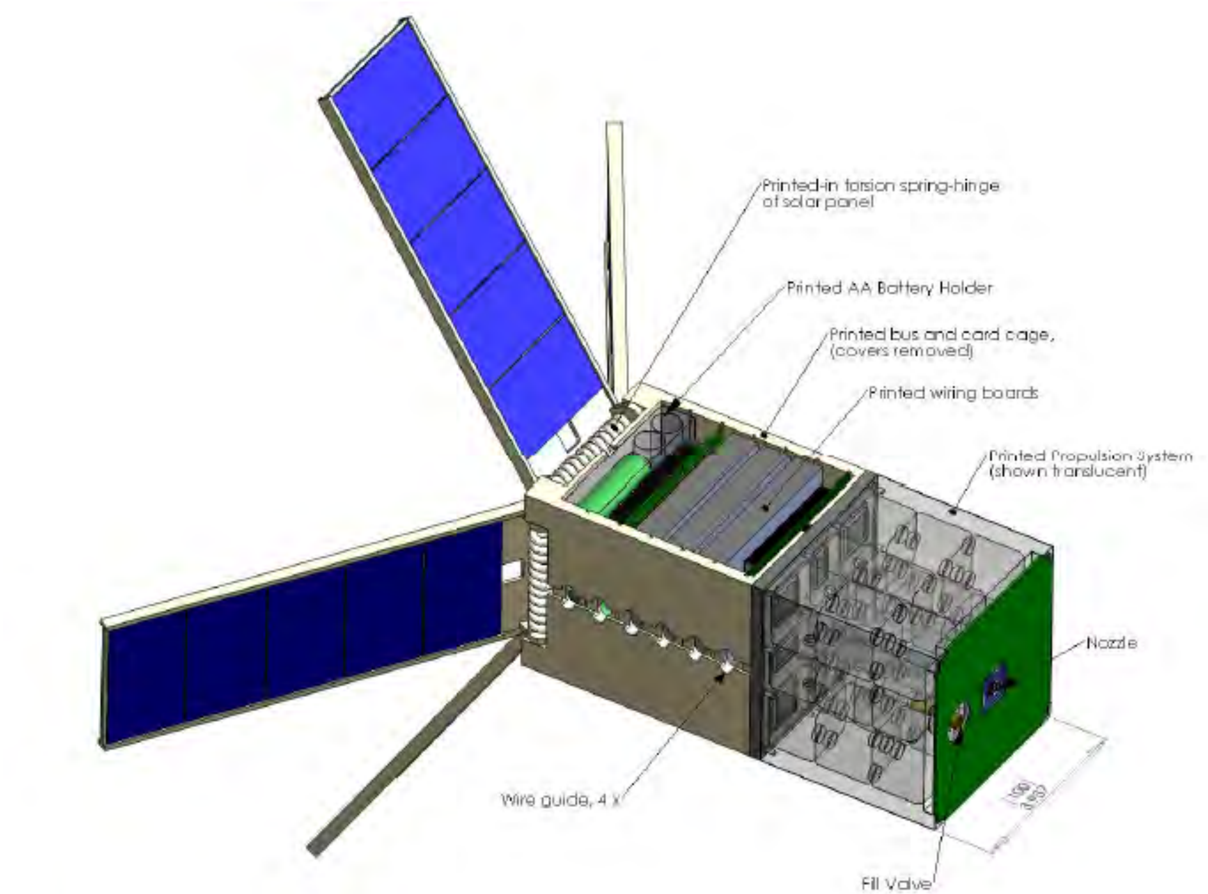


Figure 32: RAMPART satellite (Calpoly, 2010).

- Experimental Propulsion Lab's Additively Manufactured Propulsion System (AMPS) is at TRL 6-7, and has a propulsion system built via additive manufacturing technology using Windform XT 2.0 (Dushku, 2012).

6.2.4 Mechanisms

Satellite mechanisms include "one shot" devices (such as release mechanisms and deployment systems), and continuous operation systems (such as solar array drives, momentum wheels and antenna pointing mechanisms).

6.2.4.1 Antenna Pointing Mechanisms (APM)

Surrey Satellite Technology Ltd's APM, currently at TRL 9, is a low-cost mechanism designed to complete the payload downlink chain. This APM is expected to advance the downlink Effective Isotropic Radiated Power (EIRP) in the order of 13 to 17 dB, compared to a common Isoflux antenna configuration.

SSTL's APM comprises the following elements:

- X-Band antenna & RF harness
- Elevation drive module
- Azimuth drive module
- Electronics module
- Associated brackets joining the modules together

6.2.4.2 Deployment and Release Mechanisms

CubeSats and small spacecraft are typically launched into space as "piggyback" or secondary payloads. For this reason, pyrotechnic release devices are typically avoided to minimize the chance of damaging the launcher's primary payload. Industry is actively working to develop non-pyrotechnic devices to comply with specifications. The following paragraphs show three examples of SoA release devices available to small spacecraft.

6.2.4.3 HoneyComb: Solar Panel Deployment Hinges

Flight Proven on USAF's STPSat-1 in 2007, and currently at TRL 9, Honeybee has developed multiple precise locking deployment hinges for solar panels and other appendages. The hinges exhibit stiffness and strength, which requires agile maneuvering of the spacecraft attitude control system to compensate for structural flexibility of the solar arrays.

6.2.4.4 CTERA (Johns Hopkins Applied Physics Laboratory)

Driven by power and volume limitations, the Coefficient Thermal Expansion Release Actuator (CTERA) developed by Johns Hopkins Applied Physics Laboratory is inexpensive, has a single moving part, generates no shock, uses little power, is re-settable, and does not consume any flight parts in its operation. At around TRL 6-7, CTERA has successfully completed functional testing in vacuum, self-actuation testing and static load testing. The principle operation for the release mechanism relies on two parts that have complementary thermal expansion coefficients (Aplanel, et al., 2012).

6.2.4.5 Solar Array Drive Mechanisms (SADM)

The Solar Array Drive Mechanism (SADM) is a flight-tested mechanism that has flown for many years, and is SoA on many different spacecraft. All the major spacecraft manufacturers produce SADMs.

6.3 On the Horizon

A thermally-stable, high-strain, deployable structure made by L'Garde, Inc. is currently at TRL 2-4. This technology is a composite made of carbon fibers and elastomeric resin. This combination of materials will allow for a composite with higher stiffness and strain in comparison to materials currently in use for small spacecraft. The significance of this innovation is that the proposed material will enable much more capable deployable structures, as well as minimize complexity, mass, and cost. This technology can be used for the fabrication of de-orbiter devices for small satellites (Ariza, 2011).

Deployable Space Systems, Inc. (DSS), in collaboration with the University of California, Santa Barbara (UCSB), Department of Mechanical Engineering developed the Roll-Out Solar Array (ROSA). ROSA is an innovative mission-enabling solar array system that offers enhanced performance for NASA's Space Science & Exploration missions. ROSA will aid NASA's emerging Solar Electric Propulsion (SEP) Space Science & Exploration missions through its ultra-affordability, ultra-lightweight, ultra-compact stowage volume, high strength and stiffness, and its high voltage and high/low temperature operation capability within many environments (see Figure 33). It is currently at TRL 3-5.

Figure 33: ROSA "Winglet" (Image credit: NASA).

The ultra-lightweight microcellular nanocomposite foam and sandwich structures originating from Wright Materials Research Co. will have high specific mechanical properties, do not involve or release any toxicity and are currently at TRL 5-6. Potential commercial markets for this ultra-low density nanocomposite foams and sandwich structures may include electronic housing for satellites and telecommunication systems (Tan, 2012).

6.4 Conclusion

In comparison with other subsystems of the satellite, the SoA for structures and mechanisms is well developed and at high technology readiness levels. The trend in CubeSats is to use commercial products from 1U to 6U. Companies such as Pumpkin and ISIS are leading the market. However, some developers choose to create their own design from a solid block of material, thereby establishing additive manufacturing as a promising future technology.

Properties of materials are standardized. Metals are valuable for their high strength and protection against radiation. Various types of aluminum are the most popular option for most missions. A few have used titanium or experimented with other metals such as beryllium. Composite materials offer good performance but their high cost is an important downside for small satellite projects. Future options may leverage improvements in the additive manufacturing approach by using 3D printed materials. Windform XT may emerge as a viable option in the upcoming years.

Current mechanisms have a high TRL, since they need to comply with strong requirements in most of the missions. Deployment mechanisms need proven reliability before flight in order to ensure the correct behavior of other subsystems such as communications and power. Commercial companies offer interesting solutions, however various satellites still opt to develop and build their own technology.

6.5 References

Apland, C., et al.: *A Novel Release Mechanism Employing the Principle of Differential Coefficients of Thermal Expansion*. Proceedings of the 41st Aerospace Mechanisms Symposium. Jet Propulsion Laboratory, May 16-18, 2012.

Ariza, Juan Mejia: *Thermally-Stable High Strain Deployable Structures*. NASA, 2011.

CalPoly: *CubeSat Design Specification Rev. 12*. The CubeSat Program, Cal Poly SLO, 2009.

Calpoly. [Online] 2010. Available at: http://mstl.atl.calpoly.edu/~jfoley/Spring2010/Spring Workshop 2010 PDFs/April 23 Friday/0900 PCBSAT-RAMPART.pdf. [Accessed 01 August 2013]

Dushku, M.: *Additively Manufactured Propulsion Systems*. Small Satellite Conference, Logan UT, 2012.

Frame, B.J.: *Characterization and process development of cyanate ester resin composites*. Oak Ridge National Laboratory, Engineering Technology Division,1999.

Frazier, William, Verzuh, Michael, Rohrschneider, Reuben: *CubeSat Strategies for Long-Life Missions*. Low-Cost Planetary Mission Conference, 10. Ball Aerospace & Technologies Corp. June, 2013.

Inge, Kai Rokstad, Midtgård. Birkeland, Roger. Vedvik, Nils: *Investigation on the use of Composite Material for CubeSat Primary Structure*. Norwegian University of Science and Technology (NTNU), Department of Engineering Design and Materials.

International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys (Revised: February 2009).

ISIS: *Innovative Solutions In Space*. [Online] 2013. Available at: www.isispace.nl *[Accessed 08/02/2013]*

Jun, Wei: *Opportunities and Applications of 3D Additive Manufacturing*. Singapore Institute of Manufacturing Technology. 2013.

Mojica, Michelle A.: *Structural subsystem design, analysis and optimization for a nanosatellite.* San Jose State University, Department of Mechanical and Aerospace Engineering. San Jose, CA, 2012.

Ozaki, T.: *Advanced Composite Parts and Structures for Space Satellites*. 52nd, International SAMPE symposium. 2008.

Passaretti, M., Hayes, R.: *Development of a Solar Array Drive Assembly for CubeSat.* 40th Aerospace Mechanisms Symposium. Cocoa Beach, Florida, 2010.

Pumpkin Incorporated: [Online] 2013. Available at: http://www.pumpkininc.com [Accessed 04 August 2013]

Sandvik, Kim: *Development of Composite and Polymer Material CubeSat Structure with focus on Materials*. Norwegian University of Science and Technology, Department of Engineering Design and Materials. 2012.

SSTL: [Online] 2013. Available at: http://www.sstl.co.uk/Products [Accessed 08/01/2013]

Tan, Seng: *Ultra-Lightweight Nanocomposite Foams and Sandwich Structures for Space Structure Applications*. NASA Marshall Space Flight Center. Huntsville, AL, 2012.

The University of Texas: *Structural Subsystem of CubeSats*. [Online] 2003. Available at: http://courses.ae.utexas.edu/ase463q/design_pages/spring03/CubeSat/web/Paper Sections/6.0 Structural Subsystem.pdf. [Accessed 25 July 2013].

http://www.windform.it [Accessed 30 July 2013]

7. THERMAL CONTROL SYSTEM

7.1 Introduction

The examination of a satellite's thermal behavior is an iterative process that will predict temperature distributions throughout components and subsystems, all of which need to remain in an optimum temperature range for proper functionality. A small spacecraft can either passively or actively manage its thermal behavior. Passive Thermal Control Systems (PTCS) are highly attractive to the satellite designers, especially CubeSat and nanosatellites, because they are associated with low cost as well as low risk, and have proven reliability. If the spacecraft is able to preserve thermal stability without additional power requirements then it is considered "passively controlled." This method integrates thermal blankets such as multi-layer insulation (MLI), thermal coating, and thermal transfer via heat pipes, washers, bolts, and spacers. All of these techniques are the SoA for PTCS and are at TRL 9 because they have been demonstrated on several satellite missions. It should be noted that this is list is not exhaustive.

The system is actively controlled (Active Thermal Control System, ATCS) when thermal control is accomplished using additional power requirements. While PTCS are simpler and more reliable, ATCS are associated with higher precision and have been shown to be more effective for regulating thermal control (Hogstrom, 2013). However, for temperature sensitive devices such as batteries, cameras, etc., engineers are able to equip spacecraft with electric heaters and coolers to maintain operational temperatures. Until spacecraft designers are able to miniaturize current ATCS techniques, small satellites will not be able to efficiently use that technology.

7.2 State of the Art

7.2.1 Passive Thermal Control Systems

7.2.1.1 Thermal Insulation

Thermal insulation such as MLI has been used on numerous spacecraft as a radiation barrier from incoming solar flux. A standard sheet of MLI consists of 20-30 layers of ¼ mm aluminized Mylar, where the inner and outermost layers are 1-2 mm of aluminized Kapton (Baturkin, n.d.), but can be made for particular layer densities, as shown in Figure 34. MLI material consists of a series of either gold- or aluminum-plated layers divided by vacuum. Depending on the number of layers used, MLI has low effective emissivity values (0.002 – 0.05) due to neighboring layers radiating heat to one another (Hogstrom, 2013).

Figure 34: MLI (Sheldalh, 2009).

In Figure 35, Hogstrom (2013) illustrated the effective emittance compared to the number of layers of aluminized mylar, where the lowest number of layers is proportionate to highest emittance. The ratio of the solar absorptance to the emittance of the materials bombarded by the Sun is the deciding factor in the desired amount of solar energy that reaches the spacecraft (Sheldahl, 2013). While the concept of using a thermal blanket in space can be appealing to satellite engineers, the delicacy of the material and manufacturing costs may outweigh the benefits of using thermal blankets on small spacecraft (Hengeveld, et al., 2010).

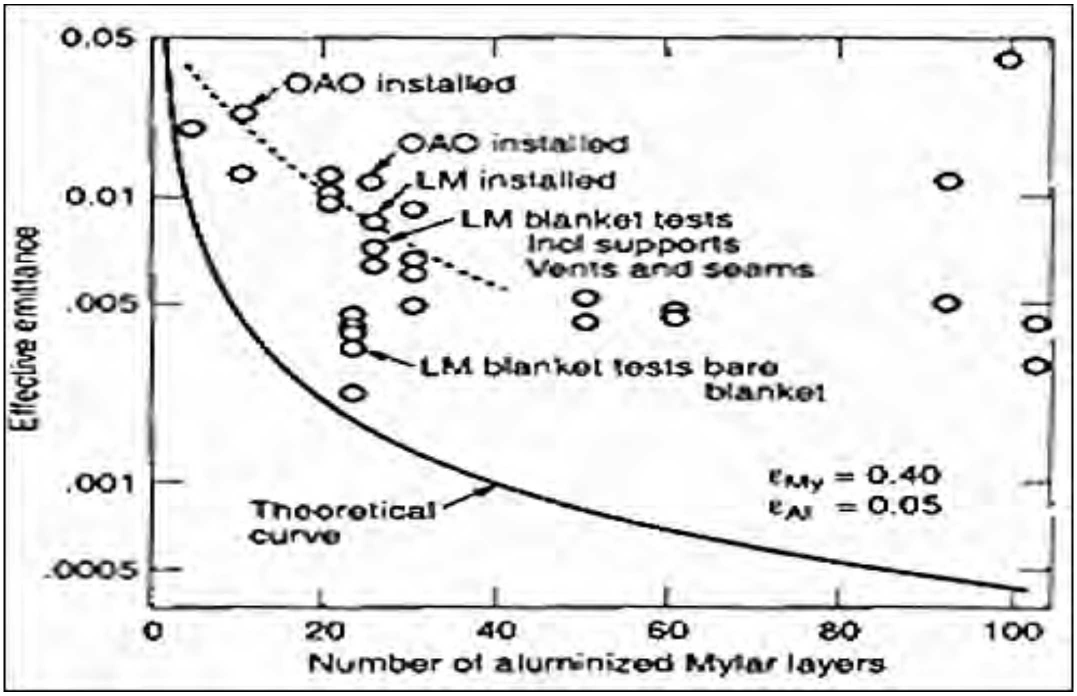
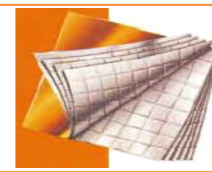


Figure 35: Effective emittance of MLI layers (Hogstrom, 2013).

DelfiC-3, a CubeSat mission, was equipped with MLI for eclipse durations, and excess heat was successfully dissipated into space via COMM power amplifiers (Rotteveel, et al., n.d.). FASTRAC was also covered in Kapton thermal blankets to assist the passive thermal system. Examples of thermal insulation SoA methods are described further in Table 31.

Table 31: Applications of SoA thermal insulation techniques for small spacecraft.

Technology	Description	Company	TRL Status	Figure
MLI blanket	Materials include polyimide films, Nome threads, and PTFE impregnated glass cloth	Aerospace, Fabrication and Materials, (USA)	**9** Sucessfully used on SCISAT I and ISS*	
MLI blanket	Aluminized polyester, polymide, or flurocarbon	Dunmore (USA)	**9** Sucessfully flown on CASSINI/HUYGENS PROBE, ISS, and FUSE*	
MLI blanket	Aluminized (one/two sided) polyester, or polymide	SHELDAHL (USA)	**9** Sucessfully applied on BIRD	
Beta Cloth 500F PTFE	type of fireproof silica fiber cloth, used in addition to MLI	Chemfab (USA)	**9** Sucessfully used on Apollo/Skylab7 space suits, ISS, & MISSE mission*	

*This technology has been flight proven on larger spacecraft. No specific small spacecraft demonstration flight could be found for specific MLI Company.

7.2.1.2 Thermal Coating

Another PTCS method changes the optical characteristics (solar absorptance and emittance) of the surface material simply by applying matte paint. In Figure 36, Anvari and colleagues (2009) illustrated the spectral absorptance/emittance ratio of white and black coatings. 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, et al., 2009).

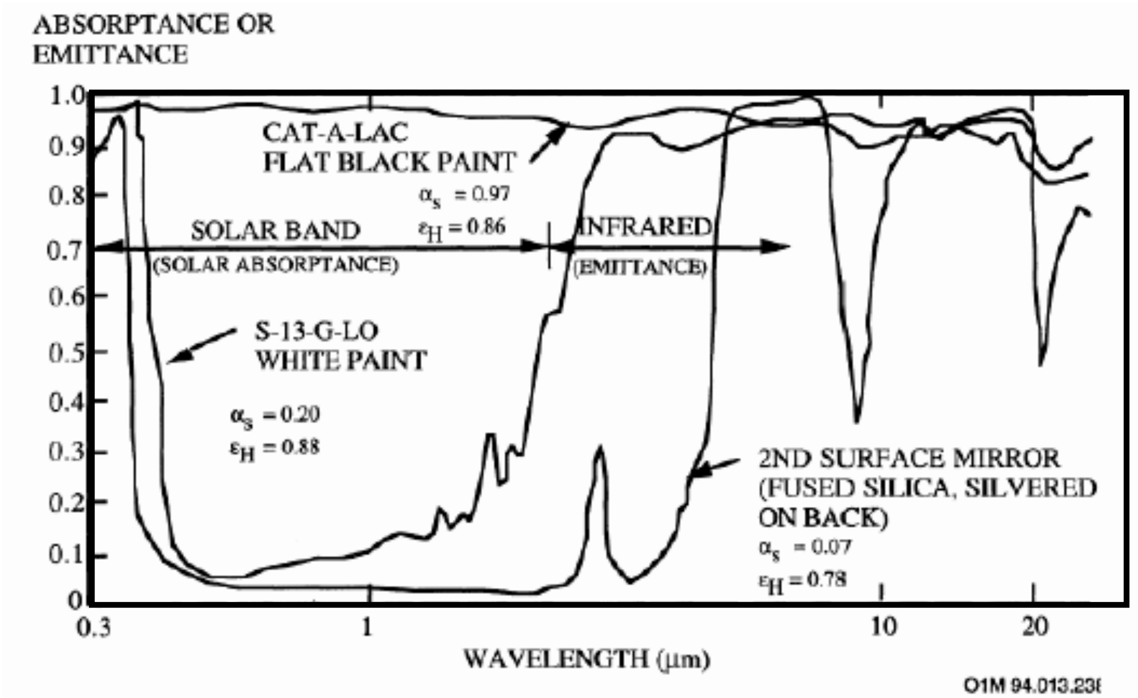


Figure 36: Absorptance/Emittance vs. wavelength for different paints (Anvari, et al., 2009).

The majority of satellite radiators in space are coated in white, or shades of grey with a range of solar absorptive values, to maximize heat rejection. For example, on small spacecraft PICARD (150 kg), SG12FD (white) paint was used, where the absorptivity and emissivity for SG121FD is 0.2+/- 0.02 and 0.88 +/-0.03 (MAP, 2013), which is similar to the absorptivity (0.25-0.5) and emissivity ranges (-.3-0.9) for AZ Technology white paints. Although this is an inexpensive method to alter the optical properties of the surface, the application of paint on a CubeSat requires an onsite professional, curing time, and has a relatively short usable lifetime (1-2 years). Figure 37 illustrates the appearance of black and white paint used for thermal coating on a small spacecraft and an optical instrument.

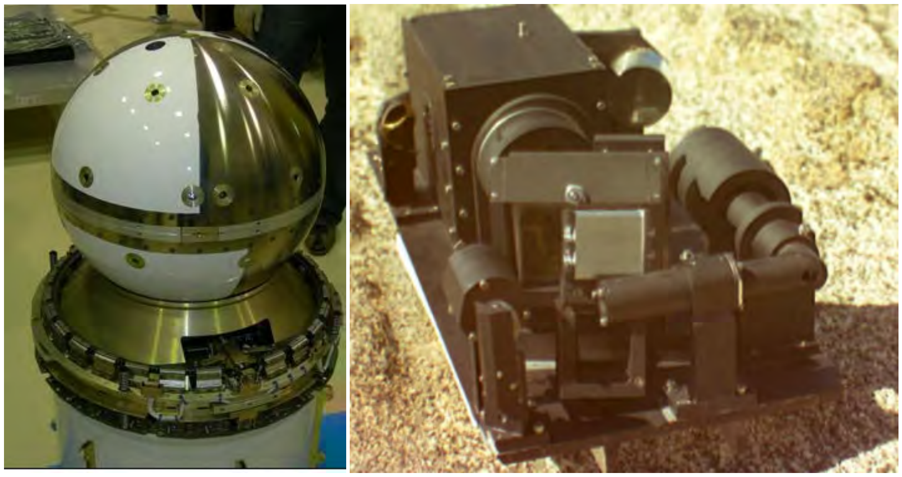
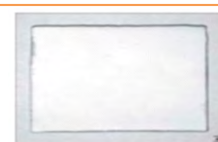


Figure 37: ANDE minisatellite with Aeroglaze276 white paint (Anon., 2013) (left) and CorMASS Optical Bench with AeroglazeZ306 black paint (University of Virginia) (right).

Tape is known to be a useful resource in the absence of paint; it is easy to both apply and remove, is relatively inexpensive, and has a longer usable lifetime than paint (NASA ARC Internal Communications, 2013). For instance, Falconsat-2 applied multiple combinations of thermal tape, aluminum and Kapton (Lyon, et al., 2002). Aluminum tape has an absorptivity of 0.14 and an emissivity of 0.09, and Kapton tape has an absorptivity of 0.39 and an emissivity of 0.63 (Lyon, et al., 2002). AZ Technology, MAP, and Astral Technology Unlimited, Inc. manufacture thermal coatings (paint and tape) for aerospace use. BIRD applied white PSG 120 FD paint to its radiator as well as to the back of the outer solar panels (Lura, et al., 2002). Small spacecraft MITA-O (170 kg) used MLI blankets on the bottom, front, and rear surfaces and painted them black to increase heat dissipation into space (Falvella, et al., 2003). In Table 32, some examples of thermal coatings for aerospace use are shown.

Table 32: SoA for thermal coating on small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
SG121FD	Non conductive white paint silicone / zinc oxide	MAP (France)	**9** Successfully flown on OUTSat and Demetre missions	N/A
PSG 120 FD	Non conductive white paint silicone / zinc oxide	Akzo Nobel Aerospace Coatings (Netherlands)	**9** Successfully used on BIRD mission	N/A
Aeroglaze A276	White paint with titanium dioxide/ polyurethane	Lord Techmark, Inc (USA)	**9** Succesfully used on ANDE mission	
AZW/LA-II	Inorganic ceramic white paint, using silacate binder	AZ tech (USA)	**9** Sucessfully flown on MISSE*	
Aeroglaze Z306	Flat black absorptive polyurethane paint	Lord Techmark, Inc (USA)	**9** Used on BLUEsat mission, and on CorMASS optical bench	

*This technology has been flight proven on larger spacecraft. No specific small spacecraft demonstration flight could be found for specific paint type.

7.2.1.3 Heat Pipes

An efficient thermal transfer technology is heat pipes. This closed-loop system transports excess heat via temperature gradients, typically from electrical devices to a heat sink, allowing the energy to dissipate into space (Steinbeck, et al., 2010). The heat pipes most commonly used on spacecraft are cylindrical in shape, and of an aluminum/ammonia type that allows optimal temperature control in the 0-40˚C range (De Parolis & Pinter-Krainer, 1996), see Figure 38. Heat pipes are available in a variety of designs (see Table 33). For example, engineers on BIRD (37 kg) used MLI, thermal coating, and cylindrical heat pipes to thermally control

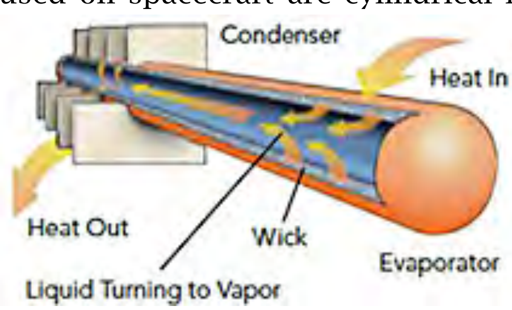


Figure 38: Heat pipe schematic (Thermacore, 2013).

spacecraft during orbit (heat pipes from KPI, National Technical University of Ukraine).

Similar to a heat pipe, a loop heat pipe is a passive, two-phase heat transfer device, in which a capillary wick moves heat from one location to a condenser, or radiator. Loop heat pipes are more advantageous than conventional heat pipes because they can operate for longer periods of time, are much more flexible in heat transfer lines, and can operate independently of gravitational forces (Baturkin, 2004). For example, on microsatellite TacSat-4, the thermal control system relied solely on a loop heat pipe to maintain thermal stability, see Figure 39 (Dussinger, et al., 2009).

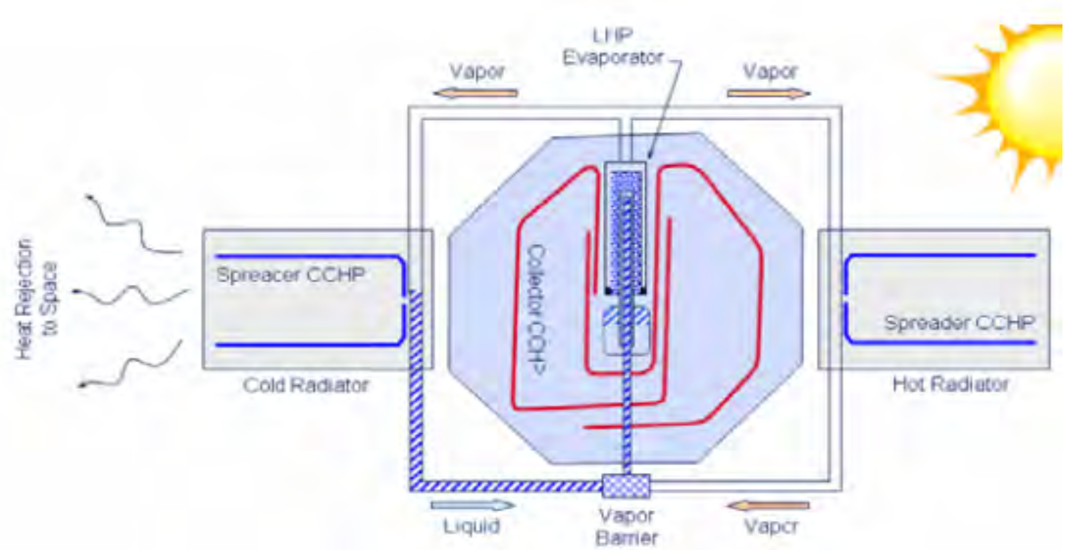


Figure 39: Loop heat pipe schematic (Dussinger, et al., 2009).

Also analogous to traditional heat pipes are flat plates—rectangular stainless steel tubing sandwiched between two aluminum plates and charged with a working fluid inside (Nakamura, et al., 2013). Designed specifically as a C-shape, this technique was incorporated on the SDS-4 (50 kg) mission and has been a successful thermal control system (Nakamura, et al., 2013; see Figure 40).

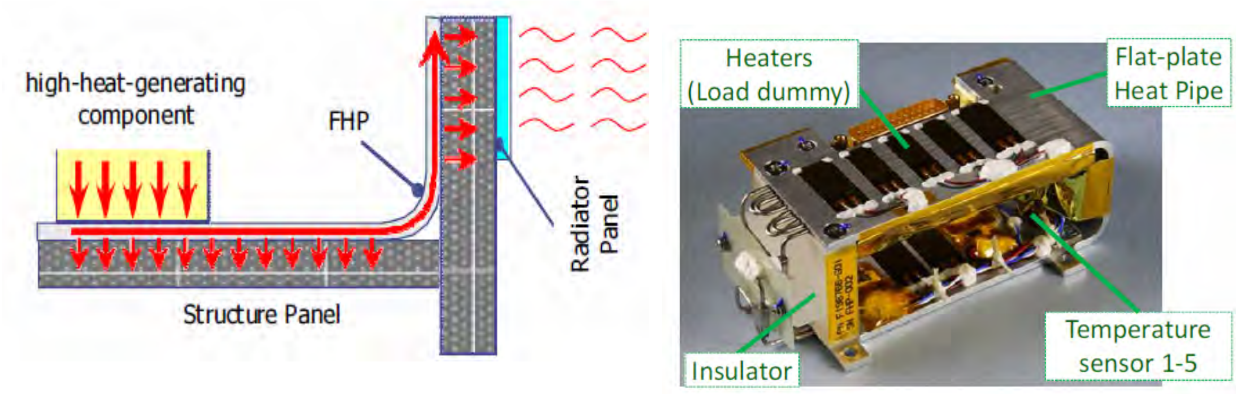
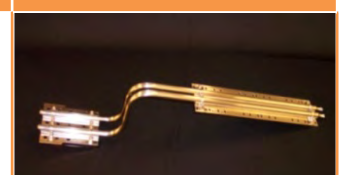
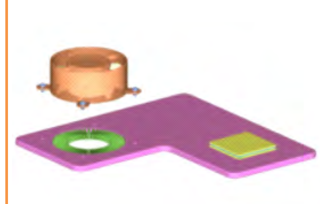


Figure 40: SDS-4 minisatellite thermal control system using flat heat pipe design (Nakamura, et al., 2013).

