The Nanosatellite Revolution: 30 Years and Continuing

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Editors

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Preface
"The Nanosatellite Revolution: 30 Years and Continuing"

This work assembles chapters from contributors across our planet to document technologies, applications, missions, licensing requirements, and lessons learned by individuals and organizations that have participated in the nanosatellite revolution. This book is not intended as a "how to" or as a university reference to design, build, and fly nanosatellites but as a deeper-level reference on what has and hasn't worked in previous nanosatellite programs. Like our previous compendium, *Small Satellites: Past, Present, and Future*, this book provides details on small-satellite efforts, in this case nanosatellites, from the perspective of the individual chapter authors. Many chapters act as a historical reference for particular programs. We realized that some important efforts such as the outstanding nanosatellite work at the NASA-Ames Research Center and in Russia and China were missing from the previous book, so we solicited and received chapters on these efforts. Our previous book was published in 