Advanced Cooling Technologies (ACT) and Thermacore Inc. produce several active and passive thermal control systems including heat pipes, loop heat pipes, flat plates, and variable conductance heat pipes for aerospace use.

Table 33: Examples of SoA heat pipe technology for small spacecraft.

Technology	Description	Company	TRL Status	Figure
Heat pipe	Close loop heat transfer system, either via capillary action or gravity	Advanced Cooling Technology, Inc. (USA)	**9** Sucessfully used on BIRD mission	
Loop heat pipe	Two-phase heat transfer device, using capillary action to move heat to a radiator	Advanced Cooling Technology, Inc. (USA)	**9** Sucessfully used as TCS on TacSat-4	
Flat plate heat pipe	Flat rectangular shape using capillary action to move heat to a radiator	Advanced Cooling Technology, Inc. (USA)	**9** Successfully flown on SDS-4	

7.2.1.4 Bolts and Washers

To limit heat transfer, materials with low thermal conductivity such as titanium bolts, washers, and spacers can be incorporated into the satellite structure. These items reduce the thermal path to sensitive areas on the spacecraft, such as the payload or battery. In one instance, Pharmasat mission engineers used titanium bolts and Ultem washers to help limit the heat transfer from the solar panels to the pressurized payload chamber (Hogstrom, 2013).

7.2.2 Active Thermal Control Systems

7.2.2.1 Electrical Resistance Heaters

Electrical resistance heaters simply supply heat to a spacecraft, specifically to the battery in smaller spacecraft. They are switched on and off according to the temperature range of a particular component, or can be left on continuously via a thermal control unit (De Parolis & Pinter-Krainer, 1996). In orbit, a CubeSat primarily relies on solar arrays for power production but is commonly unable to fully supply all of the spacecraft's required power during periodic peaks and eclipse durations (Horváth, et al., 2012). Eclipse durations can interrupt the amount of heat supplied to the battery or other crucial components and require stored electrical assistance. For example, on CubeSat MASAT-1, resistance heaters were attached to the Lithium-Ion Polymer battery to maintain operational temperature during eclipse periods (Horváth, et al., 2012). Nanosatellite OUTFI-1 also connected two heaters (250 mW each that were actuated when temperature transgressed <5ºC) for the two batteries (NOËL, 2010).

7.2.2.2 Thermo-Electric Coolers

Similar to devices that need to be kept warm during spaceflight, there are also pieces of equipment that require low operational temperatures to function. A thermoelectric cooler is made up of semi-conductor-based components that function as small heat pumps (Farison, et al., 2010). This device is able to maintain cool temperatures for sensitive devices, such as cameras and sensors, even when surrounded by a spacecraft's heated constituents.

For instance, CloudSat (3kg) required the assistance of a two-stage electric cooler, created by TE Technology, to maintain low operational temperatures of the camera-imaging detector during orbit (Farison, et al., 2010; see Figure 41).

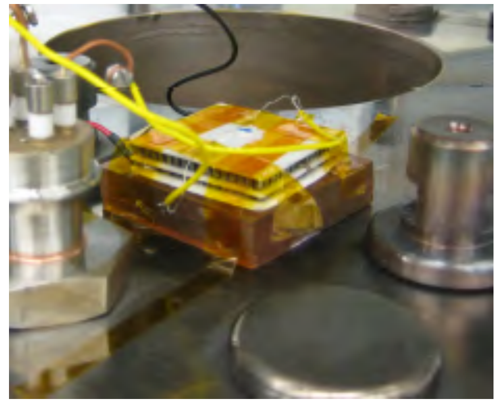


Figure 41: Two stage cooler from TE Tech. Inc., on Cloudsat (Farison, et al., 2010).

A four-stage thermoelectric cooler is available that can target more definitive temperatures than the less-sensitive two-stage thermoelectric cooler, which allows for more precise temperature control.

7.2.3 Integration and Modeling

In the early production stages, thermal calculations can be performed by treating the system as a basic sphere with uniform optical properties representative of the spacecraft's average thermal control, using only solar flux and internal power dissipation (Hogstrom, 2013). Once general thermal characteristics are known, computer software is used to evaluate detailed thermal transfer in the system. Thermal Desktop and ANSYS are known products for simulating the generated external and internal heat flux.

7.3 On the Horizon

7.3.1 Passive Thermal Control Systems

7.3.1.1 Thermal Insulation

An effective and inexpensive way to insulate a spacecraft is to use MLI on the external surface; however, this requires special handling and installation of the MLI material onto the spacecraft. Silica Aerogels, developed by NASA, have a comparable performance to MLI efficiency and have been demonstrated as an improved method of insulation. They reduced installation time by nearly 50%, cost approximately 35% less, and have an 11% reduction in mass compared to regular MLI applications (Hengeveld, et al., 2010). Aerogels have the lowest associated thermal conductivity and density value of any solid, which means they have high insulation characteristics and are lightweight, as shown in Figure 42. Although the material is fragile and brittle, the silica aerogel can sustain high compressive pressures and can be reinforced to improve mechanical properties (Burg, 2006). While silica aerogel has not been thoroughly tested on small spacecraft, it has been incorporated on the Mars Exploration Rover's thermal system (Burg, 2006); therefore current TRL is estimated to be at 4-5.

Figure 42: Silica aerogel (Image credit: Wikipedia, 2012).

7.3.1.2 Heat Pipes

While heat pipes have been a resourceful method of heat transfer for numerous small spacecraft missions, ongoing work continues to improve this technique. Inventors Youssef Habib, Lyman Rickard, Bryan John, and John Steinbeck have patented a nano-structured wick for a heat pipe that would improve upon several current technological limitations. By altering the length and spacing of the bristles and material of the internal wick, there have been several advancements in weight, size, thermal resistance, and heat flux capacity of the heat pipe. These modifications have shown a ten-fold increase in the transfer capacity in current heat pipes. In comparison to the current sintered powdered configuration, the condensed array of packed-together bristles produces high capillary pressure, increases the fluid flow in the wick, and the aligned configuration of the bristles supply clear paths for vapor venting, thus reducing thermal resistance 35-50% (Steinbeck, et al., 2010), as shown in Figure 43.

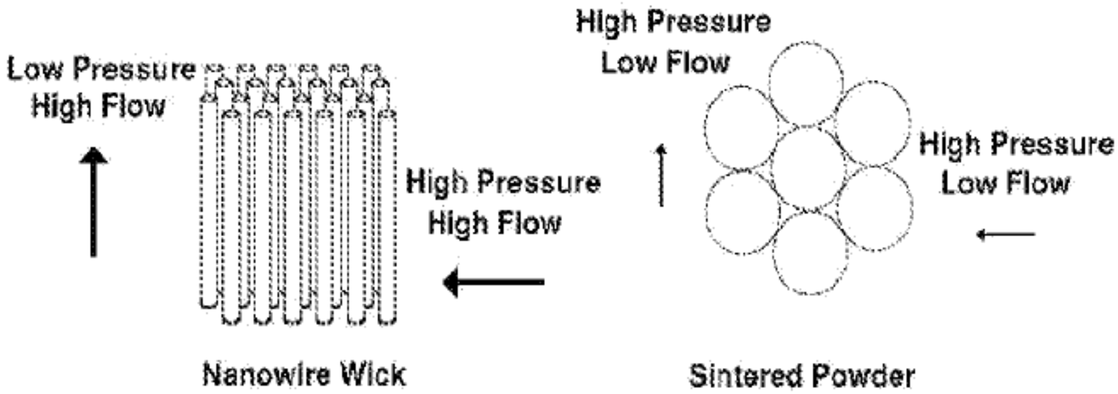


Figure 43: Nano-structured wick comparison to current sintered powder (Steinbeck, et al., 2010).

The invention of the nano-structured heat pipe was supported by a US Government Phase I SBIR Navy Contract. The European Space Agency is also currently funding development and flight tests of miniaturized loop heat pipes with multiple evaporators and condensers (Ku, et al., 2007). Validation tests have exceeded requirements for start up, heat transport, operation, thermal load sharing, and large homogeneous portfolio (LHP) model correlation in thermal vacuum environments (Ku, et al., 2007). The technology was going to be tested for flight validation under NASA's New Millennium Program ST8 Project, however this project was cancelled. Current TRL status for the nano-structured wick is 5.

7.3.2 Active Thermal Control Systems

7.3.2.1 Fluid Loops

A pumped fluid loop achieves sufficient heat transfer between multiple different locations via forced fluid convective cooling. Currently, mechanically pumped fluid loops are not attractive to small spacecraft engineers due to the heavy power consumption and small spacecraft mass limitations. However, there is a single- and two-phase mechanically pumped loop concept that is being investigated for microspacecraft thermal management (Birur, n.d.).

A single-phase pump circulates the fluid while a two-phase heat transfer takes place in the evaporator and condenser (Birur, n.d.). For the single-phase pump loop, the current mass and power targets for this fluid loop system are less than

5 kg and 5 W to manage up to 100 W of spacecraft power (Birur, n.d.). This technique is at TRL 3-4.

7.3.2.2 Cryo-Management

Improved cooling technology on small spacecraft would greatly enhance the ability to use cryogenic propellants in space. Currently, aerospace engineers are simply miniaturizing current heat pipe cooler designs to be adapted for microsatellite use. A heat pipe cooler uses 'high efficiency evaporation and condensation cycles of working fluid to transfer heat,' and is advantageous over other active thermoelectrics (fluid and loop phase cooling) due to the lower levels of energy usage and noise, higher efficiency, and structural reliability (Steinbeck, et al., 2010). CubeSat CryoCube-1 will demonstrate innovative thermal control technologies including radiation shields, MLI, and cryogenic management for low Earth orbit passive cooling. This flight test will increase the current TRL value of 4-5 to TRL 7.

7.3.2.3 Variable Emissivity Surfaces

By simultaneously altering the optical surface properties and the path of heat transfer, variable emissivity surfaces can be used as a potential method for thermal balance modulations (Hengeveld, et al., 2010). A radiator with variable emittance capability offers comparable thermal control potential to a mechanical louver (see following subsection), including decreased mass, cost, and mechanical complexity (Paris, et al., 2005).

7.3.2.3.1 Micro Louvers

A louver, or shutter system, is a useful option to transfer heat around a spacecraft. It can either provide a heat sink during hot phases (Sun illumination) or heat insulation during eclipse durations (De Parolis & Pinter-Krainer, 1996). However, the associated mechanisms and mass can limit the overall reliability of the system (De Parolis & Pinter-Krainer, 1996), which makes it very complicated for smaller satellites to utilize the louver system. Shutters and louvers utilizing MEMS technology enable nano- and picosatellite active and efficient thermal control. Inventors William Trimmer and Belle Mead have devised a micro louver by creating a reflective/absorbing device that can be configured to control heat absorption and emission by a spacecraft. This micro louver provides a reflective covering over the spacecraft's surface, which can be curled up to expose the spacecraft to the Sun, or uncurled over surface to protect it (Trimmer & Mead, 2001). The orientation of the reflective material will influence whether or not heat will be absorbed (warmed) or emitted (cooled) from the satellite. This idea is advantageous to the small spacecraft community as a basic lightweight structure.

7.3.2.3.2 Electrochromatics

Materials that are electroactive, or electrochromic, are able to reverse their reflectance in the presence of an electric field, and may be manufactured into ultra-lightweight thin-films or coatings (Paris, et al., 2005). When a small voltage is applied, a charge buildup occurs in the electrochomic materials, which modifies material reflectance (Paris, et al., 2005). Researchers at JPL and Ashwin-Ushas Corporation are improving this technique for microspacecraft use (see Figure 44), which could be developed as thermal control for multiple devices. This technology needs to be demonstrated in orbit; it is currently at TRL 4.

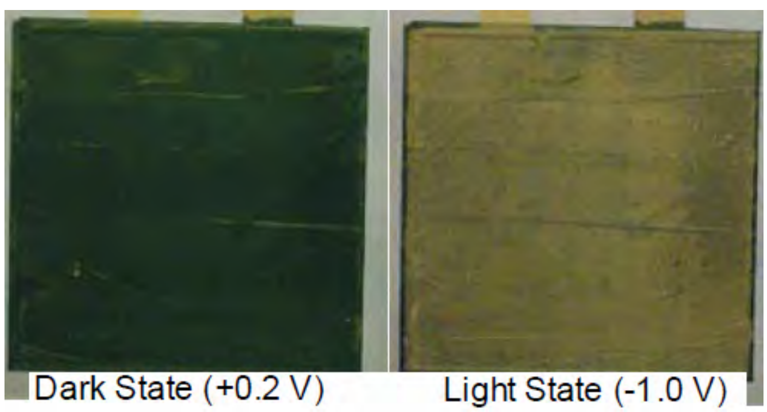


Figure 44: Dual-electrode electrochromic device (Ashwin-Ushas Corp., Inc.).

7.4 Conclusion

Miniaturizing thermal technology is vital for implementing many thermal control systems in small spacecraft. SoA techniques for small spacecraft thermal control subsystems are well developed, but current advances include improving overall weight, mass, volume, cost, durability, and efficiency of the thermal control system. Thermal insulations (MLI) and coating (paint & tape) are effective SoA techniques for PTCS for small spacecraft; however, ATCS systems are currently limited in their small spacecraft applications due to mass and power budgets.

Nevertheless, engineers are designing micro-devices for each technique that require less power and are much smaller in mass, volume, and weight. While these proposed technologies may not have been demonstrated in space just yet, future testing and validation are expected to increase their low TRL values.

7.5 References

Agency, E. S.: *Loop heat pipe.* [Online] 2007.
Available at: http://www.esa.int/TEC/Thermal_control/SEM8JNBE8YE_0.html
[Accessed August 2013].

Anvari, A., Farhani, F., Niaki, S.: *Comparative Study of Space Qualified Paints Used for Thermal Control of a Small Satellite.* Iranian Journal of Chemical Engineering, 6(2), 2009.

Baturkin, V.: *Micro-Satellites Themral Control.* Acta Astronautica, pp. 1-4, 2004.

Baturkin, V., n.d.: *Micro-Satellites Thermal Control Concepts and Components.* National Technical University of Ukraine. Kyiv Polytechnic Institute, s.n.

Birur, G., n.d.: *Thermal Control of Small Spacecraft Using Single and Two-Phase Fluid Loops.* Jet Propulsion Laboratory, California Institute of Technology, s.n.

Burg, B.: *Thermal Control Architecture for Planetary and Lunar (Sub-) Surface Exploration Robots.* Zurich, s.n., 2006.

De Parolis, M. N., Pinter-Krainer, W.: *Current and Future Techniques for Spacecraft Thermal Control 1.* Design drivers and current technologies. [Online] 1996. Available at: http://www.esa.int/esapub/bulletin/bullet87/paroli87.htm
[Accessed August 2013].

Dinh, D.: *Thermal Modeling of Nanosat.* s.l.:s.n., 2013.

Dussinger, P. M., Sarraf, D. B., Anderson, W. G.: *Loop Heat Pipe for TacSat-4.* Hunstville, AL, s.n., pp. 91-100, 2009.

Falvella, M. C. et al.: *MITA: An Italian Minisatellite for Small Missions.* Advances in Space Research, 31(2), pp. 357-361, 2003.

Farison, M., Hicks, K., Schmidt, M., Yang, S.: *Cloud CubeSat Thermoelectric Cooler Controller.* Baltimore, MD, s.n., 2010.

Hengeveld, D., Braun, J. E., Groll, E. A., Williams, A. D.: *Review of Modern Spacecraft Thermal Control Technologies.* West Lafayette, s.n., 2010.

Hogstrom, K.: *SoA Thermal Analysis Methods and Validations for Small Spacecraft.* s.l.:s.n., 2013.

Horváth, G., Marosy, G., Glisics, S. & Czifra, D.: *Battery characterization for CubeSat missions with battery tester application.* Tallinn, Electronics Conference (BEC). 13th Biennial Baltic, pp. 97 - 100, 2012.

Inc., T.: *Loop Heat Pipe for High Density Small Satellite Thermal Control.* [Online] 1995. Available at: http://sbir.nasa.gov/SBIR/successes/ss/5-043text.html [Accessed August 2013].

Ku, J., Ottenstein, L., Pham, T., Douglas, D.: *Miniature Loop Heat Pipe with Multiple Evaporators.* Greenbelt, MD, s.n., 2007.

Lam, T. T., Birur, G. C., Bhandari, P.: *Pumped Fluid Loops.* Spacecraft Thermal Control Handbook, Volume I: Fundamentals Technologies. s.l.:s.n., pp. 405- 471, 2002.

Lura, F. et al.: *Thermal Design and Pre Flight Thermal Test Program of Satellite BIRD Micro.* San Antonio, TX, s.n., 2002.

Lyon, R., Sellers, J., Underwood, C.: *Small Satellite Thermal Modeling and Design at USAFA: FalconSat-2 Applications.* s.l., Aerospace Conference Proceedings. IEEE, pp. 3391 - 3399, 2002.

Nakamura, Y. et al.: *Small Demonstration Satellite-4 (SDS-4): Development, Flight Results, and Lessons Learned in JAXA's Mircosatellite Project.* s.l., s.n., 2013.

NOËL, J.: *Thermal issues settlement and test procedure investigation of OUFTI-1 nanosatellite.* Liège, Belgium, s.n., 2010.

Olivia, A., Schaalman, G., Stanley, S.: *Design and Analysis of Subsystems for a CubeSat Mission.* Worchester Polytechnic Institute, Mechanical Engineering Department. s.n., 2011.

Paris, A. et al.: *Electrochromic Radiators for Microspacecraft Thermal Control.* s.l., s.n., 2005.

Pendleton, S., Basile, J., Fowler, E., n.d.: *Low-Cost Flat Plate Adapters for Dual Primary Payload Missions.* CSA Engineering Inc. Mountain View, CA.

Rotteveel, J. et al., n.d.: *Delfi-C3: A Student Nanosatellite Test Bed for in-orbit Demonstration of Micro Systems Technology.* s.l.:s.n.

Sarda, K. et al.: *Canadian Advanced Nanosatilllite Experiment 2: On-Orbit Experiences with a Three-Kilogram Satellite.* Logan, UT s.n., 2008.

Selva, D., Krejci, D.: *Survey and Assessment of the Capabilities of CubeSats for Earth Observation.* Journal of Acta Astronautica, Volume 74, pp. 50-68, 2012.

Steinbeck, J. W., Habib, Y. M., John, B. G., Rickard, L. H.: *Heat Pipe with Nanostructured Wick.* Patent No. US 2010/0200199 A1. PLEASANTVILLE, NY, USA, 2010.

Trimmer, W., Mead, B.: *Micro Louvers for Cooling.* Patent No. US 2002/0056790 A1. McLean, VA, USA, 2001.

University of Virginia, Department of Astronomy. Virginia Astronomical Instrumentation Laboratory. [Online] 2005. Available at: https://www.astro.virginia.edu/research/instrumentation/cormass/photos.html [Accessed November 2013].

8. COMMAND AND DATA HANDLING

8.1 Introduction

Command and data handling (C&DH) is handled by the spacecraft flight computer, usually a general purpose processor. Other on-board processing may be needed depending on the spacecraft architecture. For small spacecraft, general and application-specific processing units will be discussed agnostic to actual function. For context, a brief segment on processing functions will be provided. C&DH is the “brains” of the spacecraft, responsible for dictating spacecraft functions (i.e. spacecraft control and execution, data management, storage and retrieval) and compiling inputs and outputs of other subsystems. The key characteristic of this system is high reliability (hi-rel) since it is the central part of the spacecraft. Often this reliability is realized by redundancy and use of radiation-hardened (rad-hard) components. The processing requirement for the C&DH function has been relatively static through the years. In centralized architectures, other processing needs (e.g. payload interface, signal processing) are handled through a core C&DH processor. The push for higher processing capabilities in C&DH and other processing elements are driven by advancing scientific studies looking for higher resolution and data throughput.

In addition to the processing unit, the main components of the C&DH system include memory, clock, and interfaces to communicate with other subsystems, as shown in the architecture diagram in Figure 45.

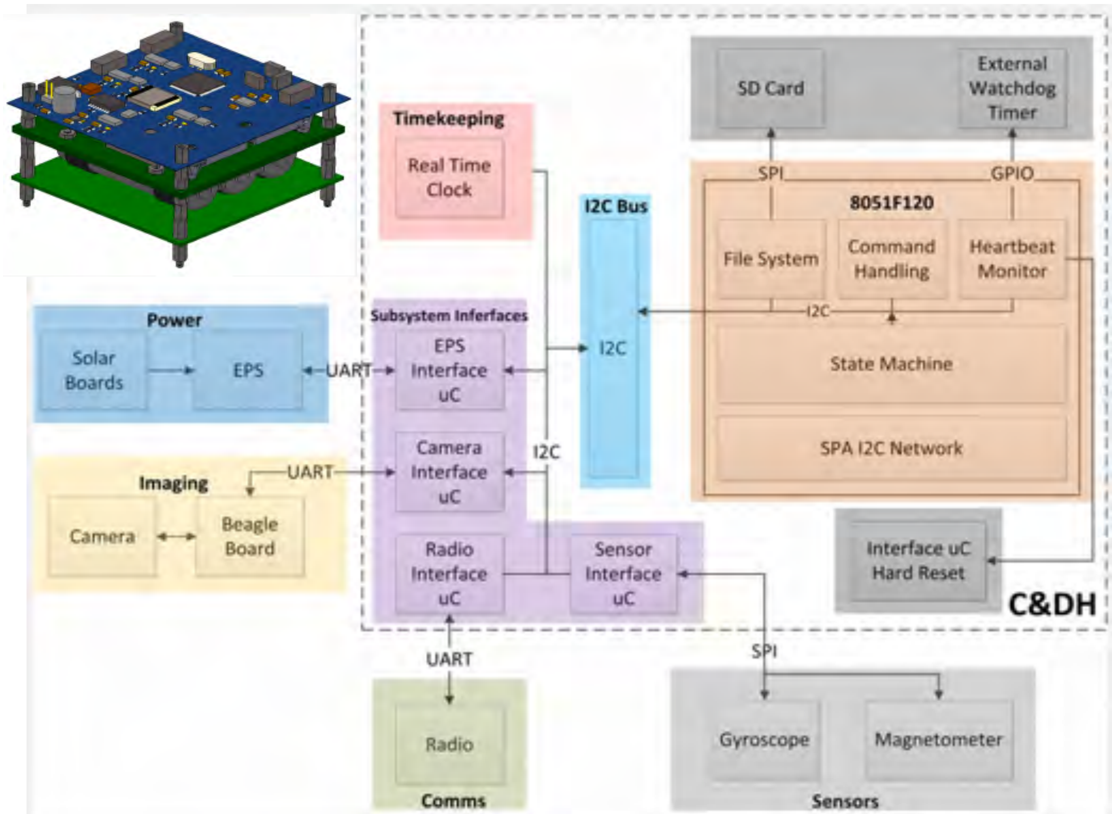


Figure 45: Typical smallsat C&DH architecture and image of C&DH board (Space Systems Laboratory).

8.2 State of the Art

A cursory attempt is made to survey SoA hardware C&DH components to capture the current state of small satellite capability. The survey, while not comprehensive or exhaustive, should still yield good insight into the current state of practice for small spacecraft. The goal of this effort is not only to convey basic research on the SoA, but to solicit inputs and sources to be shared with the greater community in future revisions.

While smallsats, especially in the nanosat class, have higher risk tolerance and are able to rely more on COTS components, much of the aerospace industry still relies heavily on stringent standards that ensure reliability. Using COTS components has been explored and debated over the years. On one side, cost savings can be demonstrated by using typical, more capable and less expensive COTS components at the price of increased risk. On the other hand, as smallsat capabilities increase, the functions that they support will have greater importance and consequently will require higher reliability. Standard COTS electronics fail with a total ionizing dose (TID) of 3 to 30 krads, while radiation hardened parts offer protection from 100 krads to Mrads. In brief, the use of COTS components in the development and experimental phases is increasing (with proficient components being brought along to higher standards), while QML Class V standards are still expected of failsafe missions.

8.2.1 Form Factor

Prior to 2000, the majority of spacecraft C&DH and on-board processing boards were custom built. As commercial technology advanced, specific standards emerged allowing collaborations across industries. Three form factors are common in space applications and are listed with dimensions in Table 34.

Table 34: C&DH form factor.

C&DH Form Factor	Dimensions [mm]
6U cPCI	233 x 160 mm
3U cPCI	100 x 160 mm
PC/104	90 x 96 mm

While the dimensions in themselves are not restrictive for the larger class of smallsats, volumetric constraints play a crucial factor in the smaller end of the spectrum. The nanosats class typically uses the PC/104 backplane-less form factor because of limited volume. Micro- and minisats use 3U-6U configurations depending on the specific functional block needed with respect to the usable area on the board. Custom configurations are still used for special cases. Beyond volume, the next main limiting factor for smallsat C&DH is power.

8.2.2 Microprocessor/Computer/Microcontroller

Spacecraft processing capability has followed the commercial market. The slow development may be due to the rigors of qualifying operations in the space environment and limited production volumes. Nonetheless, processing resources are increasing while spacecraft processing requirements have stayed relatively static. Typical C&DH systems need a processing throughput of ~30 MIPS. This does not include payload and digital signal processing, which are driving the industry towards greater processing capabilities, data throughput and storage.

Early spacecraft computers like the 32-bit RH32 and RICS/6000 provide <40 MIPS. The RAD6000 and RAD750, introduced in the 2000's timeframe, are more capable rad-hard solutions providing up to 300 MIPS. These throughput values satisfy typical C&DH functions but require a lot of power (~20 W). While this is less of a concern for the typical 1,000+ kg satellites of the time, it poses a challenge for smallsats. Typical orbit average power vs. spacecraft mass is shown in Figure 46.

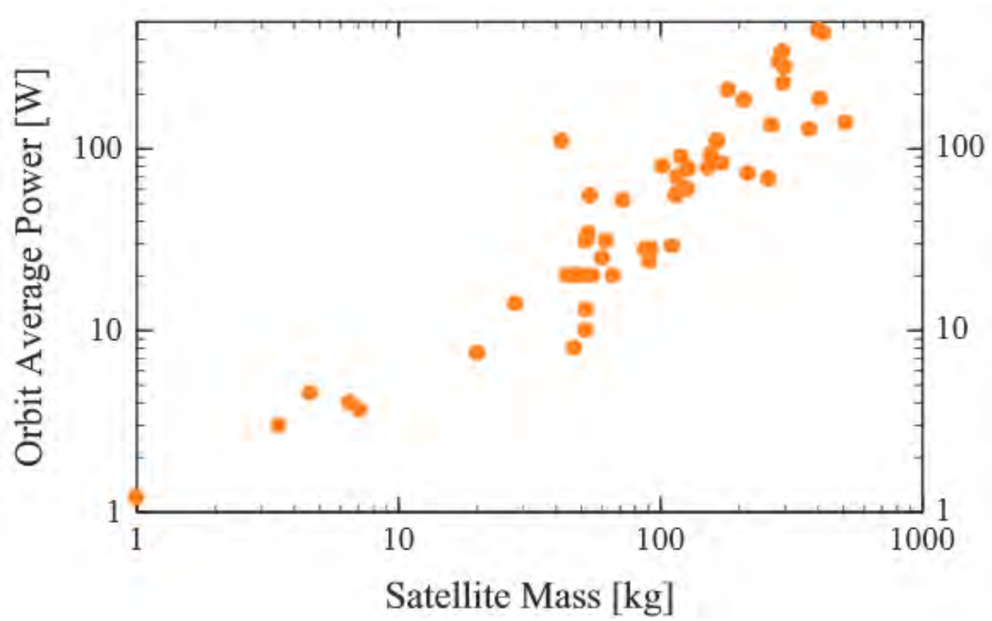
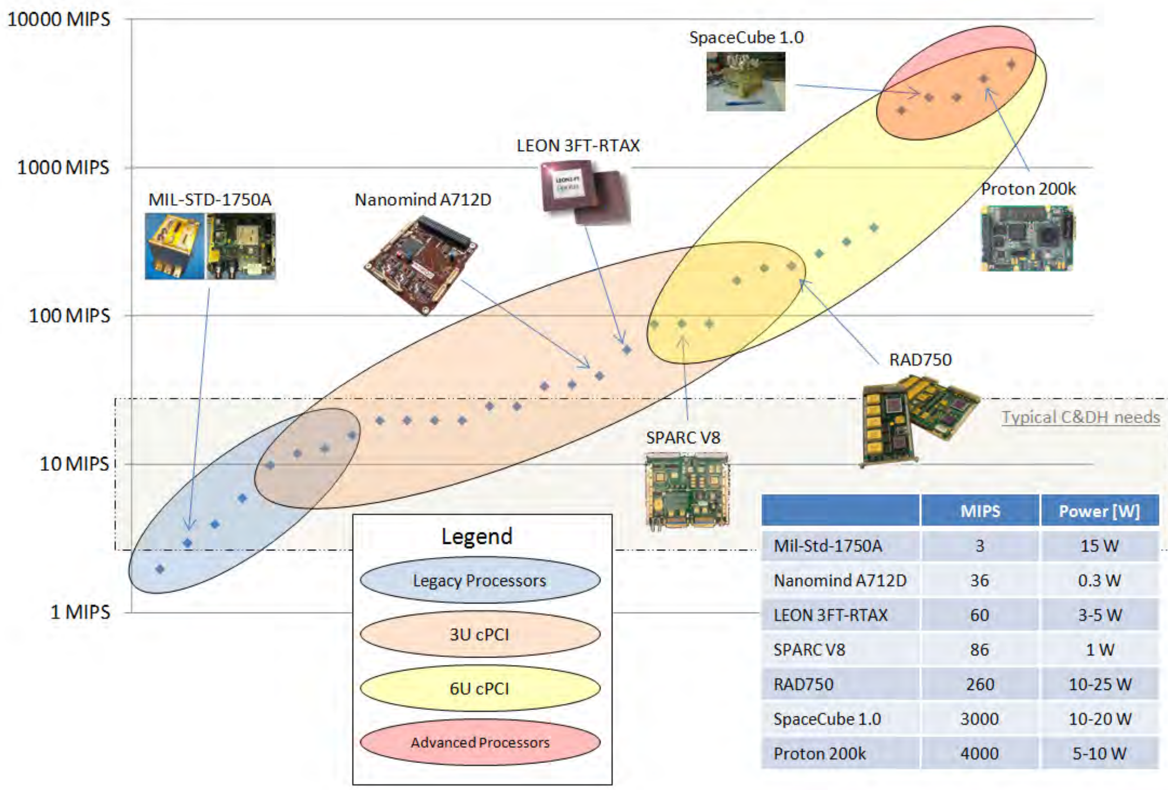


Figure 46: Orbit average power vs. satellite mass (Shimizu & Underwood, 2013).

The general trend improves with tracking arrays or pointable spacecraft, however the linear fit shows power generation typically less than 1 W per kg spacecraft mass. The smaller classes of smallsat are highly power constrained. Luckily for smallsat designers, the world of microprocessors, computers and microcontrollers is ever expanding in the commercial market. Small hand-held and mobile devices are driving smaller form factors with low power consumption. In space applications, the push for more computational power from payload and digital processing systems has driven the space industry to seek practical solutions in using COTS components and technology. In the aerospace industry, due to the higher reliability standards mentioned before, there are still just a handful of core manufacturers (Atmel, Microchip, TI, Freescale, etc.) that dictate trends in the market. Figure 47 shows the qualitative trend of processing elements used as spacecraft on-board computers.



	MIPS	Power [W]
Mil-Std-1750A	3	15 W
Nanomind A712D	36	0.3 W
LEON 3FT-RTAX	60	3-5 W
SPARC V8	86	1 W
RAD750	260	10-25 W
SpaceCube 1.0	3000	10-20 W
Proton 200k	4000	5-10 W

Figure 47: Satellite processing trends.

The size of C&DH systems has scaled down over time, to the aforementioned form factors. Performance, on the other hand has steadily increased more or less in concert with Moore's Law.

In terms of technology, there are microcontrollers (MCU), digital signal processors (DSP), field programmable gate arrays (FPGA), and traditional application specific integrated circuits (ASIC). For simple data processing, FPGAs outperform DSPs with regards to computational speed, power consumption, and volume. DSP are used for complex repetitive calculations (e.g. image processing and data compression). Often the various technologies are mixed and matched to meet specific requirements. Circa 2005, integrated RISC/DSP processors offered higher performance and lower system power. For smallsats, power, thermal and volume constraints are more apparent and various mixed technology solutions have been used. Atmel and Xilinx are two of the main manufacturers of rad-hard integrated circuits (IC) for space applications and their use can be seen throughout the industry.

There are many differentiating factors (technologies, architectures, peripheral interfaces etc.) surrounding the C&DH systems. While the goal is to be as exhaustive and inclusive as possible in capturing the SoA of smallsat capabilities, for brevity only some prominent and recent systems will be highlighted, see Table 35, Table 36 and Table 37.

Table 35: Examples of SoA processing elements for small spacecraft (1/3).

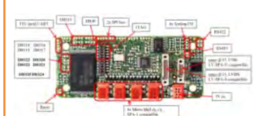
Technology Name	Description	Developer	TRL Status	Image
µRTU	Remote Terminal Units (RTU), 32-bit, fault-tolerant processor	AAC Microtech (USA)	**9** Flown on SPRITE-SAT, TechEdSat	
LEON3FT-RTAX	uses Actel RTAX2000S/SL FPGA	AeroFlex - Gaisler (Sweden)	**9** Flown on Chandrayaan-1, ARGO, & PRIMSA	
AT697F (LEON2-FT)	Rad-Hard 32-Bit SPARC V8 processor	Amtel (USA)	**9** Flown on ERNObox (prototype computer payload) on ISS in 2008 & Proba-2 in 2009	
AVR8	8-bit microcontroller	Amtel (USA)	**9** Flown on AAUSat-3	
AT91M40807	Smart ARM microcontroller, flash-based, cortex processor	Amtel (USA)	**9** Flown on SRMSAT	

Table 36: Examples of SoA processing elements for small spacecraft (2/3).

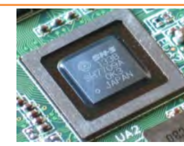
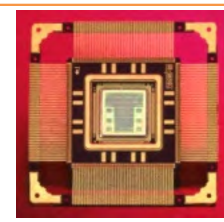
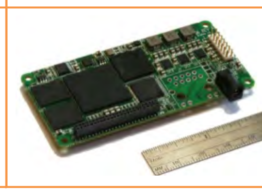
Technology Name	Description	Developer	TRL Status	Image
RAD750	RAD750 is a radiation hardened PowerPC microprocessor. It replaces RAD 6000 which is a hardened version of IBM RS/6000 used by 200+ spacecrafts	BAE System Electronic Solutions (USA)	**9** Flown on Curiosity, Juno, WISE, LRO, Kepler, & MRO; first flown on Deep Impact (2005)	
Mirideon PPC440	Single board computer using BRE440	BRE (USA)	**9** Flown on SB-Sat	
Nanomind A712D	ARM, RISC based computer processor	GOMSpace (Denmark)	**9** Flown on STRAND 1	
SH	Super H (SH), 32-bit RISC used in embedded applications (e.g. appliances, engine control, mobile phone)	Hitachi (Japan)	**9** Flown on PROITERES (2012)	
StrongARM	StrongARM SA1100/Xscale processor; 88 MHz - 220 MHz experimental	Intel (previously Digital Equipment Corp, ARM Limited) (USA)	**9** Flown on SNAP-1, X-Sat, FalconSat-2, TacSat-1, & DMC-1G	
SpaceCube II	uses HRS5000S processor	JAXA (Japan)	**9** Flown on SDS-1 & ASNARO	
RT ProASIC3	Low power, reprogrammable, flash-based FPGA	Microsemi (previously Actel) (USA)	**9** Flown on X-Sat	N/A
SpaceCube 2M	SpaceCube 2.0 Mini for CubeSats	NASA Goddard (USA)	**9** Flown/Proposed on: Intelligent Payload Experiment (IPEX), TechCube, & SDS-1	

Table 37: Examples of SoA processing elements for small spacecraft (3/3).

Technology Name	Description	Developer	TRL Status	Image
STM32F103	N/A	STMicroelectonics (Geneva)	**9** Flown on ESTCube-1	
SBC	Sparc v7(TSC695F), 21020 DSP, RTX-2010, PowerPC603e, Sparc v8(TSC697)	SwRI (USA)	**9** Flown/Proposed on Juno, WISE, Kepler, GLAST, Orbital Express, Deep Impact, Swift, Coriolis, & DS1	
Mongoose-V	R3000, 32-bit microprocessor, built for DOE applications	Synova (USA)	**9** Flown on EO-1, MAP, ST5, CONTOUR, TIMED, New Horizons, & IceSat Glas	
MSP430	Family of low power microcontroller; 16-bit RISC, used in Pumpkin FM430	Texas Instruments (USA)	**9** Flown on CSSWE, Delfi-C3, HawkSat-1, ITU-pSAT1, AIS Pathfinder 2, GOLIAT, e-st@r, & Libertad-1	
Q6 processor board	Based on Xilinx Spartan 6	Xiphos Technologies (Canada)	**9** First flew in 2011, many previous flights with prior version	

Only some missions actually use the latest and most capable elements listed above. Spacecraft missions have diverse processing requirements leading to the use of various processors and technologies. On one hand, there are novel missions like PhoneSat, which used the newest technologies available in the form of unmodified smartphones and Arduninos as the main processing element. On the other hand, it can be seen that even recent missions use some of the older processing elements. Outdated processors such as the RAD6000 and NSSC-1

(NASA Standard Spacecraft Computer-1) are not listed in Table 35, Table 36 or Table 37, though they are still used from time to time.

With many capable processing elements in the market, one of the main decisive factors leading to processor selection (other than matching functional requirements to capability) is heritage. With that in mind, parts obsolescence becomes an issue with rapidly advancing technology.

A trending study has shown an overall increase in using integrated circuits in space with a recent inclination towards FPGA's (see Figure 48). ASICs have been the preferred space-based solutions as they typically offer the highest density, lowest weight and power, but they lack flexibility, have higher cost and longer schedules. Smallsats are typically tied to smaller budgets and schedule, which leads them to use other ICs.

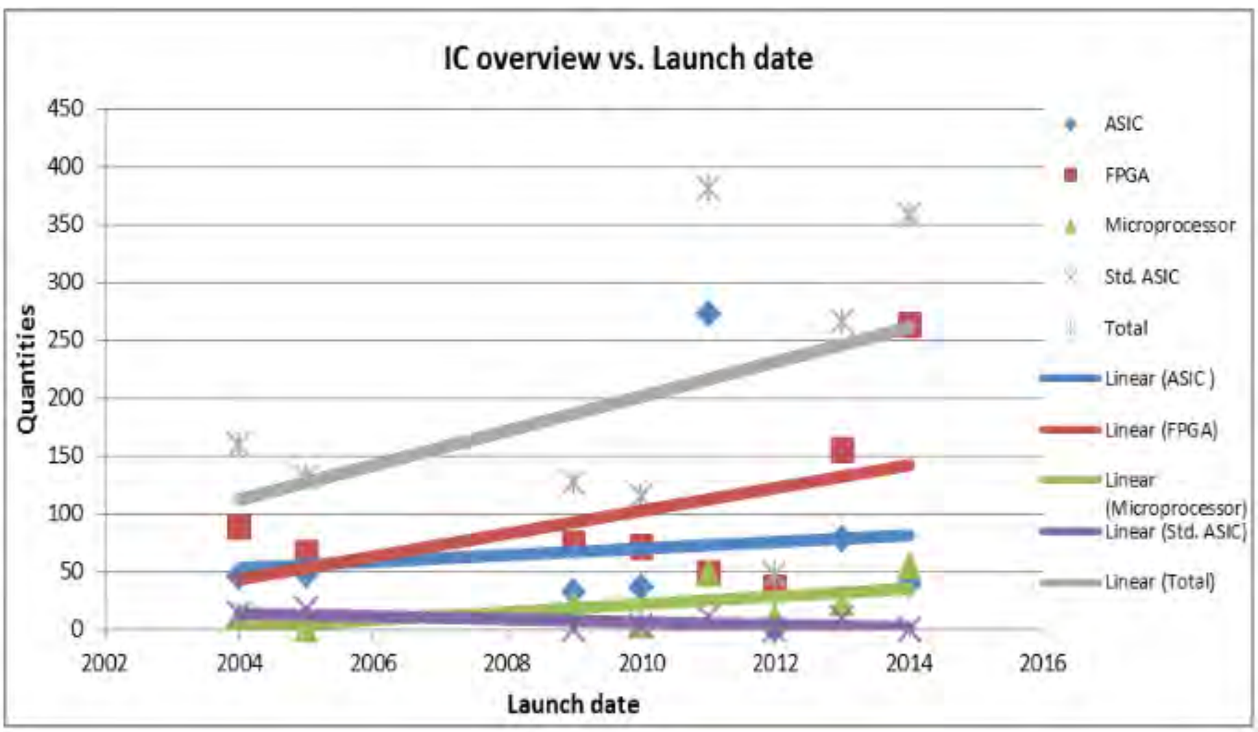


Figure 48: Trends for integrated circuits in space (ESA; Furano, 2012).

Another factor contributing to more FPGA usage in space applications is radiation tolerance. The two prominent FPGA technologies are SRAM- and antifuse-based. SRAM-based FPGAs typically offer higher densities then antifuse but are more susceptible to radiation. Mitigation techniques such as triple modular redundancy (TMR) are typically employed. Xilinx's Virtex-5QV FPGA offers a rad-hard reconfigurable processing option. Prior FPGA's have been one-time programmable.

8.2.3 Memory/Data Storage

The range of on-board memory for smallsats is wide, typically starting around 32 kb and increasing with available technology. Again, for C&DH functions, on-board memory requires high reliability. Different memory technologies are available, but SRAM is typically used. A comparative chart showing performance of various memory types is shown in Table 38.

Table 38: RAM comparison.

Feature	SRAM	DRAM	Flash	MRAM	FERAM	CRAM/PCM
Description	Static random access memory	Dynamic random access memory	EEPROM derived memory; two main types: NAND, NOR	Magnetoresistive random access memory	Ferroelectric random access memory	Chalcogenide random access memory; aka phase change memory (PCM)
Non-Volatile	No	No	Yes	Yes	Yes	Yes
Operating Voltage, ±10%	3.3-5 V	3.3 V	3.3 & 5V	3.3 V	3.3 V	3.3 V
Organization (bits/die)	512k x 8	16M x 8	16M x8; 32M x 8	128k x 8	16k x 8	N/A
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 us 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	N/A
Package	4 Mb	128 Mb	128 Mb & 256 Mb	1 Mb	1.5 Mb (12 chip package)	N/A

Thanks to the commercial industries and advancing technology, data storage has continued to increase with relatively static mass, power and volume requirements. This is complimented by more space usage and increases in reliability and heritage. Memory and data storage are currently not of great concern to smallsat designers. The limiting factor in the end-to-end information system is the data transmission rates. Typical missions can now store more than they can transmit down to ground stations. Figure 49 shows the SoA capability of solid-state recorders.

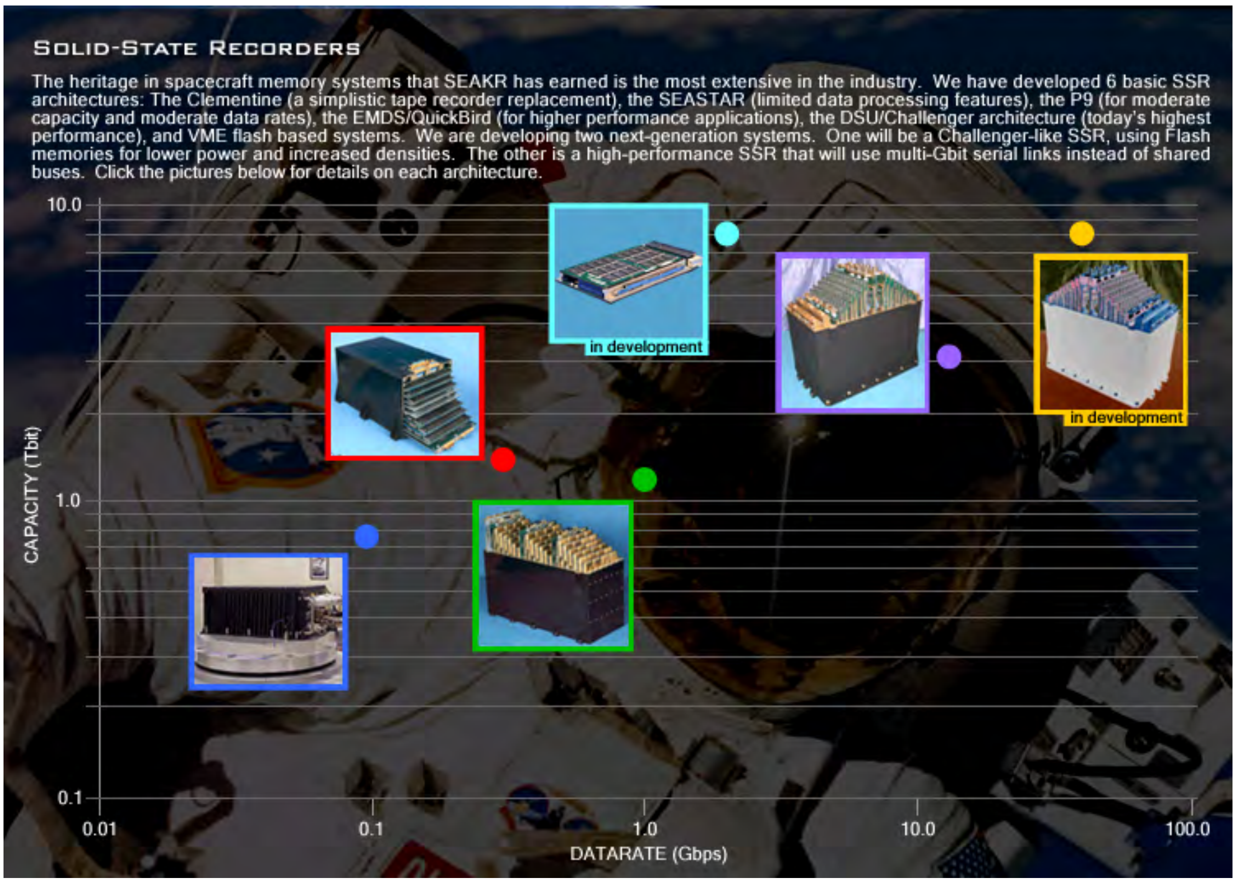
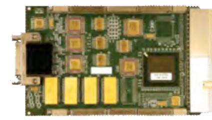
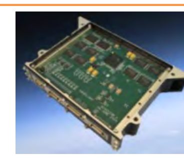


Figure 49: An example of SoA solid state recorder capability (SEAKR).

The trend for the smaller class of smallsats to use more COTS components remains true for data storage hardware. High heritage developers like SEAKR are apparent throughout the spacecraft industry, and emerging commercial companies offer high performance components. Table 39 below illustrates SoA technologies for data storage.

Table 39: Examples of SoA applications for memory components.

Technology Name	Description	Developer	TRL Status	Image
MRAM	magnetic material and silcon IC combined to form fast reliable non-volatile memory	AeroFlex	**9** Flown on M^3, SpriteSat (Rising), ALL-STAR, SOMP, & GOLIAT	
CASI	Camera and storage interface board	BRE	**9** Flown on TacSat2, XSS-11, AMS, Angels, & LADEE	
MR0A08B	Magetic polarization storage MRAM	EverSpin	**9** Flown on ALL-STAR & Rising-2	
Compact SSDR	Solid state data recorder	Innoflight	**9** Flown on RASAT, TechDemoSat-1, & DMC-1G,	
HSSU	High speed storage unit	SEAKR	**9** Flown on GeoEye-1 & WorldView-1	
SSDR	Solid state data recorder	SEAKR	**9** Flown on NEAR, ACE	
HSDR	High speed data recorder, 16 GB	SSTL	**9** Flown on Nigeriasat-2	

8.2.4 Bus and Interfaces

The system bus connects major computer system components. Modern computing systems have a variety of separate buses customized to specific needs. Interfaces significantly vary from basic to extremely complex. MIL-STD-1553 has been the standard for spacecraft and ESA's SpaceWire (SpW) is becoming more prominent. For nanosats, ATK has developed the A100 bus, especially designed for payloads less than 15 kg. These platforms are compatible with most launch systems and a wide range of payload interfaces. The A100 bus has flown on NASA's ARTEMIS mission.

While universal serial bus (USB) and controller area network (CAN) buses are being used sporadically, the I^2C data protocol seems to be the most popular standard bus system for nanosat missions, due to power reasons. I^2C consumes a very small amount of energy and is already integrated in most microcontrollers, avoiding the necessity of extra electronics. A singular and flexible interface for different payload types is desirable. Some of the most common interfaces are listed below with a brief description:

- CAN Bus – Controller Area Network Bus
- I^2C – inter-integrated circuit - low power consumption, low speed (100 kbps), multi-master capability, strong commercial support
- LVDS – low voltage differential signaling
- MIL-STD-1553 Bus – moderate speed (1 Mbps), standard for most OBDH systems
- MIL-STD-1394 Bus – high speed (100 Mbps)
- PCI Bus – Peripheral Component Interconnect, local computer bus to connect other hardware to a computer
- RS-232 – traditional standard serial connection
- RS-422 – traditional standard enabling digital differential signaling circuit
- RS-485 – traditional standard enabling multi-point system
- SerDes – serializer/deserializer
- SpaceWire – standard for high speed links (<160 Mbps)
- SPA-S – Spacecraft plug-and-play spacewire
- SPA-U – Spacecraft plug-and-play USB w/ +28V
- SPI – Serial Peripheral Interconnect
- UART – Universal Asynchronous Receiver/Transmitter
- USART–Universal Synchronous/Asynchronous Receiver/Transmitter
- USB – universal serial bus

8.2.5 Frequency Source

C&DH functions include maintaining spacecraft clock or time. Timing provided by a frequency source enables controlled timing events, time-tagged data, and navigation. Traditionally, spacecraft have employed quartz resonators for timing (Norton & Cloeren, n.d.).

Recently, DARPA has made an effort to incorporate miniaturized and low power Chip-Scale Atomic Clocks (CSAC) into small satellites. These tiny atomic clocks fit into small satellites while improving frequency performance and time references. In addition, the Integrated Micro Primary Atomic Clock Technology (IMPACT) is a project that aims to improve the capabilities of CSAC by reducing the power requirements while maintaining the accuracy and stability of the main clock. It is on its second phase and the goal is to deliver a 20 cc, 250 mW working clock that will have less than 160 ns time loss after one month (DARPA).

There are some series of cesium, rubidium, and quartz oscillators for frequency sources with proven reliability in Space. SC-cut quartz resonators provide reliability and they meet NASA Grade 1 standards. They can function under adverse temperature conditions and their output frequency ranges from 4 to 60 MHz.

Other options consider the problem of high exposure to radiation. A Radiation Tolerant Low Power Precision Time Source (LPPTS-R) has a frequency of about 10 Mhz. Some of the most popular vendors are Symmetricom, Kernco and Rakon. The classical resonators offer a reliable solution that has been used extensively in the last few years. Nevertheless, it appears that there is an effort to improve the capabilities of small satellites by adding the new micro-atomic clocks.

8.2.6 Power Distribution System Electronics

Depending on the bus disposition, different architectures can be implemented for the power distribution on board. One of the most common interface standards is the 28 V bus, which is linked with a distributed architecture. By using distinct switchers, many components can be connected to the main core of the electrical power system (EPS). Another option is to choose a centralized EPS architecture which provides more than one power bus to manage different devices. Regulators are needed in this architecture and engineers should take the potential for overloads into account in order to avoid failures. Thus, there is a trade-off between simplicity and performance, since having multiple components will increase complexity. For nanosats, volume constraints often trump added complexity. Table 40 illustrates a survey of nanosat missions with different EPS architectures.

Table 40: EPS architecture (Burt, 2012).

Mission	Size	Architecture	Distributed/Centralized	#of Buses	Bus Voltage
AAU	1U	MPPT	Centralized	1	5R
AtmoCube	1U	DET	Centralized	6	3.3R, 5R, 6R, -6R, -100
Colony 1	3U	PPT	Centralized	3	7.2bat, 3.3R, 5R
Compass One	1U	PPT	Centralized	3	3.3R, 5R
CP3	1U	PPT	Distributed	6	3R, 3.7bat
CP4	1U	PPT	Distributed	7	3R, 3.7bat
CUTE-1	1U	DET	Centralized	3	5R, 3.7bat, 3.3R
CUTE-1.7	2U	PPT	Centralized	4	3.3R, 5R, 6R, 3.8bat
Delfi-C3	3U	DET	Distributed	1	12 R
DICE	1.5U	PPT	Centralized	3	7.2bat, 3.3R, 5R
DTUsat	1U		Distributed	1	3.6R
e-st@r	1U	PPT	Centralized	3	7.4bat, 5R, 3.3R
Gollat	1U	DET	Centralized	>1	7.4bat, others
HAUSAT	1U		Centralized	3	5R, 3.3R, 3.6bat
Hermes	1U	DET	Distributed	4	7.4R, 5R, 3.3R
KUTEsat	1U		Centralized	3	5R, 3.3R, 12bat
KySat	1U	PPT	Centralized	3	12bat, 5R, 3.3R
MEROPE	1U	PPT	Centralized	5	5R, -5R, 6R, 8R
OuFTl-1	1U	DET	Centralized	3	7.2bat, 3.3R, 5R
QuakeSat	3U	DET	Centralized	2	5R, -5R
Sacred	1U		Centralized	2	5R, 3.3R
SEEDS 1	1U	DET		1	5R
XI-IV	1U	DET	Centralized	3	5R
XI-V	1U	DET	Centralized	4	5, 3, 8bat

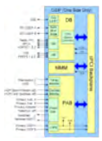
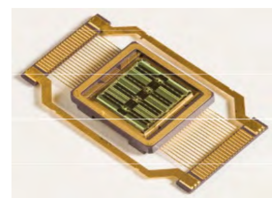
Though a centralized configuration is more common, there are studies claiming that a distributed system is more efficient as it is more flexible and has higher degree of utility (Burt, 2011). In most of the architectures shown above, the satellite distributes a 5 V, a 3.3 V, and sometimes a third regulated voltage to the battery bus.

All the electronic spacecraft components have gone through changes over the last few years. A plug-and-play approach allows a faster integration of previous designs and platforms but all the different subsystems must comply with a rigid group of physical, electrical and software standards. Customized designs are preferred by the majority of developers to allow adaptations to specific payload needs. The downside to customized electronics is increased requirements in terms of budget and time. Space plug-and-play avionics are self-describing and can be thought of as 'black boxes;' they can communicate with each other by network protocols (Bruhn et al., 2011). Plug-and play avionics are taking a more prevalent role as standards are adopted yielding the possibility of parallel development and simpler integration for different components. Some attempts to realize the plug-and-play concept have been conducted. For example, the QuadSat-PnP mission, launched in 2011, used this approach.

8.3 On the Horizon

While C&DH systems and on board processing both benefit from commercial advances and suffer from subtleties like parts obsolescence, the overall trends are promising. Companies like Texas Instruments and National Semiconductor Corporation have taken note of the challenges facing spacecraft designers and are proactively providing solutions, including guarantees of no obsolescence and continual development. There are also a number of technologies on the horizon that show good promise in advancing smallsat C&DH capabilities, illustrated in Table 41.

Table 41: Examples of C&DH technologies on the horizon.

Technology Name	Description	Developer	TRL Status	Image
Distributed Computing	Collection of networked satellites to perform parallel or distributed computing	N/A	**5**	N/A
Central instrument data handling (CIDH)	Data management system developed to handle large data volume	SwRI (USA)	**3** Analysis performed on critical functions to characterize performance	
Wireless bus	Wireless bus (bluetooth, WiFi) to reduce bus volume and design complexity	Northrop Grumman (USA), JAXA (Japan)	**3** Testbed introduced for design, build and test of wireless spacecraft bus	N/A
Phase change memory (PCM), aka CRAM or PRAM	Nonvolatile chalcogenide random access memory is inherently radiation hard utilizing amorphous state to store bits	BAE (UK), Micron (USA), Samsung (South Korea), Ovonyx (USA)	**5** Completed QML-Q testing	
Xilinx Virtex-5QV FPGA	Rad-hard reconfiguration FPGA	Xilinx (USA)	**5** testing performed in relevant environment. To be flown on COVE (2013/2014)	
SpaceCube 2.0	On board data processor, FPGA Xilinx Virtex 5 (FX130T)	NASA Goddard (USA)	**5**	

8.4 Conclusion

C&DH is a growing and rapidly advancing subsystem area for small spacecraft, with increased processing power and reduced mass, power and volume. C&DH subsystem components with the exception of memory storage devices are typically small in size, thus are not a major driver of mass and volume. While C&DH subsystem components draw considerable power, advancing technologies in commercial areas are already providing promising solutions. One drawback to fast evolving electronics is parts obsolescence (e.g. 80C32 microcontroller, TSC21020 DSP).

As mentioned, the hardware solutions to satisfy performance requirements are abundant. As such, differentiating criteria often revolve around cost, risk and heritage. It is often the case that proven heritage components are more expensive and less capable, while developmental units in the COTS realm are appealing for smaller programs more willing and capable of accepting risk.

8.5 References

Anon.: *Xilinx Virtex-5 Datasheet.* [Online] 2012. Available at: http://www.xilinx.com/support/documentation/data_sheets/ds192_V5QV_Device_Overview.pdf

Bentoutou, Y.: *A follow-up of in-orbit observations of radiation-induced effects in commercial off the shelf memories on-board Alsat-1.* Advances in Space Research, Volume 48, pp. 1147-1154, 2011.

Bentoutou, Y.: *A Real Time EDAC System for Applications Onboard Earth Observation Small Satellite.* IEEE Transactions on Aerospace and Electronic Systems, 48(1), pp. 648-657, 2012.

Bentoutou, Y., Mohammed, A. S.: *A Review of in-orbit Observations of Radiation-Induced Effects in Commercial Memories on-board Alsat-1.* s.l.: World Academy of Science, Engineering and Technology, 2012.

Bingcai, C., Haifeng, X., Wei, X.: *The Architecture of Picosatellite Nodes in Satellite Formation Network Based on Reconfigurable Distributed Computing.* Wireless Communications, Networking and Mobile Computing (WiCOM). Shanghai, 2012.

Burt, Robert: *Distributed Electrical Power Systems in CubeSat Applications.* Utah State University, 2012.

Conde, R. F. et al.: *Benefits and Lessons Learned from the use of the Compact PCI Standard for Spacecraft Avionics.* s.l., Digital Avionics Systems Conference, 2002.

Furano, G.: *Review of Rad Hard electronics activities at European Space Agency.* Topical Workshop on Electronics for Particle Physics (TWEPP). Oxford, UK, 2012.

Ibrahim, M. M., Asami, K., Cho, M.: *Fault Tolerant Architecture Alternatives for Developing Nano-Satellites Embedded Computers.* AIAA Space Conference & Exposition. Pasadena, CA, 2012.

Koizumi, H., Komurasaki, K., Arakawa, Y.: *Development of the Miniature Ion Propulsion System for 50 kg Small Spacecraft.* 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. Atlanta, Georgia, 2012.

MacLeod, T. C., Sims, W. H., Varnavas, K. A., Ho, F. D.: *Results from on-Orbit Testing of the Fram Memory Test Experiment on the Fastsat Micro-Satellite.* Integrated Ferroelectrics, 132(1), 2012.

Norton, J. R., Cloeren, J. M.: *Precision Quartz Oscillators and their use in Small Satellites.* Small Satellite Conference. Logan, UT, 1992.

Norton, J. R., Cloeren, J. M., n.d.: *Precision Quartz Oscillators and their use in Small Satellites.* Johns Hopkins University Applied Physics Laboratory. Laurel, Maryland.

Odegaard, K. A., Skavhaug, A.: *Simple Methods for Error Detection and Correction for Low-Cost Nano Satellites.* SAFECOMP. Toulouse, France, 2013.

Pingree, P. J.: *Advancing NASA's on-board processing capabilities with reconfiguratble FPGA technologies: Opportunities & Implications.* IEEE - Parallel & Distributed Processing. Atlanta, GA, 2010.

Sayyah, R., Macleod, T. C., Ho, F. D.: *Radiation-Hardened Electronics and Ferroelectric Memory for Space Flight Systems.* Ferroelectrics, 413(1), pp. 170-175, 2011.

Shimizu, T. & Underwood, C. Super-capacitor energy storage for micro-satellites: Feasibility and potential mission applications. *Acta Astronautica, 2013.*

Staehle, R. L. et al.: *Interplanetary CubeSat Architecture and Missions.* AIAA Space Conference & Exposition. Pasadena, CA, 2012.

Wang, J. J.: *Radiation effects in FPGAs.* s.l., 9th Workshop on Electronics for LHC Experiements, 2003.

9. COMMUNICATIONS

9.1 Introduction

The majority of small spacecraft missions have a primary objective to collect scientific data and to transmit that data back to researchers on Earth. One of the main impediments to data collection from in-orbit and interplanetary spacecraft is the transmission of data to and from the spacecraft. This section outlines the current SoA in small spacecraft communication technologies and also provides an overview of communication systems that are on the horizon.

9.2 State of the Art

Current small spacecraft technologies use an array of frequency bands to communicate. The majority of spacecraft, however, tend to use the following spectra:

- **Very High Frequency (VHF)** – 30 to 300 MHz
- **Ultra High Frequency (UHF)** – 300 MHz to 3 GHz
- **S Band** – 2 GHz to 4 GHz
- **X Band** – 8 GHz to 12 GHz
- **Ku Band** – 12 GHz to 18 GHz
- **K Band** – 18 GHz to 26.5 GHz
- **Ka Band** - 26.5 GHz to 40 GHz
- **Visible (LASER Communication)** – 100 THz to 800 THz

The general purpose of any communication system is to maximize the data transfer rate while minimizing hardware constraints, price, and power consumption. These factors among others dictate the frequency spectrum that is appropriate for a mission. This review of the current SoA technology will provide a general overview of the hardware behind current electricity & magnetism (E&M) communication systems. It will also encompass SoA transmitters, receivers, and antennas. In addition, a recent survey of communication systems for all cube satellites launched between the years 2003-2012 was conducted by Bryan Koflas (see Appendix I).

The maximum amount of data that can be transmitted over electromagnetic waves from point A to point B depends upon the signal to noise ratio (SnR) of the system and the available bandwidth. This maximum capacity is illustrated by the Shannon-Hartley theorem and is shown in Equation 1, where C is the maximum data transfer rate in bits/second, B is the bandwidth of the channel in Hertz, and SnR is the signal to noise ratio. Equation 1 is under the assumption that the carrier frequency does not approach the data transmission rate:

$$C = B \log_2(1 + SnR) \tag{1}$$

To increase data transmission rates there must be an increase in available bandwidth and SnR. Due to current utilization and government regulation, bandwidth is limited in the microwave frequency spectrum, but is much less restricted in the visible spectrum. SnR, however, is easily controlled by hardware specifications and is the target of current SoA research. The SnR ratio issue is addressed by increasing the signal strength and by finding better methods to filter out noise.

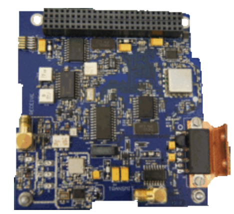
9.2.1 Transmitters

Transmitters are responsible for using an input signal to modulate a carrier wave which is then sent to an antenna. Since regulations, project budget, and expected data throughput are important factors in selecting a carrier frequency, the current non-exhaustive listing of SoA transmitters for each commonly used spectrum is identified below.

9.2.1.1 VHF/UHF Transmitters

VHF/UHF transmitters are a reliable, low cost solution for missions requiring nominal amounts of data transfer. These systems are typically used in LEO with omni-directional antennas, and therefore do not require a high level of pointing accuracy. Transceivers/transmitters in this category can cost from hundreds to a few thousand dollars. Some examples of current application of VHF/UHF Transmitters can be seen in Table 42.

Table 42: Examples of SoA VHF/UHF transmitters.

Technology Name	Description	Developer	TRL Status	Figures
Helium radio transmitter	UHV/VHF transmitter **Power consumption**: < 6 W **Mass**: ~0.1 kG **Data rate:** < 38.4 kbps	Astronautical Development (USA)	**9** Has successfully flown on multiple missions	
ISIS transceiver	VHF downlink / UHF uplink full duplex transceiver (transmit/receive) **Power consumption**: 1.7 W/0.2 W **Mass**: 0.085 kg **Data rate**: < 9600 bps / < 1200 bps	Innovative Solutions in Space (Netherlands)	**9** Over 24 units flown	
UHF/VHF transceiver	UHF/VHF transceiver (transmit/receive) **Power consumption**: 10 W/0.25 W **Mass**: 0.090 kg **Data rate**: < 9600 baud / < 1200 baud	Clyde Space (UK)	**9** Has successfully flown on multiple missions	

9.2.1.2 S-Band Transmitters

S-Band transmitters are a popular communication system being used on recent small satellite launches (see Table 43). These transmitters can be small enough in size to fit into a CubeSat, and can be scaled up in larger satellites to provide data transmission rates up to 10 Mb/s. These transmitters can range in cost from a few thousand to a few hundred thousand dollars depending upon size and reliability.

Table 43: Examples of SoA S-Band transmitters.

Technology Name	Description	Developer	TRL Status	Figures
CubeSat S-Band transmitter	S-Band transmitter for CubeSat applications **Power consumption**: < 6 W **Mass**: 0.08 kG **Data rate:** < 2 Mbps	Clyde Space (UK)	**6** Integrated in Ukube-1 and preparing for launch. Similar components can be found at TRL 9	
S-Band transmitter	High/Low mode transmitter with switchable data rates (high/low) **Power consumption**: 38 W/6 W **Mass**: 1.8 kg /0.60 kg **Data rate**: < 10 Mbps / < 38.4 kbps	Surrey Satellite Technology (UK)	**9** Over 24 Units Flown	
S-Band transponder	Integrated S-Band data transmitter and reciever. (Receive/Transmit) **Power consumption**: 5W/25W **Mass**: 2.6 kg **Data rate**: < 2 Mbps / < 8 Mbps	Thales Alenia Space (France)	**9** Has successfully flown on multiple missions	
S-Band transceiver	Integrated S-Band data transmitter and reciever. (receive/transmit) **Power consumption**: 4 W/14 W **Mass**: 0.78 kg **Data rate**: < 1 Mbps / < 6.25 Mbps	COM DEV EUROPE (UK)	**9** Has successfully flown on multiple missions	

9.2.1.3 X-Band Transmitters

X-Band transmitters start to approach the high data transfer rates currently available for fully vetted small satellite applications in the microwave frequency spectrum. These systems represent a significant increase in data transfer rate and system cost; this is a desirable class of transmitter for missions with large amounts of scientific data. For examples of X-Band transmitter applications on small spacecraft (see Table 44).

Table 44: Examples of SoA X-Band transmitters.

Technology Name	Description	Developer	TRL Status	Figures
X-Band transmitter	X-band transmitter for small satellite applications **Power consumption**: 120 W **Mass**: 4.0 kg **Data rate:** < 500 Mbps	Surrey Satellite Technology (UK)	**9** Has successfully flown on multiple missions	
X-Band transmitter	X-band transmitter for small satellite applications **Power consumption**: <90 W **Mass**:3.9 kg **Data rate**: < 400 Mbps	L-3 Cincinnati Electronics (USA)	**9** Has successfully flown on multiple missions	
X-Band transmitter	Low power low mass option **Power consumption**: 10 W **Mass**: 0.4 kg **Data rate**: < 50 Mbps	Syrlinks (France)	**6**	

9.2.1.4 K-Band/Ka-Band/Ku-Band Transmitters

The Ku-band spectrum is used primarily by fixed and broadcast services such as satellite television. Space shuttle communication systems and the ISS also use the Ku-band frequency for scientific ventures. Communication satellites most commonly use the Ka-band frequency, and the Kepler Mission uses a Ka-band transmitter to send scientific data. Table 45 shows some examples of SoA K/KA/KU-Band transmitters that are space qualified.

Table 45: Examples of SoA K,Ku,Ka-Band transmitters.

Technology Name	Description	Developer	TRL Status	Figures
Ka-Band transmitter	State of the art Ka-Band transmitter (receive/transmit) **Power consumption**: N/A **Mass**: 2.7 kg **Data rate**: < 3 Gbps	Space Micro (USA)	**3** Still scaling up performance to meet specifications	
Ku-Band transmitter	Ku-band transmitters with Ka-band and X-band options **Power consumption**: 47 W **Mass**:2.26 kg **Data rate**: < 150 Mbps	General Dynamics (USA)	**9** Has flown succesfully	
K-Band transmitter	Integrated S-Band data transmitter and Reciever. **Power consumption**: 30 W **Mass**: 2.8 kg **Data rate**: < 1.2 Gbps	L-3 Telemetry West (USA)	**6** Tested in similar environment	

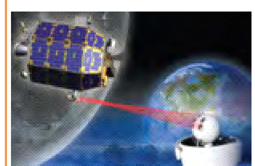
9.2.1.5 Infrared/Visible Spectrum Transmitters

Laser communication systems have been explored extensively for ground-based communication systems, but they are now starting to be explored as an option for in-orbit and interplanetary spacecraft missions. LASER communication systems can transfer large amounts of data with a significant decrease in power requirements and hardware mass from traditional microwave band-based communication systems.

The basic principle behind a LASER communication system is that a high-powered laser is incident upon an optical receiver. Due to little beam divergence and how well the laser signal can be collimated, the amount of power required to transmit a signal is reduced in comparison to radio wave-based communication systems. Because the signal is so directional, these systems produce almost no interference with other communication systems and pose little threat to congesting the spectrum like many other frequency bands have done.

This technology is being developed for ground-to-spacecraft, spacecraft-to-ground, and spacecraft-to-spacecraft systems. LASER communication systems look to be an exciting new field in the small spacecraft communications sector; Table 46 provides current information.

Table 46: An example of visible/infrared transmitters.

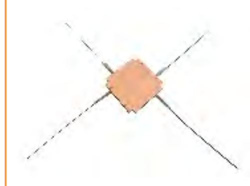
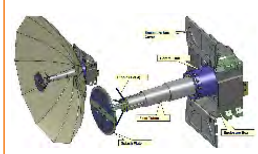
Technology Name	Description	Developer	TRL Status	Figures
Infrared/visible transmitter	LADEE laser communication demonstration, data rates from moon orbit. **Power consumption**: 50-140 W **Mass:** 30 kg (PPM/DPSK) **Data range**: <625 Mbps/<2.88 Gbps	NASA/Loral (USA)	**6** Launched on LADEE; Demonstrated in 2013	

9.2.2 Antennae

9.2.2.1 *Deployable Antennae*

High gain deployable antennae are of keen interest to many small spacecraft missions. Table 47 is a sampling of standardized deployable antennae available to small spacecraft.

Table 47: Examples of SoA deployable antennae for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
Deployable UHF/VHF antenna	A deployable antenna for cube satellite missions. Can deploy four monopole antennae. **Max RF power:** 2 W **Mass**: 0.10 kg	Innovative Solutions in Space (Netherlands)	**9** Flown on multiple successful missions	
Deployable high gain antenna	A deployable high gain antenna for cube satellites. **Max gain**: 18 dBi **Mass**: 1.0 kg	BDS Phantomworks (USA)	**6**	
Deployable high gain antenna	A deployable high gain antenna for cube satellites. **Max gain**: 15 dBi **Half angle:** 11° **Mass**: 1.0 kg	USC's Space Engineering Research Center (SERC), (USA)	**9** Launched succesfully on Aeneas CubeSat	

9.2.2.2 *Integrated Pointing Systems*

The current integrated pointing systems available provide a fully integrated system for a high gain antenna combined with accurate pointing units. The required accurate pointing technologies are not a main focus of this survey, but an example of a currently available product in this field can be found in Table 48.

Table 48: Examples of SoA integrated pointing systems for small spacecraft.

Technology Name	Description	Developer	TL Status	Figures
Integrated pointing high gain antenna	This technology provides a complete integrated system for a high gain antenna combined with a pointing unit accurate to 0.25°	Surrey Satellite Technology (UK)	**9** Flown on NigeriaSat-2	

9.2.2.3 Microstrip/Patch Antennae

There appears to be an increased use of Microstrip and Patch antennae in spacecraft communication systems. The reason for this is the microstrip and patch antenna are meant to minimize the mass and size requirements of a standard antenna while still maintaining good signal strength output. Microstrip and patch antennae are currently commercially available for a variety of frequency spectrums including the popular S-Band and X-Band (see Table 49).

Table 49: An example of patch antennae for small spacecraft.

Technology Name	Description	Developer	TL Status	Figures
S-Band patch antenna	X-band transmitter for small satellite applications **Half power angle**: 70° **Mass**: 0.08 kg **Gain:** < 7 dBiC	Surrey Satellite Technology (UK)	**9** Over 70 units flown	

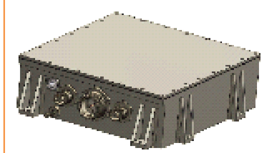
9.3 On the Horizon

There are many promising technologies in communication systems that are currently under development. These technologies cover a wide span of applications including novel transmitters, high gain antenna, and the use of additional frequency spectrums. The technology detailed is not an exhaustive list, but should provide a general idea of the areas of interest in current small spacecraft communication systems.

9.3.1 Ka-Band Transmitters

The Ka-band has the potential for even faster data transfer rates and products are currently in development to tap the large bandwidth the Ka-band has to offer. Table 50 is just one sample of upcoming Ka-band transmitters.

Table 50: Example SoA Ka-Band transmitters.

Technology Name	Description	Developer	TRL Status	Figures
Ka-Band transmitter	State of the art Ka-Band transmitter (receive/transmit) **Power consumption**: N/A **Mass**: 2.7 kg **Data rate**: < 3 Gbps	Space Micro (USA)	**3**	

9.3.2 Modulating Retro Reflectors

In an effort to reduce the power and mass load requirements placed on small spacecraft by their communication systems, research is being done to move much of that load from the satellite to the ground station. A high-powered laser from a ground station applies a pulse to a satellite; the satellite then modulates the incoming pulse and reflects it back to a ground station. This scheme provides two-way laser communication, but with all of the laser power provided by the ground station—the spacecraft communication subsystem, power, mass, and volume are very small, consisting only of the laser receiver and modulating retro reflector.

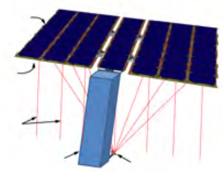
Table 51: Modulating retro reflector.

Technology Name	Description	Developer	TRL Status	Figures
Modulated retro reflectors	Modulating retro reflectors are attached to satellites which can modulated a groundbased signal and reflect it to transmit data. Designed for visible/ifrared spectrum.	NASA (USA)	**2-3**	

9.3.3 Integrated Solar Panel Reflect Arrays

Integrated solar panel reflect arrays aim to increase the data downlink rate for small spacecraft by several orders of magnitude by acting as a high gain antenna (see Table 52). This technique can be incorporated with minimal additional cost, mass, and volume as compared to a stand-alone high gain antenna. This technology is ideal for CubeSats or similar-sized spacecraft. A five month in-orbit small satellite mission, ISARA, is currently in the planning stages to validate this design.

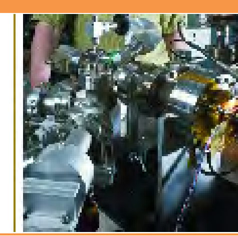
Table 52: Integrated solar panel reflect array.

Technology Name	Description	Developer	TL Status	Figures
Integrated solar panel reflect array	Using solar panels to reflect and concentrate radio waves to achieve higher data transfer rates	NASA JPL (USA)	2-3	

9.3.4 X-Ray Communication

Research is being conducted into communication systems using the X-ray frequency spectrum. Among other benefits, X-ray communication systems could overcome the re-entry communication blackout period (see Table 53). Lab demonstrations have created a digital data link > 1 Mbps. Additional in-orbit testing is currently being pursued

Table 53: X-Ray Communication.

Technology Name	Description	Developer	TRL Status	Figures
X-Ray communication	Communication using the X-ray frequency spectrum. Lab testing has been conducted with succesful digital links up to 1 Mbps	NASA (USA)	3	

9.4 Conclusion

The microwave frequency spectrum is currently highly developed for use in satellite communication systems. Current trends in this area involve using high gain antennae with high pointing precision to transmit large amounts of data.

The microwave spectrum however, is becoming quite congested and so the use of other spectrums, such as visible, seems promising. Optical communication systems are an area of heavy research and development at the moment and have the potential to provide increased data transfer rates with nominal bandwidth pollution compared to the microwave frequencies. Figure 50 below depicts the maximum achievable data transfer rates for different frequency spectrums. In spite of the early development stage, optical communication is already surpassing traditional transmitters.

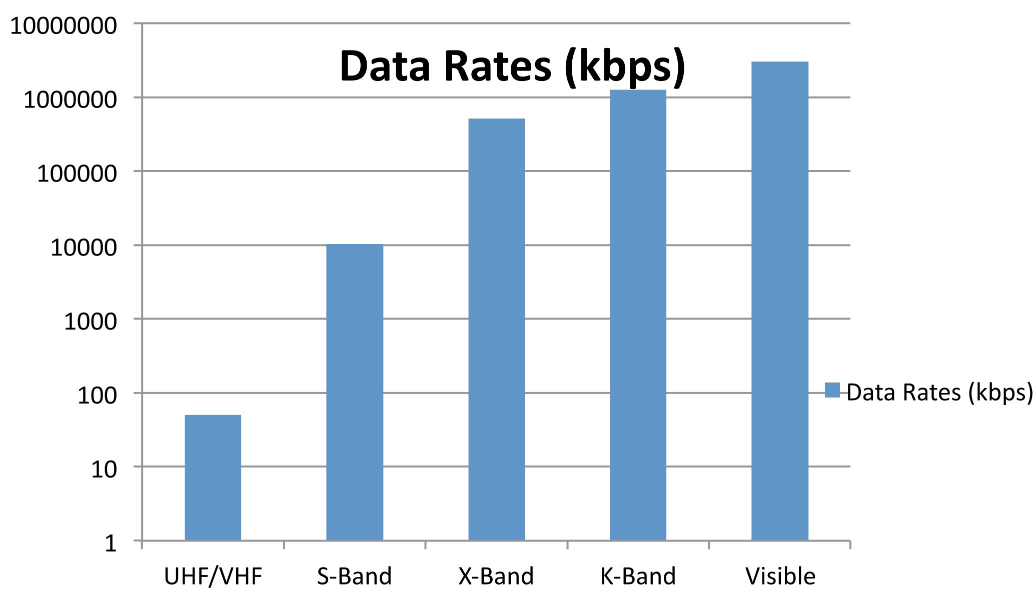


Figure 50: Data rates for frequency bands.

9.5 References

Astronautical Development: *AstroDev Helium Radios*. [e-book] Astronautical Development, 2009. http://www.astrodev.com/public_html/downloads/datasheet/Helium-Specification.pdf [Accessed: 20th August, 2013].

BDS Phantom Works: *Miniature Deployable High Gain Antenna*. [e-book] BDS Phantom Works, 2011. http://mstl.atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop2011/47_MacGillivray_Miniature_Antennas.pdf [Accessed: August 20th, 2013].

Cincinnati Electronics: *T-724A HIGH DATA RATE X-BAND TRANSMITTER*. [e-book] Cincinnati Electronics, 2013. Available at: http://www.cinele.com/images/space_datasheets/t-724a_x-band.pdf [Accessed: August 20th, 2013].

Cincinnati Electronics: *T-720 TRANSMITTER*. [e-book] Cincinnati Electronics, 2007. http://www.cinele.com/images/space_datasheets/t-720.pdf [Accessed: August 20th, 2013].

Clyde-space.com: *CPUT CMC: UHF/VHF Transceiver, Communication Systems CubeSat*. [online] 2013. Available at: http://www.clyde-space.com/CubeSat_shop/communication_systems/170_cmc-uhf-vhf-transceiver [Accessed: 26 Aug 2013].

Clyde-space.com: *CPUT CubeSat S-Band Transmitter, Communication Systems CubeSat*. [online] 2013. Available at: http://www.clyde-space.com/CubeSat_shop/communication_systems/301_CubeSat-s-band-transmitter [Accessed: 26 Aug 2013].

COM DEV EUROPE: *S-Band TT&C Transceiver*. [e-book] COM DEV EUROPE, 2010. http://www.comdev.ca/docs/TTC Data sheet V2-10.pdf [Accessed: August 20th, 2013].

Klofas, Bryan: *CubeSat Developers' Workshop 2013*. [online] 2013. Available at: http://mstl.atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop2013/

Klofas, Bryan: *CubeSat Developers' Workshop 2008*. [online] 2008. Available at: http://mstl.atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop2008/

CubeSatshop.com: *ISIS VHF downlink/UHF uplink Full Duplex Transceiver*. [online] 2012. Available at: http://www.CubeSatshop.com/index.php?page=shop.product_details&category_id=5&flypage=flypage.tpl&product_id=73&option=com_virtuemart&Itemid=67 [Accessed: 26 Aug 2013].

Directory.eoportal.org: *LADEE - eoPortal Directory - Satellite Missions - Earthnet Online*. [online] 2011. Available at:

https://directory.eoportal.org/web/eoportal/satellite-missions/l/ladee [Accessed: 26 Aug 2013].

Gendreau, K.: *X-Ray Comm*. [email] Sent August 15th, 2013.

General Dynamics: *Ku/Ka/X-Band High Rate Transmitter (HRT150)*. [e-book] General Dynamics, 2012.
http://www.gd-ais.com/Documents/High Rate Transmitter (HRT150).pdf [Accessed: August 20th, 2013].

Innovative Solutions In Space: *Deployable UHF and VHF antennas*. [e-book] Innovative Solutions In Space, 2013.
http://www.isispace.nl/brochures/ISIS_AntS_Brochure_v.7.11.pdf [Accessed: August 20th, 2013].

L3 Telemetry West: *K-Band OQPSK Transmitter*. [e-book] L3 Telemetry West, 2012.
http://www2.l-3com.com/tw/pdf/datasheets/ML601_Rev D.pdf [Accessed: August 20th, 2013].

NASA JPL. n.d.: *ISARA - Reflectarray Antenna for High Bandwidth Communications*. [e-book] NASA JPL. http://www.nasa.gov/pdf/706631main_sstp_3_projects.pdf [Accessed: August 20th, 2013].

Salas, A., Stupl, J. and Mason, J.: *Modulating Retro-Reflectors: Technology, Link Budgets And Applications*. 63rd International Astronautical Congress, 2013. [Accessed: 27 Aug 2013].

Space Micro: *μTx-300 Ka-Band Transmitter*. [e-book] Space Micro, 2013.
http://www.spacemicro.com/pdfs/KA-Band v5.0.pdf [Accessed: August 20th, 2013].

Sstl.co.uk. n.d.: *High Gain X-Band Antenna Pointing Mechanism*. [online] Available at:
http://www.sstl.co.uk/Products/Subsystems/Communication/Antennas/High-Gain-X-Band-Antenna-

10. INTEGRATION, LAUNCH AND DEPLOYMENT

10.1 Introduction

The current development of small spacecraft integration, launch, and deployment systems has largely been focused on leveraging existing launchers for much larger vehicles. To reduce costs, small spacecraft are often allocated a chunk of the mass margin leftover after the primary mission defines most launch criteria. In this paradigm, small spacecraft are certainly not the drivers of launch requirements and are usually designed explicitly for minimal interference to the primary mission. As small spacecraft grow increasingly popular and capable, launch vehicles, integration, and deployment systems must meet the challenges of rising demand and capabilities. SoA technologies in these areas 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.

SoA launch vehicles such as the Evolved Expendable Launch Vehicle (EELV) boosters were not originally designed for hosting small payloads. Since launch vehicles rarely match the exact capabilities needed by the primary customer, there is usually enough leftover mass, volume, and other performance margins available for delivery of small spacecraft. Small spacecraft can share this "free" space for a cheap ride to space. A large market of adapters and deployment technologies has been created to compactly house multiple small spacecraft on these heritage launchers. These technologies provide both a secure attachment to the launcher as well as mechanisms for departure at the appropriate time. In the future, though, the expanding capabilities of small spacecraft payloads will demand a dedicated launcher. For missions that need a very specific science orbit, interplanetary trajectories, precisely timed rendezvous, or special environmental considerations, flying the spacecraft as a primary payload may be the best method of ascent. Highly capable host spacecraft will provide greatly expanded capabilities to large launchers as well. Through innovative dedicated launchers or integration mechanisms, the mission envelope for small spacecraft can be greatly expanded. 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 Vehicles

10.2.1.1 Primary Payloads

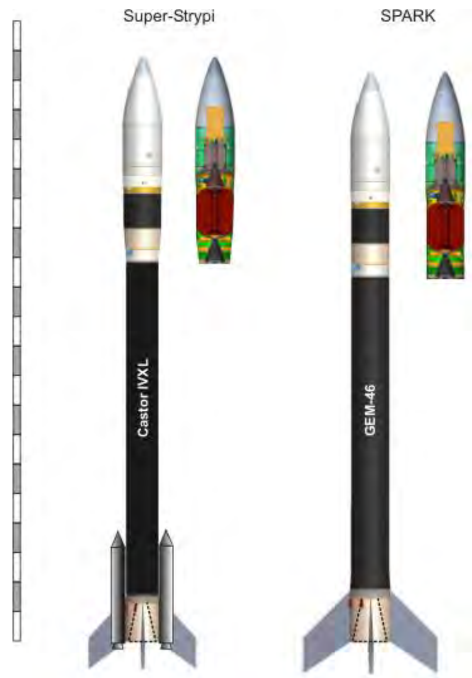


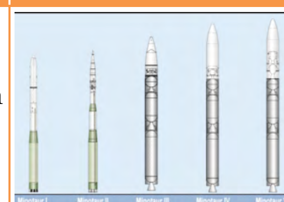
Figure 51: The Super Strypi and SPARK launchers (Brügge, n.d.).

The primary payload market for small spacecraft is currently very limited. To date, only a few modern vehicles are available specifically for small spacecraft. Since the growth in popularity of small spacecraft is a recent development, a robust market of small launchers has not yet developed. Of the vehicles on the market, though, the Super Strypi/SPARK (Spaceborne Payload Assist Rocket; see Figure 51) rocket has TRL value of 9 and is a promising technology. Developed jointly by the Innovative Satellite Launch Program at the University of Hawaii in cooperation with Sandia National Laboratories and Aerojet, SPARK is an evolved version of Sandia's Super Strypi research rocket that is designed to deliver 250 kg to a 400 km Sun-synchronous orbit from Kauai, Hawaii. It is designed to integrate payloads with the NASA Ames payload adapter and deployer. Launch of a 1U spacecraft is anticipated to be only ~$40-60K, and launch of a 12U is ~$1.5M (Taylor, 2013). The first launch is planned for October 2013 (David, 2013).

The Pegasus, an air-launched vehicle built by Orbital Sciences, is a small- to medium-lift launcher that has already built a heritage of successful launches since 1996. The system can deliver 450 kg to LEO with three solid stages. The rocket has a record of 26 consecutive fully successful missions including the recent NASA Interface Region Imaging Spectrograph (IRIS) mission launched in June 2013 aboard a Pegasus XL variant (NASA, 2013). This system allows greater mobility and flexibility in launch since the rocket is launched from a carrier aircraft (Orbital Sciences, 2013).

Another vehicle produced by Orbital Sciences, the Minotaur, is the last medium-lift launcher currently available to be considered as a SoA primary payload launch vehicle. With a payload capacity of 580 kg to LEO, the Minotaur would be overkill for most small satellite missions, but could still be valuable depending on destination and number. Out of the entire rocket family, the Minotaur I is the most applicable to small satellites since it has the lowest payload and cost, and has conducted ten missions successfully. The Minotaur I is designed with four solid stages from a converted Minuteman ballistic missile (Orbital Sciences, 2013).

Table 54: Examples of SoA primary launch vehicles for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
Minotaur	Rocket family currently with 580 kg to LEO (Minotaur I) and 437 kg to TLI (Minotaur V)	Orbital Sciences (USA)	**9** First launch of family in 2000; launch of Minotaur V in 2013	
Pegasus	Air-launched, three-stage orbital vehicle with up to 450 kg to LEO	Orbital Sciences (USA)	**9** Launched successful IRIS mission; 26 consecutive fully successful missions	
Satellite launch vehicle VLS-1	380 kg to LEO; three-stage solid, eventual evolution to some liquid stages	Brazilian Space Agency (AEB), with Russian assistance (Foreign)	**6** Multiple tests of vehicle, but no successfully flown missions yet	
Super Strypi	Small, three-stage, all-solid orbital expendable launcher with 250 kg payload to 400 km SSO	University of Hawaii, Sandia, Aerojet (USA)	**7** Will fly HiakaSat by late 2013	
NLSP nano-sat launcher (NEXT program)	15 kg to 425 km minimum specs	NASA Launch Services; Contractor not yet selected (USA)	**6 or higher** Draft RFI prepared at http://prod.nais.nasa.gov/eps/eps_data/156837-DRAFT-001-001.pdf	N/A

10.2.1.2 Secondary Payloads

Secondary payload arrangements provide far more options for immediate launch at high TRL. Workhorse vehicles like the Atlas V and Soyuz now carry secondary payloads as regular course. Since almost any large launcher can fit a small payload within mass and volume margins, there is no shortage of options for craft that want to fly as a secondary. Even on small vehicles like the Super Strypi/SPARK, there is often enough extra performance to squeeze in at least a 1U CubeSat.

The EELV program's boosters, the Atlas V and Delta IV, have been the most common and capable 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 mission to several small CubeSats in Poly Picosatellite Orbital Deployers (P-PODs). With a diverse family of launchers and a fully developed integration and launch services scheme, the EELVs are the most successful small spacecraft launchers currently available.

The Atlas V (see Figure 52) can deliver from approximately 9,800 kg to almost 19,000 kg into a 200 km LEO orbit at 28.7° depending on configuration. The Atlas program enjoys a long heritage reaching back over 600 launches, and the Atlas V has been 100% successful since its introduction. The Delta IV is a heavier lift EELV that can deliver from approximately 9,200 kg to over 28,000 kg to a 200 km LEO orbit at 28.7° depending on configuration. Although the Delta IV does not share the same long flight history as the Atlas, it provides good opportunities for secondary launches due to its extreme payload capability (United Launch Alliance, 2013).

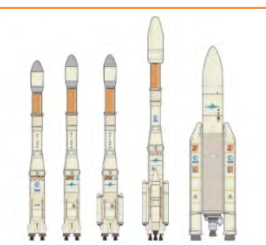
Figure 52: Atlas V with the LCROSS and LRO payloads (Atkinson, 2009).

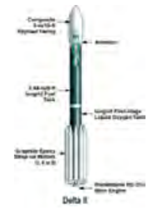
The Falcon family of rockets from Space Exploration Technologies (SpaceX) is proving to be another valuable asset to the small spacecraft community as well.

SpaceX's only current launcher is the Falcon 9, a two-stage LOX/RP-1 vehicle capable of lifting over 13,000 kg to LEO. SpaceX's contracts with NASA to provide cargo services and eventually crewed missions to the International Space Station means those opportunities to rideshare will continue into the far future. All five launches to date have been successful. SpaceX is currently redesigning the vehicle to yield higher performance and lower costs, and plans to achieve at least partial reusability which could dramatically lower costs for all spacecraft (Technologies, Space Exploration, 2013).

Foreign vehicles such as the Soyuz and Dnepr-1 are also viable competition in the market. Like the Atlas, Soyuz also enjoys a long heritage and is one of the most popular launchers in the world. Both Soyuz and Dnepr-1 are designed and built in Russia. The Soyuz is the only current launcher for human crews to the ISS.

Table 55: Examples of SoA secondary launch vehicles for small spacecraft.

Technology Name	Description	Developer	TRL Status	Figures
Antares	Two-stage launcher with solid and liquid stages for payloads over 5,000 kg to LEO	Orbital Sciences (USA)	**9** Launcher for successful PhoneSat mission	
Ariane 5	European civilian launcher family; current Ariane 5 is heavy lift vehicle capable of 20,000 kg to LEO	European Space Agency (Foreign)	**9** Ariane 1 first operational in 1979; Ariane 5 first operational in 1996	
Atlas V	Evolved expendable 9,800-18,850 kg to LEO; multiple secondary payloads aboard ESPA ring	United Launch Alliance (USA)	**9** Hot Bird 6 first launch; has flown several CubeSats and other small satellites since	

Delta II	2,700 kg - 6,100 kg to LEO; two-stage liquid with option third stage	United Launch Alliance (USA)	**9** First launch in 1989	
Delta IV	Rocket family with medium- and heavy-lift options; 8,600 kg - 22,560 kg to LEO	United Launch Alliance (USA)	**9** First launch in 2002	
Dnepr-1	4,500 kg to LEO; three-stage, hypergolic	Yuzhny Machine-Building Plant (Foreign)	**9** First launch in 1999	
Falcon 9	13,150 kg to LEO; ongoing design for reusability; LOX/RP1 two-stage booster	Space Exploration Technologies (USA)	**9** First launch 2010	
Falcon heavy	53,000 kg to LEO; ongoing design for reusability; LOX/RP1 two-stage booster	Space Exploration Technologies (USA)	**7** Multiple Falcon 9 core flights for NASA COTS/CRS missions	
H-IIA/B	10,000 kg (H-IIA) - 16,500 kg (H-IIB) to LEO	Mitsubishi Heavy Industries (Foreign)	**9** First launch of H-IIA in 2001	
International Space Station	Hand-launch or P-POD deployment for CubeSats	ISS Partners; launcher for CubeSats on JEM (Japanese Experiment Module) (Mixed)	**9** J-SSOD deployed multiple CubeSats on Expedition 33	
Kosmos-3m	1,500 kg to LEO; IRFNA/UDMH-fueled two-stage	Yuzhnoye/NPO Polyot (Foreign)	**9** First flight in 1967	
Long March	Widely varies; currently 2,400 kg - 11,200 kg to LEO	China Academy of Launch Vehicle Technology (Foreign)	**9** First of family launched in 1970; most recent launch of taikonauts in June 2013	

Minotaur	Rocket family currently with 580 kg to LEO (Minotaur I) and 437 kg to TLI (Minotaur V)	Orbital Sciences (USA)	**9** First launch of family in 2000; launch of Minotaur V in September 2013	
Pegasus	Air-launched, three-stage orbital vehicle with up to 450 kg to LEO	Orbital Sciences (USA)	**9** Launched successful IRIS mission; 26 consecutive fully successful missions	
PSLV	3,250 kg to LEO (standard)	Indian Space Research Organization (Foreign)	**9** First flight 1993	
Rokot-KM	1,950 kg to LEO; three-stage, liquid	Eurockot Launch Services (Foreign)	**9** First flight in 1990	
Soyuz	Rocket family; three-stage LOX/RP1 with 7,100 - 7,800 kg to LEO	OKB-1, TsSKB-Progress (Foreign)	**9** Large heritage of missions; currently only man-rated launcher to ISS; first flight in 1966	
Space Launch System	Initially 70,000 kg to LEO, evolved to 130,000 kg	Boeing, ATK, Pratt & Whitney Rocketdyne, NASA, and others (USA)	**7** First flight scheduled for 2017; significant use of shuttle-derived components	
Super Strypi	Small, three-stage, all-solid orbital expendable launcher with 250 kg payload to 400 km SSO	University of Hawaii, Sandia, Aerojet (USA)	**7** Will fly HiakaSat by late 2013	
Taurus	1,320 kg to LEO; four solid stages	Orbital Sciences (USA)	**9** First launch in 1994, but notable recent failures	
Vega	European small launcher with 300-2,500 kg primary payload and up to 9 CubeSats; reference mission is 1,500 kg to 700 km polar orbit	European Space Agency (Foreign)	**9** CubeSats flown in 2007 on maiden flight of vehicle	

10.2.2 Payload Adapters and Deployment

Currently no launch vehicle dedicated to payloads less than 180 kg is available, thus most small satellites must ride as secondary payloads. In order to accommodate this class, and in order to fully use available payload space on launch vehicles, adapters have been created to store, isolate and deploy secondary payloads. A broad spectrum of adapters exists to serve payloads of different sizes, as shown in Figure 53.

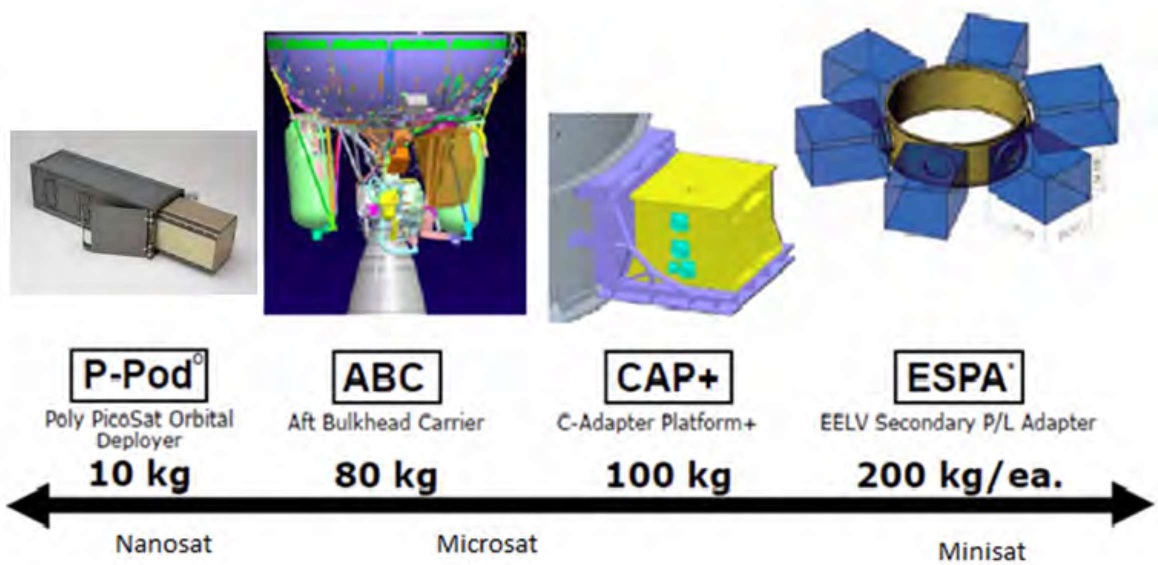


Figure 53: Examples of secondary payload adapters available to serve payloads of various masses, ranging from nanosatellites to minisatellites (Image credit: United Launch Alliance).

10.2.2.1 Nanosatellites 0-10 kg

The nanosatellite class is dominated by CubeSats. Although the CubeSat architecture does not strictly limit spacecraft mass to be less than 10 kg, to-date CubeSats missions have fit within this range. While nanosatellites exist outside the form factor of the CubeSat, they require individualized adapters. Therefore the focus of this section is on integration systems conforming to the CubeSat architecture.

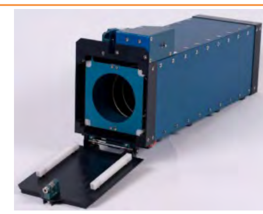
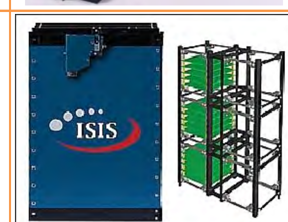
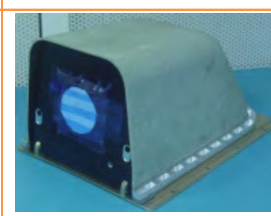
The CubeSat form lends itself to container based integration systems. While several systems exist, the standard deployer is the Poly Picosatellite Orbital Deployer, or P-POD, named for California Polytechnic State University where it was originally developed.

Figure 54: P-POD ejection spring (Image credit: http://rjwagner49.com/Personal/Work/Mayflower/).

The P-POD is a rectangular 7075-T73 aluminum container which can hold up to 10 x 10 x 34 cm 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 (see Figure 54. If more than one satellite is loaded, additional spring plungers placed between CubeSats are used to provide initial separation between payloads. The interior is anodized with a Teflon-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 m/s, though the central spring may be replaced to achieve different exit velocities (Lan, 2007). Typically P-PODs are connected to a larger secondary payload interface and not directly to the launch vehicle (see Microsatellites and Minisatellites subsections for more information).

Other POD designs exist, though the systems are essentially the same as the P-POD. Such systems include T-POD, X-POD, ISIPOD, and EZPOD. Details on these technologies may be found in Table 56. One should note these deployers are not necessarily competitors to the P-POD, but rather exist to provide various organizations rideshare opportunities when room for secondary payloads opens on launch vehicles (Kramer, 2012).

Table 56: Examples of SoA 1-3U POD deployers for small satellites.

Technology Name	Description	Developer	TRL Status	Figures
P-POD	Tubular container which deploys up to 3U CubeSats	Spaceflight, Inc. (USA)	**9** Successfully deployed 4 CubeSats from Eurockot in 2003	
T-POD	Adapter used to deploy a 1U CubeSat	University of Tokyo (Japan)	**9** Successfully used to deploy XI-V CubeSat in 2003	
X-POD	Customizable adapter which deploys up to 14kg, inlcuding CubeSat standard	UTIAS Space Flight Laboratory (Canada)	**9** Successfully used to deploy CubeSats on ISRO PSLV-C9 in 2008	
ISIPOD	CubeSat launch adapter capable of carrying 1, 2 and 3 U CubeSats	ISIS (Netherlands)	**9** 3U ISIPOD successfully deployed Cosmogia's Dove-1 and Dove-2 spacecraft in 2013	
EZPOD	US version of ISIPOD, 6U and 12U versions in development	Andrews Space, Inc. and ISIS, (USA and Netherlands)	**9** Successfully used to deploy STRanD-1 CubeSat in 2013	
J-SSOD	Deploys up to 6 1U CubeSats from the ISS	Japan Aerospace Exploration Agency (JAXA), (Japan)	**9** Successfully deployed CubeSats including RAIKO, FITSAT-1, WE WISH, NanoRacks CubeSat-1/F-1 and TechEdSat	
Rocket Pod	1U CubeSat deployer based on RocketCam system	Ecliptic Enterprises (USA)	**8** System has been tested on zero gravity and sub-orbital flights. First mission will be the BarnacleSat Mission	

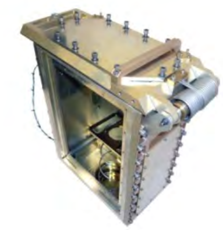
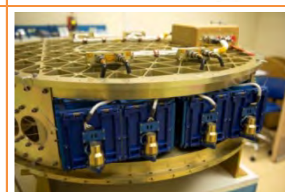
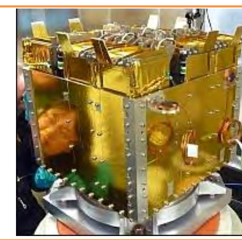
Ecliptic Enterprises developed an approach for carrying CubeSat secondary payloads on the exterior of rockets. The device, known as RocketPod™, may also be mounted on the interior of the payload fairing or on adapter rings such as ESPA and CAP (see Microsatellites and Minisatellites subsections). RocketPod™ uses mechanical and electrical interfaces flight proven on Ecliptic's RocketCam™. Like the P-Pod, ejection is achieved via a spring-loaded mechanism (Caldwell & Ridenoure, 2005).

In addition to deploying from a launch vehicle as a secondary payload, nanosatellites may also be deployed from the ISS via the Japanese Experiment Module (JEM) Small Satellite Orbital Deployer (J-SSOD). Like previous deployers, ejection is achieved via a compressed spring mechanism and guide rails (IHI Aerosapce, 2012).

As CubeSats grew in popularity, demand increased for integration systems allowing for larger CubeSat payloads, as well as more CubeSats per launch. To accommodate this demand, a variety of 6U-capable deployers based on the P-POD were developed, including Wallops' 6U deployer, Planetary Systems' Canisterized Satellite Dispenser (CSD), Andrew's 6U EZPOD, and NASA Ames' NanoSat Launch Adapter System (NLAS). While these systems have yet to fly, all have been tested in a relevant environment and achieved a TRL of at least 6. As a secondary payload adapter system, not merely a deployer, NLAS has the additional advantage of carrying a large number of CubeSats, up to a total of 24U (Ames, 2013).

Like NLAS, the Naval Postgraduate School's CubeSat launcher (NPSCul) is capable of carrying large numbers (up to 24U) of CubeSats to orbit. While NLAS is a stand-alone adapter system, NPSCul requires an additional secondary payload adapter to interface with the launch vehicle. The capabilities of the aforementioned systems are highlighted in Table 57.

Table 57: Examples of SoA 6U+ deployment systems.

Technology Name	Description	Developer	TRL Status	Figures
Wallops 6U CubeSat deployer	CubeSat deployer capable of holding 6U CubeSats	Goddard Space Flight Center/ Wallops Flight Facility (USA)	**6** Vibration and deployment testing in relevant environmnet	
Canisterized Satellite Dispenser (CSD)	CubeSat dispenser capable of deploying 3U and 6U payloads	Planetary Systems Corporation (USA)	**6** Qualified to MIL-STD-1540 level	
NLAS	Deploys 1, 3 and 6 U CubeSats, up to a total of 24U.	NASA Ames Research Center (USA)	**6** Qualified using the General Environmental Verification Standards	
NPSCul	Adapter used to carry 8 P-PODs, or up to 24U volume of CubeSats	Naval Postgraduate School (USA)	**9** Deployed 11 CubeSats for OUTSat mission	

10.2.2.2 Microsatellites 10-100 kg

Payloads in the microsatellite class have fewer dedicated integration systems. While a few adapters specifically targeted to this mass range exist, most payloads of this class must be designed to fit with minisatellite class integration systems. Indeed, integration systems specifically targeted towards microsatellites, such as the Aft Bulkhead Carrier (ABC), often evolved out of unique situations.

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 50.8 x 50.8 x 76.2 cm 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, namely the secondary payload is completely isolated from the primary, thereby relaxing electromagnetic interference and contamination concerns of the primary payload. OSL designed the ABC (see Figure 55) to host payloads in this space. The adapter carries up to 80 kg by utilizing the plate and struts previously used to house the helium tank (Willcox, 2012).

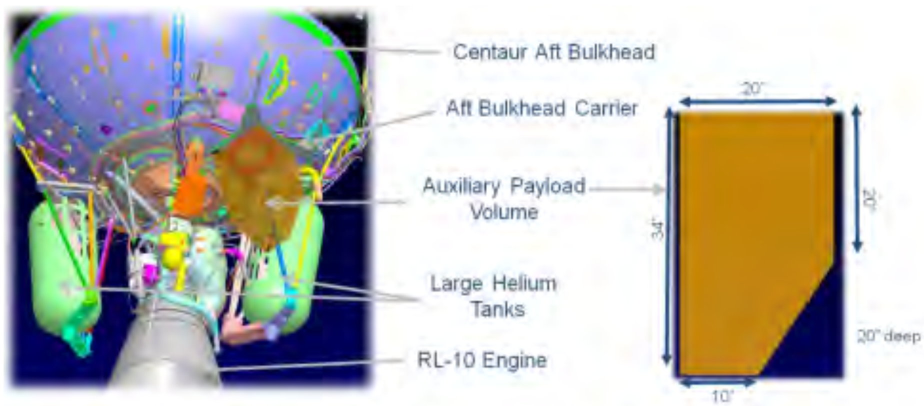
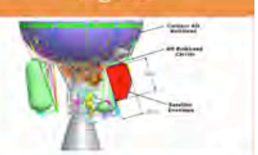
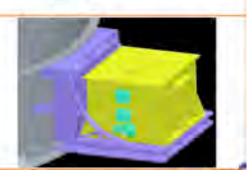


Figure 55: Aft Bulkhead Carrier (Willcox, 2012).

Another adapter, originally used to house batteries, has been converted into secondary payload volume. The C-Adapter Platform (CAP) is a cantilevered platform capable of carrying up to 45 kg in a volume of 23 x 31 x 33 cm. The platform is attached to a C-adapter ring via a 20.3 cm clampband and is compatible with Atlas V and Delta IV launch vehicles (Szatkowski, 2013). 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 (ULA, 2010).

Table 58: Microsatellite secondary payload adapters.

Technology Name	Description	Developer	TRL Status	Figures
Aft bulkhead carrier	Adapter located at the aft end of the Atlas V Centaur second-stage, carries up to 80 kg of payload	United Launch Alliance (USA)	9 Successfully used on OUTSat Mission	
C-Adapter platform	Platform compatible with C-Adapter ring. Each ring holds up to 4 platforms, and each platform holds up to 45 kg of payload	United Launch Alliance (USA)	9 Successfully launched in 2012	

10.2.2.3 Minisatellites 100-180 kg

To use additional payload space on the EELV, the Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS) contracted Moog CSA Engineering to develop what has become known as an ESPA ring, or EELV Secondary Payload Adapter. The original ESPA was designed to carry a 6,800 kg primary payload and up to six 180 kg secondary payloads (Goodwin & Wegner, 2001). Although initially designed to be compatible with the Atlas V and Delta IV launch vehicles, the adapter is also compatible with the Taurus II launch vehicle. Additionally, SpaceX has recently made an agreement with Spaceflight Inc. to host secondary payloads using Spaceflight's Secondary Payload System (SSPS), which has at its core an ESPA ring (Bergin, 2012).

ESPA is a ring of 7070 T7451 aluminum with six equally spaced 38 cm diameter bolt circles used to attach six secondary payloads. ESPA sits between the launch vehicle upper stage and the primary payload, where rings may be stacked to accommodate more secondary payloads. Each secondary is allowed to occupy a maximum volume of 61 x 61 x 96.5 cm with a 50.8 cm center of gravity requirement (Goodwin & Wegner, 2001). The deployment is left to the payload designers, but the ejection system and the payload together must fit within the size and mass constraints. Any payload that fits within these constraints and is compatible with the 38 cm bolt circles may ride as a secondary on ESPA, including the CubeSat deployers discussed previously. In addition to providing a physical link to the launch vehicle, the ESPA system also accommodates an electrical interface between launch vehicle and payload to provide power.

Moog CSA also developed the ESPA Six Unit Mount (SUM), which allows for the addition of up to 12 3U satellites. ESPA SUM makes use of the interior portion of the adapter ring to house either two 3U P-PODs or one 6U deployer behind each 38.1 cm port, in addition to the six 180 kg payloads (Moog, 2013). CubeSat deployers may be mounted internally or externally as shown in Figure 56. If mounted externally, then a total of 24 3U CubeSats may be deployed from the ESPA SUM, using CSD and P-POD deployers.

Figure 56: (Left) ESPA SUM with interior mounted CubeSats and (right) exterior mounted (Marin, n.d.).

To support payloads on the Minotaur launch vehicle, Orbital Sciences Corporation developed the Multiple Payload Adapter Plate (MPAP), a flat plate adapter capable of holding up to four 180 kg payloads in a volume of 90.2 x 78.1 x 61 cm (Orbital Sciences, 2013). Plate adapters are used in conjunction with other payload adapters to increase the overall secondary payload space. Moog CSA has developed a similar adapter, known as the Spiderman Adapter, to interface with ESPA rings. The adapter, seen in Figure , holds two 180 kg payloads (Pendleton, et al., n.d.). MPAP, ESPA, and other minisatellite payload adapter systems can be seen in Table 59.

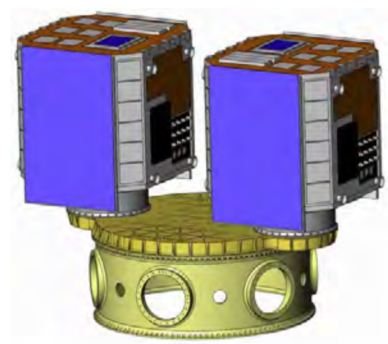
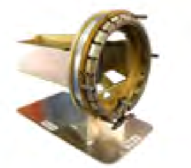
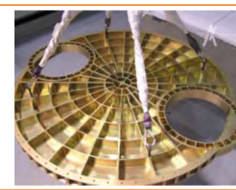


Figure 57: Two payloads attached to an ESPA ring via the Spiderman adapter (Pendleton, et al., n.d.).

Table 59: Minisatellite payload adapter systems.

Technology Name	Description	Developer	TRL Status	Figures
ESPA Ring	Payload interface which carries up to six 180 kg secondary payloads	Moog CSA (USA)	**9** Enabled STP-1 mission in 2007	
ESPA SUM	ESPA payload adapter used to carry up to twelve 3U satellites per ring	Moog CSA (USA)	**6** NASA LSP provided guidance to qualify prototype based on generic space flight parameters	
Multiple Payload Adapter Plate (MPAP)	Minotaur adapter capable of holding up to four 180 kg payloads	Orbital Sciences Corporation (USA)	**9** Successfully used on STP-S26 mission in 2010	
Spiderman flat plate adapter	Adapter plate integrates with ESPA enabling two additional 180 kg payload	Moog CSA (USA)	**6** Successfully tested under flight conditions	
Secondary Payload Adapter and Separation System (SPASS)	Capable of carrying one 200 kg primary payload, 90 kg secondary payloads, and up to 24 1U CubeSats	Space Access Technologies and ATSB (USA and Malaysia)	**9** Successfully flown on Falcon 1, used to deploy RazakSAT	

10.2.3 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 is a motorized separation system that ranges from 20.3 cm to 96.5 cm in diameter. Smaller Lightband systems are used to deploy ESPA class satellites, 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 (PSC, 2013).

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. Upon severing the connecting bolt, via bolt cutters or pyrotechnic bolts, the stored energy is rapidly released and the payload separates (Lazansky, 2012). 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. Qwksep is available in two sizes, 38.1 cm for ESPA applications and 61 cm for ESPA Grande applications (Stavast, et al., n.d.).

Other products making use of similar technology are available, but the products in Table 60 are representative of the SoA. Depending on the launch vehicle, separation systems may already be in place and available to secondary payloads.

Table 60: Band separation systems.

Technology Name	Description	Developer	TRL Status	Figures
Motorized Lightband (MLB)	System used to separate payloads from launch vehicles	Planetary Systems Corporation (USA)	**9** Has successfully flown on over 30 missions	
Qwksep	Clamp band separation system for ESPA and ESPA Grande class satellites	Sierra Nevada Corporation (USA)	**6** Significant testing has been conducted to verify system	

10.2.4 Launch Integration Services for Secondary Small Spacecraft Payloads

The sharing of a launch between a secondary small-satellite and a primary payload is not considered to be standard and thus the services required for such rideshare implementation are non-standard as well. Generally, the launch vehicle (LV) customer (not the LV manufacturer) decides whether secondary smallsat payloads will share a ride with a primary payload and if so, how these secondary smallsats are dispensed. In most cases, the LV customer is the primary payload; however, there are cases where a program or integration company can determine rideshare possibilities (Sanchez, 2013). 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 “standard” rideshare 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 smallsat-to-dispenser and dispenser-to-LV.

Rideshare integration services considered to be “non-standard” 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 include Spaceflight Services, Tyvak Nano-Satellite Systems LLC, and TriSept Corporation.

Spaceflight Services provides routine access to space for deployed and hosted smallsat payloads by using published commercial pricing, standard interfaces, and frequent flight opportunities. They have launched payloads on multiple LVs for NASA and industry (see Figure 58 for a visual representation of a smallsat ejection from a dispenser). Specific integration services provided include engineering analysis, smallsat-to-dispenser and LV integration, flight service, coordination of launch and on-orbit services, safety audits, customer manifest planning, and standard interface options for smallsats, including CubeSat (e.g., 6U, 12U and 24U) from P-POD systems (Spaceflight Services LLC, 2013).

Figure 56: *Spaceflight Services* depiction of Smallsat ejections from dispenser in low-Earth orbit (LEO) (Spaceflight Services LLC, 2013).

Tyvak Nano-Satellite Systems LLC provides smallsat space vehicle products and launch integration services such as engineering analysis, integration of complex smallsat (e.g. CubeSat) subsystems, smallsat-to-LV interface control documentation, verification of requirements, and payload certification (Tyvak Nano-Satellite Systems LLC, 2013). *Tyvak* has the experience of 11 successful launches with five launches in the planning and development stages. Other integration service capabilities include: smallsat-to-dispenser and LV integration, dispenser design, fabrication, flight certification, testing (including shock, vibrations, thermal, and thermal vacuum), launch and general mission operations, and launch coordination between US and foreign entities.

TriSept Corporation serves as the lead integrator for the Operationally Responsive Space (ORS) Office. *TriSept Corporation* has smallsat rideshare integration experience with NASA, Department of Defense (DoD), and industry, providing integration of multiple smallsats (e.g. CubeSat from P-POD) on the Athena LV and performing integration management of 45 unique smallsat payloads as part of the ORS-3 and ORS-4 missions (TriSept Corporation, 2013); see Figure for an example of a primary spacecraft integrated with a dispenser filled with secondary smallsats. Specific integration services include secondary payload integration, interface testing, smallsat-dispenser and primary-to-LV integration, engineering analysis, and payload certification (TriSept Corporation, 2013).

Figure 59: Example of primary payload integrated with smallsat secondary payloads stowed in dispenser (TriSept Corporation, 2013).

10.2.5 Isolated Environmental Control Possibilities

Services and technologies related to isolating potentially critical environments for secondary smallsat payloads (such as venting, shock, vibrations, and thermal) should be considered. To date, there have not been enough missions to properly define these environments for each combination of LV-to-smallsat dispenser system and thus this environmental information provided by LV manufacturers is applicable for the entire payload, not just the secondary. However, this does not mean the aforementioned environments are not available for isolation on or within a secondary payload. There are options for secondary payloads that allow for reduced shock and vibrations; two examples are the aforementioned shock ring from Spaceflight Services and Moog CSA's *Softride* products: *Shock Ring* and a *Tuned Mass Damper*, respectively (Moog Inc., 2013; see Figure 60). These features are independent of the primary payload and LV, meaning the secondary payload must show up to the launch site equipped with such features. Another service provided by Moog CSA is component isolation, which can be potentially valuable to instruments that require lower vibrations compared to the rest of the system. Isolated thermal control is perhaps more difficult to achieve, considering secondary smallsat payloads are generally attached to the LV's upper stage, located within the fairing with the primary payload. Isolated thermal control options are discussed more in the next section.

Figure 60: Moog CSA's shock ring (left) and tuned mass damper (right), used for both shock isolation and reduced vibrations for secondary smallsat payloads (Moog Inc., 2013).

10.3 On the Horizon

10.3.1 Launch Integration Services for Secondary Smallsat Payloads

As previously mentioned, the isolated thermal control appears to be a relatively difficult service for launch integration companies to provide. There have been paints in development, and some already developed (AZ Technology, Inc., 2008), that coat the skin of a smallsat to effectively alter its thermal environment, independent of the primary payload located within the same upper stage fairing. Additionally, smallsats can take advantage of multi-layer insulation (MLI) to create an isolated thermal environment. Many such MLI shielding combinations exist such as aluminum and black Kapton, aluminum and glass cloth, gold and polyimide, etc. (Multek Corporation, 2013) and can be used in conjunction with the aforementioned paints, increasing the thermal control available to smallsats.

10.3.2 Launch Vehicles

10.3.2.1 Primary Payload

The future holds the most promise for primary payloads launched on small and cheap boosters. Many of the prime advantages of a small satellite—including high iteration and replacement rates or large constellations—are not realizable launching only as space allows on much larger, slower, traditional missions.

Several small launchers currently in development are very promising but at a low TRL. One of the most serious programs currently in development is the Defense Advanced Research Projects Agency (DARPA) Airborne Launch Assist Space Access (ALASA) program. This program aims to produce a launcher capable of boosting on the order of approximately 45 kg into LEO for less than $1M including range support costs. It also aims to greatly simplify the launch process by eliminating or mitigating several disadvantages of fixed-base launches (including weather delays, large capital infrastructure costs, and limited inclination accessibility) through airborne launches. The program supports advanced technology development including stable propellant production and better mission planning to support small launchers (DARPA, n.d.). ALASA includes Boeing, Lockheed Martin, Northrop Grumman, Space Information Laboratories, and Virgin Galactic as partners (Messier, 2012).

As a member of the DARPA ALASA program and with a separate airborne carrier vehicle already extensively developed to host manned suborbital launches, Virgin Galactic and The Spaceship Company are at the forefront of small launcher design. The Spaceship Company is a manufacturing joint venture between Virgin Galactic, which organizes launch customers, and Scaled Composites, which designs the vehicles. These companies are developing the LauncherOne, which is designed to deliver a 225 kg payload to low-inclination LEO, or 100 kg to Sun-synchronous LEO. It will be launched off of the WhiteKnightTwo carrier aircraft (Virgin Galactic, n.d.; see Figure 61).

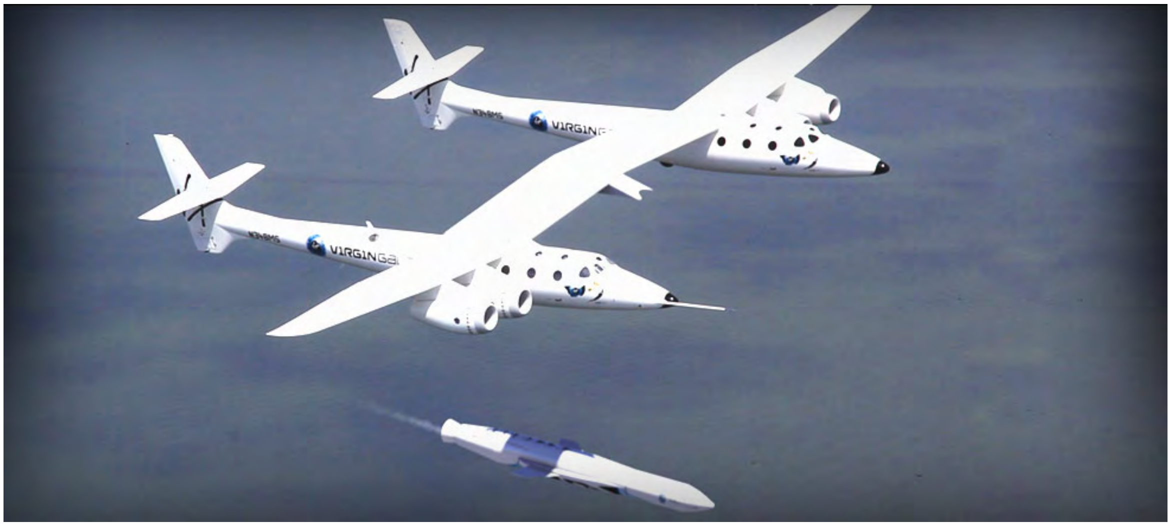
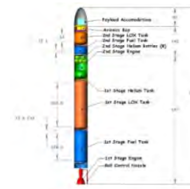
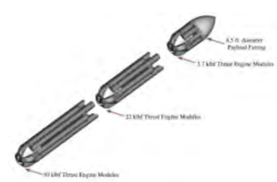


Figure 61: Artist's conception of the Virgin Galactic LauncherOne and WhiteKnightTwo

NASA itself is also working to advance small launchers. NASA Launch Services (NLS) at the Kennedy Space Center is currently soliciting information for a potential “Nano-Sat Launcher” as part of its NLS Enabling eXploration & Technology (NEXT) program. This launcher is meant to launch at least a 15 kg 3U CubeSat into a 425 km orbit at inclinations between 0 and 98° no later than December 15, 2016. This program is limited to companies with fewer than 1,000 employees to encourage small business innovation outside of traditional means of procurement (Foust, 2013).

Table 61: On the horizon primary launchers.

Technology Name	Description	Developer	TRL Status	Figures
ALASA Program	Multiple contracts to Lockheed Martin, Boeing, Virgin Galactic, Ventions LLC, Space Information Laboratories LLC	DARPA; contractor not yet selected (USA)	**5** Current phase (design risk reduction) focused on system design and technology development; Phase 2 will include build and flight tests	
Boeing small launch vehicle	Air-launched, three-stage orbital vehicle with 100 lb/45 kg payload now in development supported by DARPA ALASA program	Boeing (USA)	**5** Various components already flown, but no larger scale integration yet	
GOLauncher 2	Air-launched, single-stage rocket delivering ~45 kg (100 lb) to LEO of up to 400 km with inclinations from 0 to 98.7 degrees	Generation Orbit Launch Services, Space Propulsion Group	**4** Two-year CRADA with AFRL ongoing for computational and experimental tasks	
LauncherOne	Air-launched two-stage booster	Virgin Galactic (USA)	**5** WK2 carrier vehicle development largely complete; ongoing testing of likely hybrid rocket for SS2 suborbital manned	
Long March Micro Launch Vehicle (LM-MLV)	Smallest launch vehicle planned of LM family; other details unknown	China Aerospace Science and Technology Corporation, China National Space Administration (China)	**?** Unknown	N/A
Lynx	Suborbital space plane with dorsal-launched small orbital booster, 650 kg to LEO	XCOR Aerospace (USA)	**3** Mark I in development, but Mark III necessary for orbital launch would be a redesigned new vehicle	
Microsat Launch Vehicle (VLM)	150 kg to 300 km orbit; 3 solid stages	Brazilian Space Agency (AEB), German Space Agency (DLR) (Brazil/ Germany)	**4** Projected launch in 2015	

Minimum cost launch vehicle	22.7 kg to LEO; NO2/Rubber hybrid rocket	Whittinghill Aerospace (USA)	**5** NASA SBIR 08-2 S4.01-8692; will be at TRL 6 by completion of contract	
Nano launch vehicle	Pump-fed, 2-stage nano launch vehicle for low-cost on demand placement of cube and nano-satellites into LEO	Ventions (USA)	**4** NASA SBIR 12-1 E1.02-9215	N/A
Nanosat launch vehicle (a.k.a Garvey 10/250)	Orbital nanosat launcher with 10 kg to 250 km orbit	Garvey Spacecraft (USA)	**4** NASA SBIR 12-1 E1.02-9091	
Neptune	Three-stage vehicle with 30-50 kg (variants 5 and 7, respectively) to circular polar orbit at 310 km	Interorbital Systems (USA)	**5** Multiple missions on manifest for 2013, but no test flight yet; multiple components tested	
North Star Launch Vehicle	10 kg to 350 km polar LEO; evolved sounding rocket design	NAMMO, Norwegian Space Centre, ESA (Norway)	**3** First launch planned for 2020	
S3 vehicle (unnamed)	250 kg to LEO, air-launched, three-stage	Swiss Space Systems (S3) (Switzerland)	**3** Company launched in March 2013	
SWORDS	25 kg to 750 km orbit at 28.5 degree inclination; 24 hours from storage to launch ready; Tridyne pressure-fed engine with LOX/CH4	U.S. Army; Contractor not yet selected	**5** Ground engine test, suborbital flight test, and orbital flight test in summer 2014	

10.3.2.2 Secondary Payload

One advantage of the secondary launch market is that market forces from both small and large spacecraft can collectively drive development and cost-reduction. Even advances in large, heavy-lift boosters like NASA's Space Launch System or SpaceX's Falcon Heavy can help to open space to more parties. The Falcon Heavy is one of the most promising in this area. Projected to cost just over $1K/kg, the Falcon Heavy will be one of the cheapest vehicles on the market while throwing 53,000 kg into LEO. Innovative features like propellant cross-feed from the side-mounted boosters to the core for payloads over 45,000 kg help to maximize performance and efficiency. Advances in reusability or Merlin rocket engine enhancements will be shared across the Falcon line (Space Exploration Technologies, 2013).

10.3.3 Payload Adapters and Deployment

10.3.3.1 CubeSat Deployers

Several CubeSat integration systems are under development to support increased demand for CubeSat launches. Planetary Systems is developing 12U and 27U versions of CSD allowing for larger, more complex CubeSat payloads (Williams, 2013). Spaceflight Services is developing DecaPOD to enable more CubeSat secondary payloads per launch. DecaPOD holds up to ten 3U CubeSats and is compatible with Spaceflight's Secondary Payload System (SSPS). Two DecaPODs fit on each of SSPS's five ports, allowing for a total of 100 3U CubeSats if fully loaded (Spaceflight, 2012).

Table 62: Examples of "on the horizon" small spacecraft deployers.

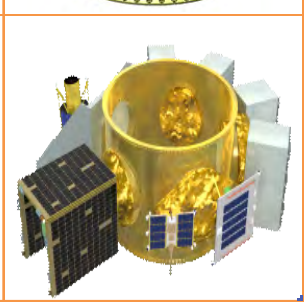
Technology Name	Description	Developer	TRL Status	Figures
Canisterized Satellite Dispenser (CSD)	CubeSat dispenser capable of deploying 12U and 27U Payloads	Planetary Systems Corporation (USA)	**3** Analyzed with finite element model under relevant conditions	
DecaPOD	System capable of transporting and deploying 10 3U CubeSats	Spaceflight, Inc. (USA)	**5** Deployment subsystem has successfully flown	

10.3.3.2 Adapter Rings

A scaled version of the ESPA ring is in development, known as Small Launch ESPA. Small Launch ESPA is designed to be compatible with Minotaur IV, Taurus and Delta II launch vehicles. It is particularly well suited to host CubeSat and sub-ESPA class payloads (Maly, et al., 2009). As mentioned previously, fewer adapters exist to serve the microsatellite class. However, Small Launch ESPA will greatly increase interface options for microsatellites, especially by increasing the number of compatible launch vehicles.

Spaceflight Services is developing an ESPA based adapter system known as SSPS, to be compatible with intermediate class launch vehicles such as Falcon 9, Antares and EELV. At its core the system has an ESPA Grande ring, a five port ESPA ring capable of carrying up to 300 kg payloads per port, either standalone spacecraft or CubeSat deployers. What is unique about SSPS is the inclusion of an avionics suite, power supply, and batteries to supply power to hosted payloads, provide telemetry to ground stations, and provide general mission management (Spaceflight, Inc., 2012). The ability to host secondary payloads after launch vehicle separation could greatly increase the mission lifetime of secondary payloads, and may even enable new missions.

Table 63: Examples of "on the horizon" small spacecraft adapter rings.

Technology Name	Description	Developer	TRL Status	Figures
Small Launch ESPA	Carries up to six 100 kg payloads on Minotaur IV and Delta II	Moog CSA (USA)	**3** Analyzed with finite element model under launch conditions	
Spaceflight Secondary Payload System (SSPS)	Hosts up to five 300 kg spacecraft	Spaceflight, Inc. (USA)	**5** Adapter ring and deployment subsystems have successfully flown	

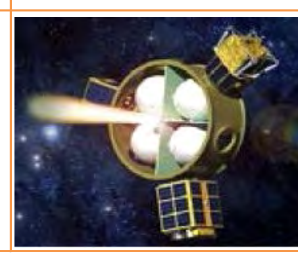
10.3.3.2 Space Tugs

One of the main disadvantages of riding as a secondary payload is the inability to launch into your desired orbit. In the future secondary payloads may no longer need to be limited by the primary payload orbit. By using a space tug, or some on orbit servicing vehicle, secondary payloads will be able to maneuver into desired orbits.

Moog CSA is currently developing the ESPA Orbital Maneuvering System (OMS) to fill this role. OMS uses an ESPA adapter ring as the base of a free flying spacecraft. The ring is designed to separate from the launch vehicle and use its own propulsion and avionics to navigate to desired orbits (Maly, et al., 2009).

Spaceflight Services is developing a similar technology known as the SHERPA Tug, or Shuttle Expendable Rocket for Payload Augmentation. The vehicle has SSPS at its base, but includes solar panels to provide up to 250 W for hosted payloads, and a propulsion system for orbital maneuvering. Two propulsion systems exist, one contains a monopropellant thruster capable of delivering up to 400 m/s deltaV, and one contains a bi-propellant thruster capable of delivering up to 2,200 m/s deltaV (Spaceflight, Inc., 2012).

Table 64: On the Horizon for small spacecraft for Space tugs.

Technology Name	Description	Developer	TRL Status	Figures
Orbital Maneuvering System	Propulsion system is integrated into ESPA ring allowing adapter to act as an independent spacecraft	Moog CSA (USA)	**5** Adapter ring and deployment subsystems have successfully flown	
SHERPA Tug	Orbital servicing vehicle capable of changing secondary payload orbit and host payloads for up to one year	Spaceflight, Inc. (USA)	**5** Adapter ring and deployment subsystems have successfully flown	

10.3.4 Launch Integration Services for Secondary Smallsat Payloads

As mentioned in this section's state of the art counterpart, isolated thermal control appears to be a relatively difficult service for launch integration companies to provide. There have been paints in development (and some already developed) that coat the skin of a smallsat to effectively alter its thermal environment, independent of the primary payload located within the same upper stage fairing. Additionally, smallsat can take advantage of MLI to create an isolated thermal environment. Many such MLI shielding combinations exist (e.g., gold-gold, platinum-glass, etc.) and can be used in conjunction with the aforementioned paints, increasing the thermal control available to smallsats.

10.4 Conclusion

A wide variety of integration and deployment systems exists to provide rideshare opportunities for small satellites 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 needed to fully utilize the advantages provided by small satellites. Dedicated launch vehicles may be used to take advantage of rapid iteration and mission design flexibility, enabling small satellites to dictate mission parameters. New integration systems will greatly increase the mission envelope of small satellites 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. As we move into the future these technologies may yield exciting advances in space capabilities and understanding.

10.5 References

Ames, N.: *NASA-Built Nanosatellite Launch Adapter System Ready for Flight.* [Online] 2013. Available at: http://www.nasa.gov/centers/ames/news/2013/NLAS-ready-for-flight.html - .Ug8RzZLVBsk [Accessed 16 August 2013].

Atkinson, N.: *The Atlas V with LRO and LCROSS at the pad.* [Online] 2009.
Available at: http://www.universetoday.com/32779/lrolcross-ready-for-launch-to-the-moon/lro-left-vif1s/

Bergin, C.: *SpaceX deal boosts Falcon 9's secondary payload manifest.* [Online] 2012.
Available at: http://www.nasaspaceflight.com/2012/06/spacex-deal-falcon-9s-secondary-payload-manifest/ [Accessed 16 Aug 2013].

Brügge, N., n.d.: *Super-Strypi >SPARK.* [Online] Available at: http://www.b14643.de/Spacerockets_2/United_States_7/SPARK/Versions/SPARK.htm
[Accessed 19 August 2013].

Caldwell, D., Ridenoure, R.: *RocketPod™: A Method for Launching CubeSat-Class Payloads on ELVs and Spacecraft.* North Logan, UT, s.n. 2005.

DARPA, n.d.: *Airborne Launch Assist Space Access (ALASA).* [Online]
Available at:
http://www.darpa.mil/Our_Work/TTO/Programs/Airborne_Launch_Assist_Space_Access_(ALASA).aspx [Accessed 18 August 2013].

David, L.: *A Space Aloha: Hawaii Gears Up for First Satellite Launch.* [Online] 2013.
Available at: http://www.space.com/20849-hawaii-small-satellite-launch.html

Foust, J.: *NASA seeks to buy a dedicated nanosatellite launch.* [Online] 2013.
Available at: http://www.newspacejournal.com/2013/08/14/nasa-seeks-to-buy-a-dedicated-nanosatellite-launch/

Goodwin, J., Wegner, P.: *Evolved Expendable Launch Vehicle Secondary Payload Adapter.* Albuquerque, NM, s.n. 2001.

IHI Aerosapce: *JEM Small Satellite Orbital Deployer (J-SSOD)* Fitch Check Case Instruction Manual, Tomioka: IHI Aerospace co., Ltd. 2012.

Kramer, H. J.: *CubeSat Concept.* [Online] 2012.
Available at: https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/CubeSat-concept [Accessed 16 August 2013].

Lan, W.: *Poly PIcosatellite Orbital Deployer MK III ICD.* California Polytechnic State University. San Luis Obispo, 2007.

Lazansky, C.: *Refinement of a Low-Shock Separation System.* s.l., Jet Propulsion Laboratory, 2012.

Maly, J. R., Stavast, V. M., Sanford, G. E., Evert, M. E.: *Adapter Ring for Small Satellites on Responsive Launch Vehicles.* Los Angeles, CA, s.n. 2009.

Marin, C., n.d.: *Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Six Unit Mount (SUM),* s.l.: LSP Mission Integration, Kennedy Space Center.

Messier, D.: *DARPA Awards 6 Small Airborne Launch Vehicle Contracts.* [Online] 2012.
Available at: http://www.parabolicarc.com/2012/07/02/darpa-awards-6-small-launch-vehicle-contracts/

Moog: *Other Adapters.* [Online] 2013.
Available at: http://www.csaengineering.com/products-services/other-adapters/ [Accessed 16 August 2013].

NASA: *IRIS Reaches Orbit.* [Online] 2013.
Available at: http://www.nasa.gov/mission_pages/iris/launch/index.html - .UhIFupLvvh5

Orbital Sciences: *Fact Sheet.* [Online] 2013.
Available at: http://www.orbital.com/NewsInfo/Publications/Pegasus_fact.pdf

Orbital Sciences: *Minotaur IV V VI User's Guide.* Orbital Sciences Corporation. Dulles, VA, 2013.

Orbital Sciences: *Taurus.* [Online] 2013. Available at: http://www.orbital.com/SpaceLaunch/Taurus/

Pendleton, S., Basile, J., Fowler, E., n.d.: *Low-Cost Flat Plate Adapters for Dual Primary Payload Missions.* CSA Engineering Inc. Mountain View, CA.

PSC: *2000785 Rev D User's Manual for Mark II Lightband.* Planetary Systems Corporation. Silver Spring, MD, 2013.

Space Exploration Technologies: *Falcon Heavy.* [Online] 2013.
Available at: http://www.spacex.com/falcon-heavy

Spaceflight, Inc.: *Spaceflight, Inc. Secondary Payload Users Guide.* Spaceflight, Inc. Tukwila, WA, 2012.

Spaceflight: *Spaceflight Unveils Its DecaPOD CubeSat Deployer.* [Online] 2012.
Available at: http://spaceflightservices.com/spaceflight-unveils-its-decapod-CubeSat-deployer/ [Accessed 23 August 2013].

Stavast, V., Lazansky, C., Helgesen, B., n.d.: *SNC Qwksep - A Simple, Reliable, Stiff and Low-Shock Separation System for Small Sat Missions.* s.l.: IEEE Xplore.

Szatkowski, J.: *ULA Rideshare Smallsat Missions for Lunar & Inter-Planetary Exploration.* Cal Tech, CA, s.n. 2013.

Taylor, B.: *The University of Hawai'i Innovation Initiative.* [Online] 2013.
Available at: http://www.hawaii.edu/offices/op/innovation/taylor.pdf

Technologies, Space Exploration: *Falcon 9.* [Online] 2013.
Available at: http://www.spacex.com/falcon9

ULA: *Atlas V Launch Services User's Guide.* Centennial, CO: ULA. 2010.

United Launch Alliance: *Technical Summary.* [Online] 2013.
Available at:
http://www.ulalaunch.com/site/docs/product_cards/AV_product_card.pdf

Virgin Galactic, n.d.: *Performance and Specification.* [Online]
Available at: http://www.virgingalactic.com/launcherOne/performance-and-specification/ [Accessed 18 August 2013].

Willcox, T.: *Atlas V Aft Bulkhead Carrier Rideshare System.* AIAA/USU. North Logan, UT, 2012.

Williams, R.: *Containerized Satellite Dispenser (CSD) Data Sheet.* Planetary Systems Corp. Silver Spring MD, 2013.

11. GROUND SYSTEMS AND OPERATIONS

11.1 Introduction

11.1.1 General ground system setup

In the general case, a ground system consists of a network of ground stations and different control centers such as the Spacecraft Operations Control Center (SOCC), the Payload Operations Control Center (POCC) and the Mission Control Center (MCC). These elements may or may not be located at the same geographical location depending on the type, size and complexity of the mission. In all cases the different elements are supposed to work together with the overall goal to support the spacecraft and the users of the data generated by the mission.

Figure 62 shows the functional relationship between the space segment and the ground segment of a space mission. The ground segment is made up of the users of the mission data and the ground system, which has two functions: (i) supporting the space segment (spacecraft and payload), and (ii) relaying the mission data to the users. To support the spacecraft, the ground system must command and control the bus and the payload, monitor their health, track the spacecraft to determine its orbital position, and determine the spacecraft's attitude using ADCS sensor information (for more information on ground systems, refer to Chapter 15 of Larson & Wertz, 2004).

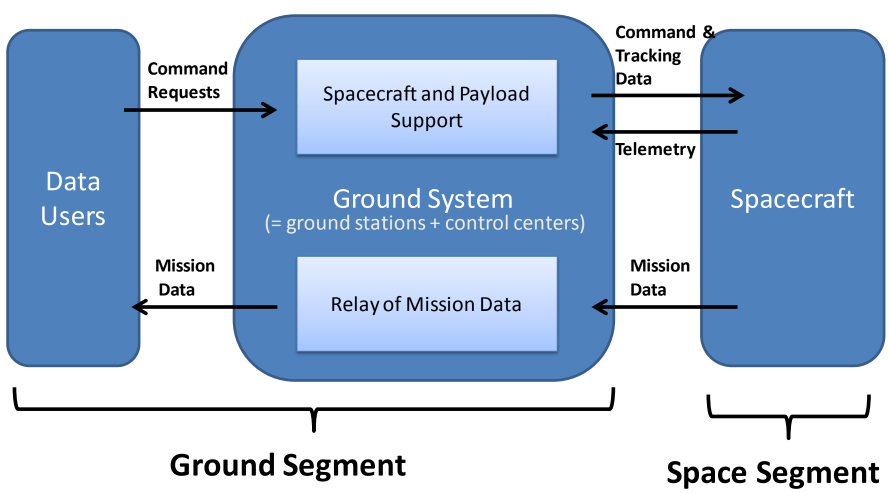


Figure 62: Functional relationship between space segment and ground segment (Larson & Wertz, 2004)

11.1.2 Differences with small spacecraft ground systems

The ground systems architecture for small spacecraft missions often takes a different form compared to the classical architectures used for large spacecraft missions. The low-cost paradigm shift mentioned in Section 1 and the accessibility of COTS technology for the space sector have not only changed how designers think about a spacecraft but also how a ground systems architecture can be conceived. Both the ground systems of small spacecraft missions and the demographics of the data user community differ from the common scheme of Figure 62. An overview of such potential differences (shown in Table 65) highlights the extent to which CubeSat ground systems can differ from their classical counterparts. Due to length limitations, the entries of Table 65 are not discussed in detail: refer to Schmidt (2011) for an exhaustive treatise on the characteristics of small spacecraft ground systems.

Table 65: Fundamental differences between a small spacecraft ground system and classical ground systems for large spacecraft (see §2.2 of Schmidt [2011] for more information).

Classical Ground System	CubeSat Ground System
Legacy systems	New systems
High-cost, high complexity	Low-cost (COTS), low complexity
Clear distinction between mission control and ground station network	Standalone system: MCC, SOCC, POCC and principal ground station are often aggregated into a single entity
Supports a small to moderate number of different missions in parallel. Different types of antennas and hardware enable capability of communicating with more than one spacecraft simultaneously	Capability to support a large number of missions sequentially. Only one antenna, therefore no capability to communicate with more than one spacecraft simultaneously
Supports missions with long lifetimes	Supports missions with short lifetimes
Provides high quality of service (security, reliability, etc.)	Does not guarantee high quality of service
Commercial or institutional operators	Typically academic or amateur operators
Hierarchical topology with a small number of nodes distributed strategically around the globe	Peer-to-peer topology with typically a large number of ad-hoc nodes participating on a voluntary basis

No flexibility in the use of the topology’s individual nodes	Many missions use nearly the same frequency bands, so individual nodes in the topology may be exchangeable
S-band and higher frequencies	Typically UHF and VHF
CCSDS based long-haul communication protocols	TCP/IP based communication protocols
Big dishes	Small dishes or no dish at all (Ham-type antennas)
Support high power (> 40W) spacecraft	Support low power (< 5W) spacecraft
Large bandwidth, data rate and throughput	Small bandwidth, data rate and throughput
Large software requirements	Small software requirements
Large number of facilities and personnel with much expertise	Small number of facilities and personnel with usually less expertise

Figure 63 illustrates the variety in ground system architectures that can be used for small spacecraft missions. Image (a) shows an example of a classical ground system setup, i.e. the Air Force Satellite Control Network (AFSCN). The topology of the AFSCN is hierarchical, with 12 nodes organized around a central master node at Schriever AFB, CO. Image (b) depicts the distributed network of ground stations used for the PhoneSat project (http://www.phonesat.org). PhoneSat was supported by 1,343 volunteer nodes organized in a distributed topology. Image (c) shows an example of a common small spacecraft ground segment topology—a single node consisting of a university ground station and control room.

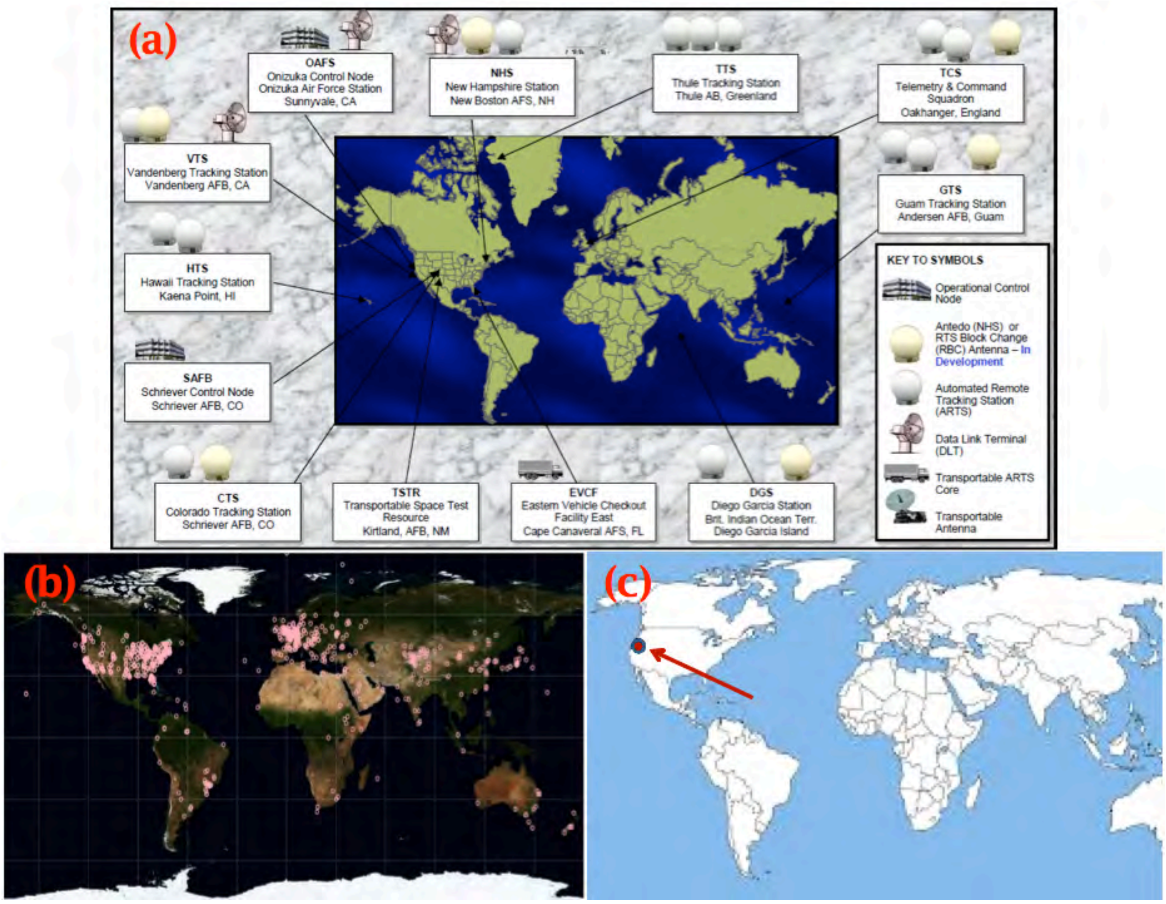


Figure 63: Various ground system architectures encountered in small spacecraft missions. (a) depicts the US Air Force Satellite Control Network (AFSCN) as an example of a conventional hierarchical ground system setup (image credit: USAF). (b) shows the 1343 nodes that participated on a voluntary basis in the distributed ground system architecture of Phonesat (image credit: http://www.phonesat.org). (c) illustrates the case where a smallsat mission is managed and operated using a single ground station only.

The principal driver for a small spacecraft ground system is cost. To lower costs, a typical SoA ground system merges the three conventional control centers—MCC, SOCC, and POCC—into a single unit positioned in one geographical location. The whole mission is often managed from a single lab room modified for that purpose. The ground station is either a fixed or mobile COTS antenna connected to mission control using standard cabling. Common frequency bands are VHF, UHF and sometimes S-band at the higher frequency limit. Tracking, Telemetry and Command (TT&C) for both platform and payload is managed by a single desktop computer.

11.2 State of the Art

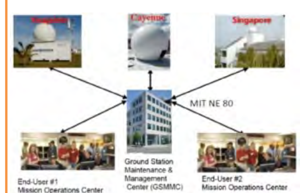
11.2.1 Ground Systems

Figure 64 compares the size and scope of typical large and small spacecraft ground systems.

Figure 64: Differences in size and scope between large (left-hand side) and small spacecraft ground systems (right-hand side). Top left: NASA's Deep Space Network (DSN) ground station in Goldstone, CA. Top right: GENSO roof-top ground station at the International Space University, Strasbourg, France. Bottom left: NASA MCC at JSC, Houston, TX. Bottom right: Student operating the small spacecraft MCC at the University of Santa Clara, CA.

In Table 66, a selection of developers providing turnkey solutions for small spacecraft ground systems is listed. Prices usually range between 10,000 and 100,000 USD.

Table 66: Examples of small spacecraft ground system solutions.

Technology Name	Description	Developer	TRL Status	Figures
ISIS Small Satellite Ground Station	Comprehensive ground system setup for microsatellites and CubeSats (VHF, UHF, S-band options)	Innovative Solutions In Space (Netherlands)	**9** Has been used successfully in at least one mission: Delfi-C3 nanosat mission (2008)	 
Open System of Agile Ground Systems (OSAGS)	Low-cost network of three equatorial S-band ground stations	Espace, Inc. (USA)	**8** Successfully used in 2002 to operate the MIT HETE-2 mission. Can accommodate CubeSats	
Satellite Tracking and Control Station (STAC)	Comprehensive ground system setup for microsatellites and CubeSats (VHF, UHF, L-band and 2.4 GHz options)	Clyde Space (Scotland)	**8** Installed on the roof at the University of Strathclyde, Glasgow, Scotland. Operational for 2 years. No available information on missions	
Mobile CubeSat Command & Control Ground Station (MC3)	Network of fully autonomous ground stations supporting the NRO's Colony Program	Naval Postgraduate School (USA)	**6** TRL assessment supported by Griffith (2011)	

In addition to purchasing new equipment for mission operations, small spacecraft operators can also resort to existing capabilities. An example of an existing ground system supporting high-frequency communications for small satellites is the Open System of Agile Ground Stations (OSAGS). 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, et al., 2012). The stations operate in S-band with a 2.025 - 2.0120 GHz uplink and 2.20 - 2.30 GHz downlink frequency. They can handle communication requirements up to 3.5 Mbps. The system is agile and can support different satellite missions simultaneously. The system 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.

11.2.2 Operations

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., these regulations are governed by the Federal Communications Commission (FCC). Missions have the option to use amateur radio frequencies for communications, for which licenses are simple and quick to obtain. Since this kind of license is not available to governmental entities, whose missions are regulated by the National Telecommunications and Information Administration (NTIA), a number of partnerships have emerged between governmental players and academia. For instance, a number of CubeSat missions developed by NASA Ames Research Center are operated from the MOC at the University of Santa Clara. 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 satellites.

Traditionally, amateur radio bands have been the preferred means for CubeSats to communicate with the ground. 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. Recent CubeSat missions are indeed moving to higher, non-amateur frequency bands to support their data requirements. For instance, the 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, their ground system requirements change. Unlike amateur radio licenses that allow CubeSats to autonomously beacon data to any listening amateur radio operator, non-amateur radio licenses prohibit satellite data beaconing. They are typically point-to-point, meaning any ground station interacting with the satellite must be similarly licensed. Clearly, as CubeSats shift to non-amateur communication bands, their ground systems will have to adapt accordingly.

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 from the International Space Station (ISS) in October 2012, had a mission goal to investigate this inter-satellite communication method. The satellite had Quake Global Q1000 and Q9602 modems onboard to test communications with both the Iridium and Orbcomm constellations (Löfgren, et al., 2013). Unfortunately, the satellite 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 satellite 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 10 hours worth of data to the Iridium constellation over a 24-hour period, which is a significant improvement over typical satellite-to-ground transmission durations for CubeSats.

Inter-satellite communication will be tested again soon using TechEdSat-3p, a 3U CubeSat launched to the ISS on August 3, 2013 (Harding, 2013). After deployment, TechEdSat-3p will attempt to communicate with the Iridium satellite network using two redundant Quake Global Q9603 modems. There are also plans for the 1U AztechSat to test communications with the Globalstar constellation. These missions are actively proving the value of inter-satellite communications to relay data to the ground. The potential for saved costs and improved quality that can result from small satellites exchanging ground stations with existing satellite phone constellations certainly warrants further investigation.

11.3 On the Horizon

As the ground system and communication options for small satellites and particularly CubeSats expand, project managers have to consider the trade-off between data quality/size and cost. In the past, many missions depended entirely on amateur radio ground stations to support satellite operation and communication, and the amateur radio community has indeed proved invaluable to the CubeSat community. But as mission complexity and data requirements increase, more projects are looking to non-amateur ground stations and other options like inter-satellite communications with satellite-phone constellations to meet their needs. These options, however, tend to present higher costs associated with radio frequency licenses, software specific to a given service provider, and sometimes the service itself based on data size or communication duration. Many factors can affect the cost and 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 satellite 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.

In light of the distributed and highly dynamic ground system topology for small spacecraft missions (see Figure), 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 system. The Global Educational Network for Satellite Operations (GENSO) system by ESA is an example of this. GENSO 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. Data collection for a given satellite could increase from minutes per day via one ground station to many hours per day via the GENSO network. Unfortunately, the GENSO project is currently on hold, with little expectation of resuming progress. While the prospect of GENSO's future is unknown, the general concept of a distributed network of amateur radio ground stations to support small spacecraft operations is still a concept worth looking into. Planning & scheduling and data management are two areas of ongoing research within the field of small spacecraft ground systems software.

The future will see an increasing number of small spacecraft missions involving not only single satellites but also swarms, constellations and formations of spacecraft (see e.g., Raymond, et al., 2000). A distributed infrastructure of small spacecraft made up of dozens, if not hundreds, of units is likely to become a standard to conduct low-cost Earth observation and science missions. However, the scalability of mission operations without significant automation is limited. Siewert & McClure (1995) recall that the number of operators usually scales linearly with the number of telemetry nodes needed to monitor the satellite. The authors propose that, assuming a best case scenario in which a single small satellite requires roughly ten operators to ensure mission success (not including payload operators), a constellation of hundreds of satellites 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 satellite 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.

11.4 Conclusion

The development of small satellite integration, launch, and deployment systems to date has largely been focused on leveraging existing launchers for much larger payloads. Many of these heritage vehicles are available with excess mass capacity for secondary spacecraft, and a wide variety of integration and deployment systems have been developed to provide rideshare opportunities. These rideshares help to reduce costs but are often allocated only after the primary mission defines most launch criteria. Integration and deployment mechanisms are thus designed for minimal interference to the primary mission, usually by providing electromagnetic shielding and shock absorption. Adapters exist to both secure and deploy secondary payloads of various sizes. Multiple "POD" based deployment systems are used to launch 1U to 6U CubeSats, while flat plate adapters and ESPA rings are used to host larger payloads. SoA technologies in these areas are also responding to increased demand and capability for small satellite missions. EELV rockets (United Launch Alliance's Atlas V and Delta IV) are currently the most frequent launchers, especially after the development of the ESPA ring. Current launch vehicles, though, are often unable to meet demands for missions that need a very specific science orbit, interplanetary trajectories, precisely timed rendezvous, or special environmental considerations. Launching as a secondary payload also limits the impact of small satellite advantages such as quick iteration time and low total capital costs.

11.5 References

Cahoy, K. et al.: *S-Band CubeSat communications with the Open System of Agile Ground Stations (OSAGS).* Cal Poly CubeSat Developers' Workshop. San Luis Obispo, 2012.

Green, M.: *PhoneSat Flight Demonstrations: Successful PhoneSat Mission Completed.* [Online] 2013.
Available at:
http://www.nasa.gov/directorates/spacetech/small_spacecraft/phonesat.html
[Accessed 23 August 2013].

Griffith, R. C.: *Mobile CubeSat Command and Control (MC3).* Naval Postgraduate School. Monterey, CA, USA, 2011.

Harding, P.: *Japan's HTV-4 launches supplies and science to the ISS.* [Online] 2013. Available at: http://www.nasaspaceflight.com/2013/08/japans-htv-4-launches-supplies-scienceiss/ [Accessed 23 August 2013].

Hsiao, F.-B., Liu, H.-P., Chen, C.-C.: *The Development of a Low-Cost Amateur Microsatellite Ground Station for Space Engineering Education.* Global J. of Engng. Educ., 4(1), pp. 83-88, 2000.

Klofas, B., Leveque, K.: *The Future of CubeSat Communications: Transitioning Away from Amateur Radio Frequencies for High-speed Downlinks.* AMSAT Symposium. Orlando, FL, 2012.

Larson, W. J., Wertz, J. R.: *Space Mission Analysis and Design.* 3rd ed. Microcosm Press. El Segundo, CA, 2004.

Löfgren, H. et al.: *TechEdSat: a minimal and robust 1U CubeSat architecture using plug-and-play avionics.* 9th IAA Symposium on Small Satellites for Earth Observation. Berlin, Germany, 2013.

Raymond, C. A., Bristow, J. O., Schoeberl, M. R.: *Needs for an Intelligent Distributed Spacecraft Infrastructure.* NASA Earth Science Technology Workshop. Arlington, VA, 2000.

Schmidt, M.: *Ground Station networks for Efficient Operation of Distributed Small Satellite Systems.* Universitaet Wuerzburg: Schriftenreihe Wuerzburger Forschungsberichte in Robotik und Telematik. Band 6, Wuerzburg, 2011.

Shirville, G., Klofas, B.: *GENSO: A Global Ground Station Network.* Cal Poly State University. San Luis Obispo, 2004.

Siewert, S., McClure, L. H.: *A System Architecture to Advance Small Satellite Mission Operations.* 9th AIAA/Utah State University Conference on Small Satellites. Logan, UT, 1995.

12. CONCLUSION

This report provides an overview and assessment of the SoA for small spacecraft technology. After introducing small satellites, the SoA of spacecraft integration was presented, and the SoA of each of the relevant subsystems was addressed in turn. Conclusions are given at the end of each section of this report.

This report will be regularly updated as emerging technologies mature and become SoA. 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.

The appendix that follows provides additional information and a set of raw data collected while researching this report.

APPENDIX: TABLES AND ADDITIONAL DATA

Table A.1: List of small spacecraft missions that have been used as a reference for the research presented in the report

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
JAWSat	01/27/2000	Tech Demo	191.4	USAF	USA			LEO
OCS	01/27/2000	Tech Demo	22.0	USA	USA	L'Garde, Inc.	USA	LEO
Falconsat 1	01/27/2000	Education	52.0	United States Air Force Academy	USA			LEO
ASUSat	01/27/2000	Education	5.0	Arizona State University	USA	Arizona State University	USA	LEO
Artemis-Thelma	01/27/2000	Education	0.5	Santa Clara University	USA	Santa Clara University	USA	LEO
Artemis-Louise	01/27/2000	Education	0.5	Santa Clara University	USA	Santa Clara University	USA	LEO
StenSat	01/27/2000	Education	0.2	USA	USA			LEO
Tsinghua 1	06/28/2000	Tech Demo	50.0	Tsinghua University	China	SSTL	UK	SSO
MITA-O	07/15/2000	Tech Demo	170.0	Italy	Italy	Carlo Gavazzi Space	Italy	SSO
Bird-Rubin	07/15/2000	Tech Demo	37.0	DLR	Germany	OHB Systems	Germany	LEO
Tiungsat 1	09/26/2000	Tech Demo	50.0	Malaysia	Malaysia	SSTL	UK	LEO
Megsat 1	09/26/2000	Comm & Positioning	56.0	MegSat	Italy	MegSat	Italy	LEO
Unisat	09/26/2000	Tech Demo	10.0	University of Rome	Italy	University of Rome	Italy	LEO
Saudisat 1A	09/26/2000	Tech Demo	10.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	LEO
Saudisat 1B	09/26/2000	Tech Demo	10.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	LEO
H ETE 2	10/09/2000	Science	124.6	NASA	USA	NASA	USA	LEO
STRV 1C	11/16/2000	Tech Demo	100.0	DERA	UK	DERA	UK	Elliptical
STRV 1D	11/16/2000	Tech Demo	100.0	DERA	UK	DERA	UK	Elliptical

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
Munin	11/21/2000	Science	6.0	Swedish Institute of Space Physics	Sweden	Swedish Institute of Space Physics	Sweden	SSO
LDREX	12/20/2000	Tech Demo	182.0	JAXA	Japan			Elliptical
LRE	08/29/2001	Comm & Positioning	90.0	JAXA	Japan	JAXA	Japan	Elliptical
Starshine 3	09/30/2001	Science	91.0	NASA Space Grant Consortium	USA	Utah State University Space Dynamics Laboratory	USA	LEO
PICOSat 9	09/30/2001	Tech Demo	67.0	USAF	USA	SSTL	UK	LEO
PCSat	09/30/2001	Comm & Positioning	17.5	US Naval Academy	USA	US Naval Academy	USA	LEO
Sapphire	09/30/2001	Tech Demo	16.0	Stanford University	USA	Stanford University	USA	LEO
PROBA 1	10/22/2001	Tech Demo	94.0	EU	EU	Verhaert	Belgium	SSO
BIRD 1	10/22/2001	EO	92.0	DLR	Germany	DLR	Germany	SSO
Starshine 2	12/05/2001	Science	38.0	NASA	USA			LEO
Compass	12/10/2001	Science	80.0	Izmiran	Russia/CIS	GRTsKB Makeyev	Russia/CIS	SSO
BADR-2	12/10/2001	Tech Demo	70.0	SUPARCO	Pakistan	SUPARCO	Pakistan	SSO
MAROC-TUBSAT	12/10/2001	EO	45.0	Royal Center for Remote Sensing	Morocco	Technical University of Berlin	Germany	SSO
Reflector	12/10/2001	Comm & Positioning	7.0	Air Force Research Laboratory	USA	NII Kosmicheskovo Priborostroeniya	Russia/CIS	SSO
Kolibri	11/26/2001	Education	20.0	Russian Academy of Sciences	Russia/CIS			LEO
QuikTOMS	09/21/2001	EO	168.0	NASA	USA			SSO
DASH	02/04/2002	Tech Demo	86.0	JAXA	Japan	NEC TOSHIBA Space Systems, Ltd.	Japan	GTO

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
Alsat 1	11/28/2002	EO	90.0	Algeria	Algeria	SSTL	UK	SSO
Mozhayets	11/28/2002	Tech Demo	64.0	Mozhaisky military academy	Russia/CIS	Information Satellite Systems	Russia/CIS	SSO
FedSat	12/14/2002	Tech Demo	58.0	CRCSS	Australia	Space Innovation Limited	UK	SSO
WEOS	12/14/2002	Science	50.0	Chiba Institute of Technology	Japan	Chiba Institute of Technology	Japan	SSO
μ-LabSat	12/14/2002	Tech Demo	53.0	JAXA	Japan	JAXA	Japan	SSO
Rubin 2	12/20/2002	Tech Demo	14.0	OHB Systems	Germany	OHB Systems	Germany	LEO
Latinsat A	12/20/2002	Tech Demo	12.0	Aprize Satellite Argentina	Argentina	Aprize Satellite	USA	LEO
Latinsat B	12/20/2002	Tech Demo	12.0	Aprize Satellite Argentina	Argentina	Aprize Satellite	USA	LEO
Saudisat 1C	12/20/2002	Tech Demo	15.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	LEO
Unisat 2	12/20/2002	Tech Demo	10.0	University of Rome	Italy	University of Rome	Italy	LEO
HTSTL 1	09/15/2002		50.0	Hangtian Tsinghua Satellite Technology Ltd.	China			SSO
IDEFIX	05/04/2002	Comm & Positioning	6.0	AMSAT-France	France	AMSAT-France	France	SSO
CHIPSat	01/13/2003	Science	60.0	NASA	USA	SpaceDev, Inc.	USA	
XSS-10	01/29/2003	Tech Demo	28.0	USAF	USA	Air Force Research Laboratory	USA	LEO
MIMOSA	06/30/2003	Science	66.0	Czech Astronomical Institute	The Czech Republic			LEO
DTUsat	06/30/2003	Education	1.0	Technical University of Denmark	Denmark	Technical University of Denmark	Denmark	SSO
MOST	06/30/2003	Science	51.3	CSA	Canada	Dynacon	Canada	SSO

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
CUT E-I	06/30/2003	Education	1.0	Tokyo Institute of Technology	Japan	Tokyo Institute of Technology	Japan	SSO
Quakesat	06/30/2003	Science	3.0	QuakeFinder	USA	Stanford University	USA	SSO
AAU CubeSat	06/30/2003	Education	1.0	Aalborg University	Denmark	Aalborg University	Denmark	SSO
Can X-1	06/30/2003	Education	1.0	University of Toronto	Canada	University of Toronto	Canada	SSO
CubeSat XI-IV	06/30/2003	Education	1.0	University of Tokyo	Japan	University of Tokyo	Japan	SSO
SciSat 1	08/13/2003	Science	150.0	CSA	Canada	Bristol Aerospace	Canada	LEO
Rubin 4	09/27/2003	Tech Demo	45.0	OHB Systems	Germany	OHB Systems	Germany	LEO
ST Sat 1	09/27/2003	Tech Demo	100.0	KAIST	S Korea	SaTReC	S Korea	SSO
Mozhayets 4	09/27/2003	Tech Demo	64.0	Mozhaisky military academy	Russia/CIS	Information Satellite Systems	Russia/CIS	LEO
BNSCSat 1	09/27/2003	EO	80.0	BNSC	UK	SSTL	UK	SSO
Nigeriasat 1	09/27/2003	EO	80.0	NASRDA	Nigeria	SSTL	UK	SSO
Bilsat 1	09/27/2003	EO	130.0	TUBITAK	Turkey	SSTL	UK	SSO
Naxing 1	04/18/2004	Tech Demo	25.0	Tsinghua University	China	Tsinghua University	China	SSO
DEMETER	06/29/2004	Science	130.0	CNES	France	CNES	France	SSO
SaudiComsat 1	06/29/2004	Tech Demo	12.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	SSO
SaudiComsat 2	06/29/2004	Tech Demo	12.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	SSO
Saudisat 2	06/29/2004	Tech Demo	35.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	SSO
Latinsat C	06/29/2004	Tech Demo	15.0	Aprize Satellite Argentina	Argentina	Aprize Satellite	USA	SSO
Latinsat D	06/29/2004	Tech Demo	15.0	Aprize Satellite Argentina	Argentina	Aprize Satellite	USA	SSO
Unisat 3	06/29/2004	Tech Demo	12.0	University of Rome	Italy	University of Rome	Italy	SSO

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
AMSat Echo	06/29/2004	Comm & Positioning	12.0	AMSAT-NA	USA	AMSAT-NA	USA	SSO
Nanosat	12/18/2004	Tech Demo	15.0	INTA	Spain	INTA	Spain	SSO
Essaim 1	12/18/2004	Security & Military	120.0	Ministry of Defense (France)	France	Astrium	EU	SSO
Essaim 2	12/18/2004	Security & Military	120.0	Ministry of Defense (France)	France	Astrium	EU	SSO
Essaim 3	12/18/2004	Security & Military	120.0	Ministry of Defense (France)	France	Astrium	EU	SSO
Essaim 4	12/18/2004	Security & Military	120.0	Ministry of Defense (France)	France	Astrium	EU	SSO
PARASOL	12/18/2004	Science	120.0	CNES	France	CNES	France	SSO
KS5MF2	12/24/2004	Tech Demo	50.0	NSAU	Ukraine	KB Yuzhnoye	Ukraine	
Ralphie	12/21/2004	Education	24.0	Air Force Research Laboratory	USA	University of Colorado	USA	
Sparky	12/21/2004	Education	21.0	Air Force Research Laboratory	USA	Arizona State University	USA	
Tatiana	01/20/2005		30.0	Lomonosov Moscow State University	Russia/CIS	Lomonosov Moscow State University	Russia/CIS	LEO
Sloshsat FLEVO	02/12/2005	Tech Demo	127.0	EU	EU	National Aerospace Laboratory	Netherlands	GTO
TNS-0	02/28/2005	Tech Demo	5.0	Russia	Russia/CIS	Russia	Russia/CIS	LEO
XSS-11	04/11/2005	Tech Demo	145.0	Air Force Research Laboratory	USA	Lockheed Martin	USA	LEO
Hamsat	05/05/2005	Comm & Positioning	42.5	AMSAT India	India	ISRO	India	LEO
INDEX	08/23/2005	Science	70.0	JAXA	Japan	JAXA	Japan	SSO
China-DMC+4	10/27/2005	EO	150.0	Tsinghua University	China	SSTL	UK	SSO

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
TopSat	10/27/2005	Security & Military	115.0	BNSC	UK	SSTL	UK	SSO
UWE 1	10/27/2005	Education	1.0	University of Wurzburg	Germany	University of Wurzburg	Germany	SSO
Sinah 1	10/27/2005	Tech Demo	160.0	Iranian Research Organisation for Science & Technology	Iran	PM Polyot	Russia/CIS	SSO
SSETI Express	10/27/2005	Education	77.0	SSETI	EU	SSETI	EU	SSO
XI-V	10/27/2005	Education	1.0	University of Tokyo	Japan	University of Tokyo	Japan	SSO
Mozhayets 5	10/27/2005	Tech Demo	90.0	Mozhaisky military academy	Russia/CIS	Information Satellite Systems	Russia/CIS	SSO
Cosmos 1	06/21/2005	Tech Demo	40.0	Planetary Society	USA	NPO Lavochkin	Russia/CIS	
NCube 2	10/27/2005	Education	1.0	Norwegian Space Centre	Norway	Norwegian University of Science and Technology	Norway	SSO
ST5-A	03/22/2006	Tech Demo	25.0	NASA	USA	NASA	USA	Elliptical
ST5-B	03/22/2006	Tech Demo	25.0	NASA	USA	NASA	USA	Elliptical
ST5-C	03/22/2006	Tech Demo	25.0	NASA	USA	NASA	USA	Elliptical
FORMOSAT-3/COSMIC_A	04/15/2006	EO	62.0	National Space Program Office	Taiwan	Orbital Sciences Corporation	USA	Circular
FORMOSAT-3/COSMIC_C	04/15/2006	EO	62.0	National Space Program Office	Taiwan	Orbital Sciences Corporation	USA	Circular
FORMOSAT-3/COSMIC_D	04/15/2006	EO	62.0	National Space Program Office	Taiwan	Orbital Sciences Corporation	USA	Circular
FORMOSAT-3/COSMIC_E	04/15/2006	EO	62.0	National Space Program Office	Taiwan	Orbital Sciences Corporation	USA	Circular

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
FORMOSAT-3/COSMIC_F	04/15/2006	EO	62.0	National Space Program Office	Taiwan	Orbital Sciences Corporation	USA	Circular
COMPASS-2	05/27/2006	Science	80.0	Izmiran	Russia/CIS			LEO
HIT-SAT	09/22/2006	Education	2.7	Hokkaido Institute of Technology	Japan	Hokkaido Institute of Technology	Japan	
GeneSat-1	12/16/2006	Science	4.5	NASA	USA	NASA	USA	
FalconSat 2	03/24/2006	Tech Demo	19.5	USAF	USA	Air Force Academy(USA)	USA	
CUTE-1.7+APD	02/21/2006	Tech Demo	3.8	Tokyo Institute of Technology	Japan	Tokyo Institute of Technology	Japan	
LAPAN-TUBSAT	01/10/2007	Tech Demo	56.0	LAPAN		Technical University of Berlin	Germany	SSO
THEMIS 1	02/17/2007	Science	128.0	NASA	USA	Swales Aerospace	USA	Elliptical
THEMIS 2	02/17/2007	Science	128.0	NASA	USA	Swales Aerospace	USA	Elliptical
THEMIS 3	02/17/2007	Science	128.0	NASA	USA	Swales Aerospace	USA	Elliptical
THEMIS 4	02/17/2007	Science	128.0	NASA	USA	Swales Aerospace	USA	Elliptical
THEMIS 5	02/17/2007	Science	128.0	NASA	USA	Swales Aerospace	USA	Elliptical
MidSTAR-1	03/09/2007	Tech Demo	118.0	US Naval Academy	USA	US Naval Academy	USA	
STPSat-1	03/09/2007	Tech Demo	156.3	NRL	USA			LEO
FalconSat-3	03/09/2007	Tech Demo	53.9	Air Force Academy(USA)	USA	SpaceQuest, Ltd.	USA	
CFESat	03/09/2007	Tech Demo	158.6	Los Alamos National Laboratory	USA	SSTL	UK	LEO
EgyptSat-1	04/17/2007	EO	100.0	National Authority for Remote Sensing and Space Sciences (Egypt)	Egypt			Polar
SaudiSat-3	04/17/2007	EO	200.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	Polar
SaudiComsat-7	04/17/2007	Tech Demo	15.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	SSO

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
SaudiComsat-6	04/17/2007	Tech Demo	15.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	SSO
SaudiComsat-5	04/17/2007	Tech Demo	15.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	SSO
SaudiComsat-4	04/17/2007	Tech Demo	15.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	SSO
SaudiComsat-3	04/17/2007	Tech Demo	15.0	KACST Space Research Institute	Saudi Arabia	KACST Space Research Institute	Saudi Arabia	SSO
MAST	04/17/2007	Tech Demo	3.0	Tethers Unlimited, Inc.	USA	Tethers Unlimited, Inc.	USA	SSO
CP3	04/17/2007	Education	1.0	California Polytechnic State University	USA	California Polytechnic State University	USA	SSO
LIBERTAD-1	04/17/2007	Education	1.0	Universidad Sergio Arboleda	Colombia	Universidad Sergio Arboleda	Colombia	SSO
CAPE1	04/17/2007	Education	1.0	University of Louisiana	USA	University of Louisiana	USA	SSO
AVM	04/23/2007		185.0	ISRO	India			LEO
AIM(SMEX9)	04/25/2007	Science	197.0	NASA	USA	Orbital Sciences Corporation	USA	LEO
Zhejiang University pico satellite	05/25/2007	Tech Demo	2.5	Zhejiang University	China	Zhejiang University	China	LEO
Can X-6	04/28/2008	Tech Demo	6.5	University of Toronto	Canada	University of Toronto	Canada	
Cute-1.7+APD II	04/28/2008	Science	5.0	Tokyo Institute of Technology	Japan	Tokyo Institute of Technology	Japan	Polar
Indian Mini Satellite-1	04/28/2008	EO	83.0	ISRO	India	ISRO		SSO
AAUSAT-II	04/28/2008	Education	0.7	Aalborg University	Denmark	Aalborg University	Denmark	Polar
Delfi-C3	04/28/2008	Tech Demo	6.5	Delft University of Technology	The Netherlands	Delft University of Technology	Netherlands	Polar
Can X-2	04/28/2008	Tech Demo	3.5	University of Toronto	Canada	University of Toronto	Canada	Polar

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
SEEDS	04/28/2008	Education	3.0	Nihon University	Japan	Nihon University	Japan	Polar
Rubin 8	04/28/2008	Tech Demo	8.0	OHB Systems	Germany	OHB Systems	Germany	Polar
Orbcomm FM37	06/19/2008	Comm & Positioning	115.0	ORBCOMM	USA	OHB Systems	Germany	LEO
Orbcomm FM38	06/19/2008	Comm & Positioning	115.0	ORBCOMM	USA	OHB Systems	Germany	LEO
Orbcomm FM39	06/19/2008	Comm & Positioning	115.0	ORBCOMM	USA	OHB Systems	Germany	LEO
Orbcomm FM40	06/19/2008	Comm & Positioning	115.0	ORBCOMM	USA	OHB Systems	Germany	LEO
Orbcomm FM41	06/19/2008	Comm & Positioning	115.0	ORBCOMM	USA	OHB Systems	Germany	LEO
Orbcomm-CDS3	06/19/2008	Comm & Positioning	80.0	ORBCOMM	USA	OHB Systems	Germany	LEO
RapidEye #1	08/29/2008	EO	150.0	RapidEye AG	Germany	SSTL	UK	SSO
RapidEye #2	08/29/2008	EO	150.0	RapidEye AG	Germany	SSTL	UK	SSO
RapidEye #3	08/29/2008	EO	150.0	RapidEye AG	Germany	SSTL	UK	SSO
RapidEye #4	08/29/2008	EO	150.0	RapidEye AG	Germany	SSTL	UK	SSO
RapidEye #5	08/29/2008	EO	150.0	RapidEye AG	Germany	SSTL	UK	SSO
Ratsat(dummy payload)	09/28/2008	Tech Demo	165.0	SpaceX	USA	SpaceX	USA	LEO
Trailblazer	08/03/2008	Tech Demo	83.5	DoD	USA	SpaceDev, Inc.	USA	
PRISM	01/23/2009	Tech Demo	8.0	University of Tokyo	Japan	University of Tokyo	Japan	Polar
SDS-1	01/23/2009	Tech Demo	100.0	JAXA	Japan	JAXA	Japan	Polar
SOHLA-1	01/23/2009	Tech Demo	50.0	SOHLA	Japan	JAXA	Japan	Polar
SPRITE-SAT	01/23/2009	Science	50.0	Tohoku University	Japan	Tohoku University	Japan	Polar
STARS	01/23/2009	Tech Demo	8.0	Kagawa University	Japan	Kagawa University	Japan	Polar

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
KKS-1	01/23/2009	Education	3.0	Tokyo Metropolitan College of Industrial Technology	Japan	Tokyo Metropolitan College of Industrial Technology	Japan	
Omid	02/02/2009	Tech Demo	25.0	Iran	Iran	Iran	Iran	
SPIRALE-A	02/12/2009	Security & Military	117.3	Ministry of Defense (France)	France	Astrium	EU	Elliptical
SPIRALE-B	02/12/2009	Security & Military	117.3	Ministry of Defense (France)	France	Astrium	EU	Elliptical
ANUSAT	04/20/2009	Tech Demo	40.0	Anna University	India	Anna University	India	LEO
PharmaSat	05/19/2009	Science	4.6	NASA	USA	Stanford University	USA	LEO
HawkSat-1	05/19/2009	Tech Demo	1.0	Hawk Institute for Space Sciences	USA	Hawk Institute for Space Sciences	USA	
CP 6	05/19/2009	Education	1.0	California Polytechnic State University	USA	California Polytechnic State University	USA	
AeroCube 3	05/19/2009	Tech Demo	1.0	Aerospace Corporation	USA	Aerospace Corporation	USA	
RazakSAT	07/14/2009	EO	180.0	ATSB	Malaysia	Satrec Initiative	S Korea	LEO
DRAGONSat2	07/15/2009	Tech Demo	15.0	Texas A&M University	USA	Texas A&M University	USA	LEO
DRAGONSat1	07/15/2009	Tech Demo	15.0	University of Texas	USA	University of Texas	USA	LEO
ANDE-2 POLLUX SPHERE	07/15/2009	Science	25.0	NRL	USA			LEO
Sterkh 1	07/21/2009	Comm & Positioning	170.0	Russia	Russia/CIS	PM Polyot	Russia/CIS	Polar
Deimos 1	07/29/2009	EO	90.0	Deimos Imaging SL	Spain	SSTL	UK	Polar
Dubaisat 1	07/29/2009	EO	190.0	EIAST	UAE	Satrec Initiative	S Korea	Polar
UK-DMC2	07/29/2009	EO	96.5	SSTL	UK	SSTL	UK	Polar

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
Aprizesat 3	07/29/2009	Comm & Positioning	12.0	Aprize Satellite	USA	SpaceQuest, Ltd.	USA	Polar
Nanosat 1B	07/29/2009	Tech Demo	22.0	INTA	Spain	INTA	Spain	Polar
Aprizesat 4	07/29/2009	Comm & Positioning	12.0	Aprize Satellite	USA	SpaceQuest, Ltd.	USA	
Sumbandila	09/17/2009	Tech Demo	81.1	Republic of South Africa	Republic of South Africa	Stellenbosch University	S Africa	
Rubin-9.1&Rubin-9.2	09/23/2009	Tech Demo	16.0	LuxSpace	Luxembourg	LuxSpace	Luxembourg	
Proba-2	11/02/2009	Tech Demo	130.0	EU	EU	Verhaert	Belgium	SSO
Xi Wang-1	12/15/2009		60.0	China	China	Dongfanghong Satellite Co.	China	SSO
WASEDA-SAT2	05/20/2010	Education	1.2	Waseda University	Japan	Waseda University	Japan	LEO
Negai	05/20/2010	Education	1.0	Soka University	Japan	Soka University	Japan	LEO
KSAT	05/20/2010	Education	1.5	Kagoshima University	Japan	Kagoshima University	Japan	LEO
UNITEC-1	05/20/2010	Education	21.0	UNISEC	Japan	UNISEC	Japan	Mars Transfer Orbit
PICARD	06/15/2010	Science	150.0	CNES	France	CNES	France	SSO
STSAT-2B	06/10/2010	Science	100.0	KARI	South Korea	SaTReC	S Korea	
Alsat 2A	07/12/2010	EO	116.0	Algerian National Space Technology Centre	Algeria	Astrium	EU	
AISSAT-1	07/12/2010	Comm & Positioning	6.5	Norwegian Space Centre	Norway	University of Toronto	Canada	
TISAT-1	07/12/2010	Education	1.0	Scuola Universitaria Professionale della Svizzera italiana	Switzerland			

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
STUDSAT	07/12/2010	Education	1.0	Team STUDSAT	India			
STPSat-2	11/20/2010	Tech Demo	110.0	USAF	USA	Ball Aerospace & Technologies Corp.	USA	LEO
FASTSAT	11/20/2010	Tech Demo	148.0	NASA	USA	NASA	USA	LEO
FalconSat-5	11/20/2010	Science	160.7	Air Force Academy(USA)	USA			
FASTRAC-1	11/20/2010	Tech Demo	23.1	University of Texas	USA	University of Texas	USA	
FASTRAC-2	11/20/2010	Tech Demo	23.1	University of Texas	USA	University of Texas	USA	
O/OREOS	11/20/2010	Science	5.4	NASA	USA	NASA	USA	LEO
RAX	11/20/2010	Science	3.0	University of Michigan	USA	University of Michigan	USA	
NanoSail-D	11/20/2010	Tech Demo	3.9	NASA	USA	NASA	USA	
Youthsat	04/20/2011	Science	92.0	ISRO	India	ISRO		
X-SAT	04/20/2011	EO	106.0	Nanyang Technological University (NTU)	Singapore	Nanyang Technological University (NTU)	Singapore	
Rasad 1	06/15/2011	EO	15.3	Malek-Ashtar University of Technology	Iran	Malek-Ashtar University of Technology	Iran	
PSSCT 2	07/08/2011	Tech Demo	4	USAF	USA	Aerospace Corporation	USA	
EduSAT	08/17/2011	Tech Demo	10	Sapienza University of Rome	Italy	Sapienza University of Rome	Itaria	SSO
NigeriaSat-X	08/17/2011	EO	88.1	NASRDA	Nigeria	SSTL	UK	SSO
RASAT	08/17/2011	EO	93	TUBITAK	Turkey	TUBITAK	Turkey	SSO
Sich-2	08/17/2011	EO	176	National Space Agency of Ukraine	Ukraine	KB Yuzhnoye	Ukraine	SSO
Jugnu	10/12/2011	EO	3	IIT Kanpur	India			
SRMSat	10/12/2011	Education	10.9	SRM University	India			

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
Vesselsat-1	10/12/2011	Comm & Positioning	28.7	ORBCOMM	USA	LuxSpace	Luxembourg	
AubieSat-1	10/28/2011	Education	1.03	Auburn University	USA	Auburn University	USA	
RAX-2	10/28/2011	Science	2.8	University of Michigan	USA	University of Michigan	USA	
Chibis-M	10/30/2011	Science	40	Space Research Institute of the Russian Academy of Sciences(RAN/IKI)	Russia/CIS	Space Research Institute of the Russian Academy of Sciences(RAN/IKI)	Russia/CIS	Circular
ELISA E12	12/17/2011	Security & Military	120	CNES	France	Astrium	EU	SSO
ELISA E24	12/17/2011	Security & Military	120	CNES	France	Astrium	EU	SSO
ELISA W11	12/17/2011	Security & Military	120	CNES	France	Astrium	EU	SSO
SSOT	12/17/2011	EO	117	Chilean Ministry of National Defense	Chile	Astrium	EU	SSO
Vesselsat-2	01/09/2012	Comm & Positioning	28.6	ORBCOMM	USA	LuxSpace Sarl	Luxembourg	LEO
Navid	02/03/2012	EO	50	Iran University of Science and Technology(IUST)	Iran	Iranian Space Agency	Iran	LEO
ALMASAT-1	02/13/2012	Tech Demo	12.5	University of Bologna	Italy	University of Bologna	Italy	Elliptical
e-St@r	02/13/2012	Education	1	Polytechnic University of Turin	Italy	Polytechnic University of Turin	Italy	Elliptical
Goliat	02/13/2012	Education	1	University of Bucharest	Romania	University of Bucharest	Romania	Elliptical
MaSat-1	02/13/2012	Education	1	Budapest University of Technology and Economics	Hungary	Budapest University of Technology and Economics	Hungary	Elliptical
PW-Sat-1	02/13/2012	Education	1	Warsaw University of Technology	Poland	Warsaw University of Technology	Poland	Elliptical

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
Robusta	02/13/2012	Education	1	University of Montpellier 2	France	University of Montpellier 2	France	Elliptical
UniCubeSat-GG	02/13/2012	Education	1	University of Rome	Italy	University of Rome	Italy	Elliptical
Xatcobeo	02/13/2012	Education	1	National Institute for Aerospace Technology (INTA)	Spain	University of Vigo	Spain	Elliptical
Tiantuo-1	05/10/2012	Tech Demo	9	National University of Defense Technology (NUDT)	China	National University of Defense Technology (NUDT)	China	
Horyu-2	05/17/2012	Tech Demo	7.1	Kyushu Institute of Technology	Japan	Kyushu Institute of Technology	Japan	
SDS-4	05/17/2012	Tech Demo	48	JAXA	Japan	JAXA	Japan	
exactView-1	07/22/2012	EO	100	COM DEV International	Canada	SSTL	UK	SSO
MKA-PN-1	07/22/2012	Science	110	Federal Space Agency(Russia)	Russia/CIS	NPO Lavochkin	Russia/CIS	SSO
TET-1	07/22/2012	Tech Demo	120	DLR	Germany	Kayser-Threde	Germany	SSO
SFERA	08/01/2012	Science	9.2	Russia	Russia/CIS			LEO
PROITERES	09/09/2012	Tech Demo	14	Osaka Institute of Technology	Japan	Osaka Institute of Technology	Japan	Polar
ORBCOMM Generation 2	10/08/2012	Comm & Positioning	142	ORBCOMM	USA	Sierra Nevada Corporation	USA	
HummerSat-1	11/18/2012	Tech Demo	160	CAST	China	CASC	China	SSO
XY 1	11/18/2012	Tech Demo	140	China	China	CAST	China	SSO
Kwangmy	12/12/2012	EO	100	North Korea	N Korea	North Korea	N Korea	SSO
STSAT 2C	01/30/2013	Tech Demo	100	MEST	S Korea	SaTReC	S Korea	Elliptical
AAUSat-3	02/25/2013	Education	0.8	Aalborg University	Denmark	Aalborg University	Denmark	SSO

Name	Launch Date	Mission	Weight (kg)	Owner	Owner Country	Maker	Maker Country	Orbit
BRITE-AUSTRIA	02/25/2013	Science	14	University of Graz	Austria	UTIAS-SFL	Canada	SSO
NEOSSAT	02/25/2013	Science	65	CSA	Canada	Microsat Systems Canada Inc.(MSCI)	Canada	SSO
SAPPHIRE	02/25/2013	Security & Military	148	Department of National Defense (Canada)	Canada	MacDonald, Dettwiler and Associates Ltd.	Canada	SSO
STRAND 1	02/25/2013	Tech Demo	3.5	SSTL	UK	SSTL	UK	SSO
UNIBRITE	02/25/2013	Science	14	UTIAS-SFL	Canada	University of Vienna	Austria	SSO
ESTCube-1	05/07/2013	Education	1.33	University of Tartu	Estonia	University of Tartu	Estonia	SSO
Proba-V	05/07/2013	EO	138.2	EU	EU	QinetiQ Space	Belgium	SSO
IRIS	06/28/2013	Science	200	NASA	USA	Lockheed Martin	USA	SSO

Table A.2: CubeSat communications technology - part 1*.

Version 4. Bryan Klofas. bklofas@gmail.com. August 9, 2013. Green are University CubeSats; Red are Commercial or Private; Blue are US Government.

Launch	Satellite	Object	Size	Radio	Frequency	Satellite Service	Power
Eurockot launch 30 June 2003	AAU1 CubeSat	27846	1U	Wood & Douglas SX450	437.475 MHz	amateur	500 mW
	DTUsat-1	27842	1U	RFMD RF2905	437.475 MHz	amateur	400 mW
	CanX-1	27847	1U	Melexis	437.880 MHz	amateur	500 mW
	Cute-1	27844	1U	Alinco DJ-C4 (data)	437.470 MHz	amateur	350 mW
	(CO-55)			Maki Denki (beacon)	436.8375 MHz	amateur	100 mW
	QuakeSat-1	27845	3U	Tekk KS-960	436.675 MHz	amateur	2 W
	XI-IV	27848	1U	Nishi RF Lab (data)	437.490 MHz	amateur	1 W
	(CO-57)			Nishi RF Lab (beacon)	436.8475 MHz	amateur	80 mW
SSETI Express 27 Oct 2005	XI-V	28895	1U	Nishi RF Lab (data)	437.345 MHz	amateur	1 W
	(CO-58)			Nishi RF Lab (beacon)	437.465 MHz	amateur	80 mW
	NCube-2	28897[4]	1U		437.505 MHz	amateur	
	UWE-1	28892	1U	PR430	437.505 MHz	amateur	1 W
M-V-8 22 Feb 2006	Cute-1.7+APD	28941	2U	Alinco DJ-C5	437.505 MHz	amateur	300 mW
	(CO-56)			Telemetry (beacon)	437.385 MHz	amateur	100 mW
Minotaur-1 11 Dec 2006	GeneSat-1	29655	3U+	Microhard MHX-2400	2.4 GHz	experimental	1 W
				Stensat (beacon)[7]	437.067 MHz	amateur	500 mW
Dnepr 2 17 Apr 2007	CSTB1	31122	1U	Yaesu VX-2R	400.0375 MHz	experimental	300 mW
	AeroCube-2	31133	1U	FreeWave FGRM	915 MHz	experimental	2 W
	CP4	31132	1U	TI CC1000/RF2117	437.325 MHz	amateur	1 W
	Libertad-1	31128	1U	Stensat	437.405 MHz	amateur	400 mW
	CAPE1	31130	1U	TI CC1020	435.245 MHz	amateur	1 W
	CP3	31129	1U	TI CC1000/RF2117	436.845 MHz	experimental	1 W
	MAST[10]	31126	3U	Microhard MHX-2400	2.4 GHz	experimental	1 W
NLS-4/PSLV-C9 28 Apr 2008	Delfi-C3	32789	3U	Custom (transponder)	145.9-435.55 MHz	amateur	200 mW
	(DO-64)			Custom (beacon)	145.870 MHz	amateur	400 mW
	Seeds-2	32791	1U	Musashino Electric (data)	437.485 MHz	amateur	450 mW
	(CO-66)			Musashino Electric (beacon)	437.485 MHz	amateur	90 mW
	CanX-2	32790	3U	Custom S-Band	2.2 GHz	space research	500 mW
	AAUSAT-II	32788	1U	Holger Eckhardt (DF2FQ)	437.425 MHz	amateur	610 mW
	Compass-1	32787	1U	Holger Eckhardt (data)	437.405 MHz	amateur	300 mW
				BC549 (beacon)	437.275 MHz	amateur	200 mW
Minotaur 1 19 May 2009	AeroCube-3	35005	1U	FreeWave FGRM	915 MHz	experimental	2 W
	CP6	35003	1U	CC1000/RF2117	437.365 MHz	amateur	1 W
	HawkSat-1	35004	1U	Microhard MHX-425	437.345 MHz	amateur	1 W
	PharmaSat	35002	3U+	Microhard MHX-2400	2.4 GHz	experimental	1 W
				Stensat (beacon)[7]	437.465 MHz	amateur	500 mW
ISILaunch 01/ PSLV-C14 23 Sep 2009	BEESAT-1	35933	1U	STE BK-77B	436.000 MHz	amateur[13]	500 mW
	UWE-2	35934	1U	Custom	437.385 MHz	amateur	
	ITUpSAT-1	35935	1U	Microhard MHX-425	437.325 MHz	amateur	1 W
				BeeLine/CC1050	437.325 MHz	amateur	350 mW
	SwissCube	35932	1U	Butler oscillator/RF5110G	437.505 MHz	amateur	1 W
				RF2516 (beacon)	437.505 MHz	amateur	100 mW
H-IIA F17 20 May 2010	Hayato	36573	1U	Custom	13.275 GHz	Earth exploration	100 mW
	Waseda-SAT2	36574	1U	TXE430-301A	437.485 MHz	amateur	150 mW
				TXE430-301A (beacon)	437.485 MHz	amateur	100 mW
	Negai-Star	36575	1U	Data	437.305 MHz	amateur	150 mW
				Beacon Radio	437.305 MHz	amateur	100 mW

*The original version of this Table can be found on http://www.klofas.com/comm-table/ . The Table has been divided in two parts for better visualization.

Launch	Satellite	Object	Size	Radio	Frequency	Satellite Service	Power
NLS-6/ PSLV-C15 12 July 2010	TIsat-1	36799	1U	Alinco DJ-C6	437.305 MHz	amateur	500 mW
				CC1010 (beacon)	437.305 MHz	amateur	400 mW
	StudSat	36796	1U	CC1020	437.505 MHz	amateur	500 mW
				MAX1472 (beacon)	437.860 MHz	amateur	10 mW
STP-S26 19 Nov 2010	RAX-1	37223	3U	Lithium-1	437.505 MHz	amateur	750 mW
	O/OREOS	37224	3U+	Microhard MHX-2400	2.4 GHz	experimental	1 W
				Stensat (beacon)[7]	437.305 MHz	amateur	500 mW
	NanoSail-D2	37361	3U+	Microhard MHX-2400	2.4 GHz	experimental	1 W
				Stensat (beacon)[7]	437.270 MHz	amateur	500 mW
Falcon 9-002 8 Dec 2010	Perseus (4)	37251	1.5U			government	
	QbX (2)	37249	3U	TTC	450 MHz	government	1 W
	SMDC-ONE	37246	3U	Pericle	UHF	government	
	Mayflower	37252	3U	Microhard MHX-425	437.000 MHz	unlicensed	1 W
				Stensat (beacon)[7]	437.600 MHz	unlicensed	1 W
PSLV-C18 12 Oct 2011	Jugnu	37839	3U	CC1070/RF5110G	437.505 MHz	amateur	1 W
				MAX1472 (beacon)	437.505 MHz	amateur	10 mW
ELaNa-3/ NPP 28 Oct 2011	AubieSat-1	37854	1U	Melexis TH72011	437.475 MHz	amateur	800 mW
	DICE (2)	37851	1.5U	L3 Cadet	465 MHz	meteorological	1 W
	HRBE	37855	1U	CC1000	437.505 MHz	amateur	850 mW
	M-Cubed	37855	1U	Lithium-1	437.485 MHz	amateur	1 W
	RAX-2	37853	3U	Lithium-1	437.345 MHz	amateur	1 W
ELaNa-6/NROL-36 13 Sep 2012	SMDC-ONE (2)	38766	3U	Pericle	UHF	government	
	AeroCube-4 (3)	38767	1U	FreeWave MM2	915 MHz	experimental	2 W
				CC1101	915 MHz	experimental	1.3 W
	Aeneas	38760	3U	MHX-425	437.000 MHz	experimental	1 W
				Stensat (beacon)[7]	437.600 MHz	amateur	1 W
	CSSWE	38761	3U	Lithium-1	437.345 MHz	experimental	1 W
	CP5	38763	1U	CC1000/RF2117	437.405 MHz	amateur	500 mW
	CXBN	38762	2U	Lithium-1	437.525 MHz	amateur	1 W
	CINEMA	38764	3U	Emhiser	2200 MHz	space research	1 W
	Re	38765	3U	Helium-100	915 MHz	government	1 W
ISS 4 Oct 2012	FITSat-1	38853	1U	High-speed Custom	5.84 GHz	amateur	2 W
				Custom (data)	437.445 MHz	amateur	
				Custom (beacon)	437.250 MHz	amateur	10 mW
	TechEdSat[16]	38854	1U	Stensat (beacon)[7]	437.465 MHz	amateur	1 W
	F-1	38855	1U	VX-3R	145.980 MHz	amateur	1 W
				VX-3R	437.485 MHz	amateur	200 mW
	WE-WISH	38856	1U	(data)	437.505 MHz	amateur	100 mW
				(beacon)	437.505 MHz	amateur	
	RAIKO	38852	2U	Custom	13 GHz		
PSLV-C20 25 Feb 2013	STRaND-1	39090	3U	Custom SSTL	437.575 MHz	amateur	1.6 W
	AAUSAT3	39087	1U	ADF7021/AWT6388	437.425 MHz	amateur	900 mW

Launch	Satellite	Object	Size	Radio	Frequency	Satellite Service	Power
Soyuz/Bion M1 19 April 2013	OSSI-1	39131	1U	ADF7021	437.525 MHz	amateur	2 W
				ADF7021 (beacon)	145.980 MHz	amateur	80 mW
	SOMP	39135	1U		437.485 MHz	amateur	500 mW
				Si4420	437.485 MHz	amateur	500 mW
	BEESAT-2	39136	1U	STE BK-77B	435.950 MHz	amateur	500 mW
	BEESAT-3	39134	1U	STE BK-77B	435.950 MHz	amateur	500 mW
	Dove-2	39132	3U	Custom UHF	401.3 MHz	experimental	1.6 W
				MHX-2420	2.4 GHz	experimental	1 W
Antares Demo 21 April 2013	Phonesat 1.0 (Graham)[16]	39146	1U	Stensat (beacon)[7]	437.425 MHz	amateur	1 W
	Phonesat 1.0 (Bell)	39145	1U+	Stensat (beacon)[7]	437.425 MHz	amateur	1 W
				Iridium Q9602	1616 MHz	experimental	1.6 W
	Phonesat 2.0b (Alexander)[16]	39144	1U	Stensat (beacon)[7]	437.425 MHz	amateur	1 W
	Dove-1	39143	3U	Custom UHF	401.3 MHz	experimental	1.6 W
				D3-8225	8.225 GHz	experimental	3 W
Long March-2D/ Gaofen 1 19 April 2013	TurkSat-3USat	39152	3U	Custom Transponder	435.225 MHz	amateur	
				BeeLine/Astrodev?	437.225 MHz	amateur	1 W
	CubeBug-1	39153	2U	Lithium-1	437.445 MHz	amateur	1 W
	NEE-01 Pegasus	39154	1U	Custom	910 MHz		1.9 W
Vega VV02 7 May 2013	ESTCube-1	39161	1U	Data	437.505 MHz	amateur	500 mW
				Beacon	437.250 MHz	amateur	100 mW

[1] Satellite never heard from in space.
[2] As of April 2008.
[3] Used a modified Pacsat protocol on top of AX.25. Source code available upon request.
[4] This object separated from SSETI Express months later and is presumed to be NCube-2.
[5] This is also the main satellite processor.
[6] The radio module accepts serial data and uses an internal TNC.
[7] This beacon is based on a Atmel ATA8402.
[8] No uplink commands received by spacecraft.
[9] The CAPE1 team knew the receiver was dead before integration but had no time to fix it.
[10] One identical radio per satellite section, so three total radios onboard.
[11] Since no on-board telemetry storage exists on this satellite, this figure is not for commanded data and cannot be directly compared to the other spacecraft. This figure is beacon data and includes duplicate beacons
[12] This figure includes all data from the spacecraft, including beacons, bad packets, and retransmissions.
[13] This satellite was not coordinated through the IARU.
[14] There were no solar cells on this satellite.
[15] This spacecraft did receive uplink commands, but it died before before downlink could be established.
[16] These satellites did not have command receivers.

Table A.2: CubeSat communications technology - part 2

Version 4. Bryan Klofas. bklofas@gmail.com. August 9, 2013. Green are University CubeSats; Red are Commercial or Private; Blue are US Government.

Launch	TNC	Protocol	Data Rate/Modulation	Downloaded	Lifetime	Antenna	Status	Updated
Eurockot launch 30 June 2003	MX909	AX.25, Mobitex	9600 baud GMSK	1 kB	3 months	dipole	Dead	April 2013
		AX.25	2400 baud FSK	0[1]	0 days	canted turnstile	DOA	April 2013
		Custom	1200 baud MSK	0[1]	0 days	crossed dipoles	DOA	April 2013
	MX614	AX.25	1200 baud AFSK	>10 MB[2]	118+ months	monopole	Alive	April 2013
	PIC16LC73A	CW	50 WPM	N/A		monopole		
	BayPac BP-96A	AX.25[3]	9600 baud FSK	423 MB	7 months	turnstile	Dead	April 2013
	PIC16C622	AX.25	1200 baud AFSK	>11 MB[2]	118+ months	dipole	Alive	April 2013
	PIC16C716	CW	50 WPM	N/A		dipole		
SSETI Express 27 Oct 2005	PIC16C622	AX.25	1200 baud AFSK		90+ months	dipole	Alive	April 2013
	PIC16C716	CW	50 WPM	N/A		dipole		
		AX.25	1200 baud AFSK	0[1]	0 days	monopole	DOA	April 2013
	H8S/2674R[5]	AX.25	1200/9600 baud AFSK		3 weeks	end-fed dipole	Dead	Apri 2013
M-V-8 22 Feb 2006	CMX589A	AX.25/SRLL	1200 AFSK/9600 GMSK	<1 MB	2.5 months	dipole	Deorbited	April 2013
	H8S/2328[5]	CW	50 WPM	N/A		dipole		
Minotaur-1 11 Dec 2006	Integrated[6]	Proprietary		500 kB	3 months	patch	Deorbited	April 2013
	PIC12C617	AX.25	1200 baud AFSK	N/A		monopole		
Dnepr 2 17 Apr 2007	PIC	Proprietary	1200 baud AFSK	6.77 MB	18 months	dipole	Dead	April 2013
	Integrated[6]	Proprietary	38.4 kbaud	500 kB	1 week	patch	Dead	April 2013
	PIC18LF6720	AX.25	1200 baud FSK	487 kB	2 months	dipole	Dead	April 2013
		AX.25	1200 baud AFSK	0[8]	1 month	monopole	Dead	April 2013
	PIC16LF452	AX.25	9600 baud FSK	0[9]	4 months	dipole	Dead	April 2013
	PIC18LF6720	AX.25	1200 baud FSK	2.0 MB[2]	19+ months	dipole	Dead	April 2013
	Intgrated[6]	Proprietary	15 kbps	>2 MB	0.75 months	monopole	Dead	April 2013
NLS-4/PSLV-C9 28 Apr 2008	N/A	Linear	40 kHz wide	N/A	60+ months	turnstile	Alive	April 2013
	PIC18LF4680	AX.25	1200 baud BPSK	60 MB[11]		turnstile		
		AX.25	1200 baud AFSK	500 kB[2]	60+ months	monopole	Alive	April 2013
		CW		N/A		monopole		
	Integrated	NSP	16-256kbps BPSK	250 MB	60+ months	patch	Active	April 2013
	PIC18LF6680	AX.25	1200 baud MSK	8 MB[22]	60+ months	dipole	Alive	April 2013
	C8051F123, FX614	AX.25	1200 baud AFSK/MSK	<1 MB[2]	60+ months	dipole	Alive	April 2013
	PIC12F629	CW	15 WPM	N/A		dipole		
Minotaur 1 19 May 2009	Integrated	Proprietary	77 kbaud GFSK	52 MB	7 months	patch	Deorbited	April 2013
	PIC18LF6720	AX.25	1200 baud FSK		4 months	dipole	Deorbited	April 2013
	Integrated	Proprietary		0 kB	0 days	monopole	DOA	April 2013
	Integrated	Proprietary	10 kbps	650 kB	10 days	patch	Deorbited	April 2013
	Integrated	AX.25	1200 baud AFSK	N/A	1 month	monopole		

Launch	TNC	Protocol	Data Rate/Modulation	Downloaded	Lifetime	Antenna	Status	Updated
ISILaunch 01/ PSLV-C14 23 Sep 2009	CMX909B	Mobitex	4800/9600 baud GMSK		43+ months	monopole	Alive	April 2013
		AX.25	1200 baud AFSK		1 week	dipole	Dead	April 2013
	Integrated	Proprietary	19200 baud	0 kB[8]	43+ months	dipole	Alive	April 2013
		CW		N/A		monopole		
	MSP430F1611	AX.25	1200 baud FSK	6 MB	43+ months	monopole	Active	April 2013
	Integrated	CW	10 WPM	N/A		monopole		
H-IIA F17 20 May 2010	Integrated		10 kbps/1 Mbps BPSK	0 kB[8]	18 days	patch	Deorbited	April 2013
	H8/3052F[5]	AX.25	9600 baud FSK	0 kB	0 days	monopole	DOA	April 2013
	H8/3052F[5]	CW		N/A		dipole	Deorbited	
		AX.25	1200 baud FSK		1 month	dipole	Deorbited	April 2013
		CW	50 WPM	N/A		dipole		
NLS-6/ PSLV-C15 12 July 2010	MSP430F169	AX.25	1200 baud AFSK		33+ months	monopole	Active	April 2013
	MSP430F169	CW	15-110 WPM	N/A		monopole		
	UC3A0512[5]	Custom AX.25	4800 baud FSK	0 kB[8]	5 days	monopole	Dead	April 2013
	UC3A0512[5]	CW	22 WPM	N/A		monopole		
STP-S26 19 Nov 2010	Integrated	AX.25	9600 baud GMSK	4.8 MB	2 months	turnstile	Dead	April 2013
	Integrated	Proprietary	Variable	8 MB	29+ months	patch	Alive	April 2013
	Integrated	AX.25	1200 baud AFSK	N/A		monopole		
	Integrated	Proprietary	Variable		5 days[14]	patch	Deorbited	April 2013
	Integrated	AX.25	1200 baud AFSK	N/A		monopole		
Falcon 9-002 8 Dec 2010					1 month	dipole	Deorbited	April 2013
			9600 baud GMSK		1 month	quadrafilar helix	Deorbited	April 2013
					1 month	turnstile	Deorbited	April 2013
	Integrated	Proprietary	Variable	0 kB[8]	2 days	dipole	Deorbited	April 2013
	Integrated	AX.25	1200 baud AFSK	N/A				
PSLV-C18 12 Oct 2011		AX.25	2400 baud FSK		18+ months	monopole	Alive	April 2013
		CW	20 WPM	N/A		monopole		
ELaNa-3/ NPP 28 Oct 2011	ATmega1281[5]	CW	20 WPM	0 kB	18+ months	dipole	Alive	April 2013
	Integrated	Proprietary	1.5 Mbps BPSK		18+ months	dipole	Active	April 2013
		AX.25	1200 baud FSK	[11]	18+ months	monopole	Active	April 2013
	Integrated	AX.25	1200 baud FSK	0 kB[8]	18+ months	monopole	Alive	April 2013
	Integrated	AX.25	9600 baud GMSK	242 MB	18+ months	turnstile	Active	April 2013
Vega VV01 13 Feb 2012	Integrated	AX.25/CW	1200 baud MSK/20 WPM		14+ months	turnstile	Active	April 2013
	PIC18F4580[5]	AX.25	1200 baud AFSK	0 kB[15]	2 days	dipole	Dead	April 2013
	PIC16	AX.25	1200 baud AFSK	0 kB[8]	3 days	dipole	Dead	April 2013
	FX614/MSP430	AX.25/CW	1200 baud AFSK/20 WPM		1 week	monopole	Dead	April 2013
	Integrated	Proprietary	Variable	0 kB[15]		patch		
	Integrated	AX.25/CW	1200 baud BPSK/12 WPM		10 months	dipole	Dead	April 2013
	dsPIC33F[5]	Custom/CW	GFSK/120 CPM	305 MB	14+ months	monopole	Active	April 2013
	Integrated	AX.25/CW	9600 baud GFSK	0 kB[8]	2 days	dipole	Dead	April 2013
ELaNa-6/NROL-36 13 Sep 2012						turnstile	Alive	April 2013
	Integrated	Proprietary	38.4 kbaud		8+ months	patch	Active	April 2013
	Integrated	Proprietary	500 kbps FSK			patch		
	Integrated	Proprietary	Variable		8+ months	monopole	Alive	April 2013
	Integrated	AX.25	1200 baud FSK	N/A	8+ months	monopole		
	Integrated	AX.25	9600 baud GFSK	60 MB	8+ months	monopole	Active	April 2013
	PIC18LF6720	AX.25	1200 baud FSK	500 kB	4 months	dipole	Dead	April 2013
	Integrated	AX.25	9600 baud GFSK		8+ months	turnstile	Active	April 2013
	FPGA	Proprietary	1 Mbps FSK		8+ months	patch	Active	April 2013
	Integrated	AX.25	57.6 kbps FSK			dipole		April 2013

Launch	TNC	Protocol	Data Rate/Modulation	Downloaded	Lifetime	Antenna	Status	Updated
ISS 4 Oct 2012	PIC16F886		115.2 kbps FSK		9 months	patch	Deorbited	Aug 2013
	PIC16F1519	AX.25	1200 baud AFSK			monopole		
	PIC16F1519	CW		N/A		monopole		
	Integrated	AX.25	1200 baud AFSK	N/A	7 months		Deorbited	Aug 2013
	PIC18F	AX.25	1200 baud AFSK	0 kB	0 days	dipole	Deorbited	Aug 2013
	PIC16F	FM PWM CW	20 WPM	N/A		dipole		
		SSTV	30 kbps SSTV		5 months	monopole	Deorbited	Aug 2013
		CW				monopole		
					10 months	patch	Deorbited	Aug 2013
PSLV-C20 25 Feb 2013		AX.25	9600 baud FSK		6+ months	turnstile	Alive	Aug 2013
	ATmega32U4	CCSDS/CW	2400 bps/30 WPM		6+ months	turnstile	Alive	Aug 2013
Soyuz/Bion M1 19 April 2013		AX.25	9600 baud FSK	0 kB	0 days	dipole	DOA	Aug 2013
		CW	12 WPM	N/A		monopole		
		Custom	23 kbps BPSK		2+ weeks	turnstile	Alive	April 2013
		CW/AX.25	12 WPM/1200 baud FSK			turnstile		
	CMX909B	Mobitex	4800 bps GMSK		2+ weeks	monopole	Alive	April 2013
	CMX909B	Mobitex	4800 bps GMSK		2+ weeks	monopole	Alive	April 2013
			2.4 kbps FSK		4+ months	monopole	Alive	Aug 2013
	Integrated	Proprietary	variable			patch		
Antares Demo 21 April 2013	Integrated	AX.25	1200 baud FSK		1 week	monopole	Deorbited	Aug 2013
	Integrated	AX.25	1200 baud FSK		1 week	monopole	Deorbited	Aug 2013
	Integrated	Proprietary	340 byte packet			Patch		
	Integrated	AX.25	1200 baud FSK		1 week	monopole	Deorbited	Aug 2013
			2.4 kbps FSK		1 week	monopole	Deorbited	Aug 2013
		IP over DVB-S2	4 Mbps QPSK			patch		
Long March-2D/ Gaofen 1 19 April 2013	N/A	N/A	50 kHz	N/A	1 week	monopole	Dead	Aug 2013
	Integrated	CW/AX.25	9600 baud FSK			monopole		
	Integrated	AX.25	1200 baud AFSK		4+ months	turnstile	Alive	Aug 2013
		SSTV/Audio			1 month		Dead	Aug 2013
Vega VV02 7 May 2013		AX.25	9600 baud FSK		3+ months	monopole	Alive	Aug 2013
		CW	18 WPM			monopole		

[1] Satellite never heard from in space.
[2] As of April 2008.
[3] Used a modified Pacsat protocol on top of AX.25. Source code available upon request.
[4] This object separated from SSETI Express months later and is presumed to be NCube-2.
[5] This is also the main satellite processor.
[6] The radio module accepts serial data and uses an internal TNC.
[7] This beacon is based on a Atmel ATA8402.
[8] No uplink commands received by spacecraft.
[9] The CAPE1 team knew the receiver was dead before integration but had no time to fix it.
[10] One identical radio per satellite section, so three total radios onboard.
[11] Since no on-board telemetry storage exists on this satellite, this figure is not for commanded data and cannot be directly compared to the other spacecraft. This figure is beacon data and includes duplicate beacons.
[12] This figure includes all data from the spacecraft, including beacons, bad packets, and retransmissions.
[13] This satellite was not coordinated through the IARU.
[14] There were no solar cells on this satellite.
[15] This spacecraft did receive uplink commands, but it died before before downlink could be established.
[16] These satellites did not have command receivers.

APPENDIX: LIST OF ACRONYMS

ABC	Aft Bulkhead Carrier
ACT	Advanced Cooling Technologies
ADCS	Attitude Determination and Control System
ADN	Ammonium di-nitramide
AFB	Air Force Base
AFSCN	Air Force Satellite Control Network
ALASA	Airborne Launch Assist Space Access
AMPS	Additively Manufactured Propulsion System
APM	Antenna Pointing Mechanisms
ARC	Ames Research Center
ARCS	Austrian Research Centres Seibersdoorf
ASIC	Application Specific Integrated Circuits
ASRG	Advanced Stirling Radioisotope Generator
ATCS	Active Thermal Control System
BOL	Beginning of Life
C&DH	Command and Data Handling
CAN	Controller Area Network
CAP	C-Adapter Platform
CAT	CubeSat Ambipolar Thruster
CDS	CubeSat Design Specification
CMGs	Control Moment Gyros
CNC	Computer Numerical Controller
COTS	Commercial off the shelf
CPU	Computer Processing Unit
CSAC	Chip-Scale Atomic Clocks
CSD	Canisterized Satellite Dispenser
CTERA	Coefficient Thermal Expansion Release Actuator
DARPA	Defense Advanced Research Projects Agency
DET	Direct Energy Transfer
DICE	Dynamic Ionosphere CubeSat Experiment
DoD	Department of Defense
DSS	Deployable Space Systems, Inc.
E&M	Electricity & Magnetism
EDM	Electrical Discharge Machining
EIRP	Effective Isotropic Radiated Power
EMC	Electromagnetic Compatibility
EOL	End of Life
EPS	Electrical Power Systems
ESPA	EELV Secondary Payload Adapter

FASTSAT	Fast, Affordable, Science and Technology Satellite
FCC	Federal Communications Commission
FPGA	Field Programmable Gate Arrays
GENSO	Global Educational Network for Satellite Operations
GEO	Geostationary Orbit
GNSS	Global Navigation Spacecraft Systems
GPIM	Green Propellant Infusion Mission
GS	Ground Station
HAN	Hydroxyl Ammonium Nitrate
hi-rel	High Reliability
HNF	Hydrazinium Nitroformate
IC	Integrated Circuits
IMPACT	Integrated Micro Primary Atomic Clock Technology
Isp	Specific Impulse
ISS	International Space Station
J-SSOD	Japanese Small Satellite Orbital Deployer
JEM	Japanese Experiment Module
LEO	Low Earth Orbit
LHP	Large Homogeneous Portfolio
LPPTS-R	Radiation Tolerant Low Power Precision Time Source
LS	Laser Sintering
LV	Launch Vehicle
MCC	Mission Control Center
MCU	Micro Controller Unit
MEMS	Micro-Electromechanical systems
MEMS	Micro-Electro-Mechanical Systems
MEO	Medium Earth Orbit
MiXI	Miniature Xenon Ion Thruster
MLI	Multi-Layer Insulation
MMRTG	Multi-Mission RTG
MOC	Mission Operations Center
MPACS	Micro Propulsion Attitude Control System
MPAP	Multiple Payload Adapter Plate
NEXT	NLS Enabling eXploration & Technology
NLAS	NanoSat Launch Adapter System
NLS	NASA Launch Services
NOFB	Nitrous Oxide Fuel Blend
NPSCul	Naval Postgraduate School's CubeSat Launcher
NTIA	National Telecommunications and Information Administration
OMS	Orbital Maneuvering System
OSAGS	Open System of Agile Ground Stations
OSL	Office of Space Launch

P-POD	Poly Picosatellite Orbital Deployer
POCC	Payload Operations Control Center
PPT	Peak Power Tracking
PPT	Pulsed Plasma Thrusters
PPUs	Power Processing Units
PTCS	Passive Thermal Control Systems
RAMPART	RApidprototyped MEMS Propulsion and Radiation Test
RHU	Radioisotope Heating Units
ROSA	Roll-Out Solar Array
RTGs	Radioisotope Thermal Generators
S/C	Spacecraft
SADM	Solar Array Drive Mechanism
SEP	Solar Electric Propulsion
SnR	Signal to Noise Ratio
SoA	State of the Art
SOCC	Spacecraft Operations Control Center
SpaceX	Space Exploration Technologies
SpW	SpaceWire
SRPS	Small Radioisotope Power System
SSO	Sun Synchronous Orbit
SSPS	Spaceflight Secondary Payload System
SSTP	Small Spacecraft Technology Program
SSTP	Small Spacecraft Technology Program
SUM	Six Unit Mount
TASC	Triangular Advanced Solar Cell
TBD	To Be Determined
TCS	Thermal Control Systems
TID	Total Ionizing Dose
TMR	Triple Modular Redundancy
TRL	Technology Readiness Level
TRL	Technology Readiness Level
TT&C	Tracking, Telemetry and Command
UCSB	University of California, Santa Barbara
USB	Universal Serial Bus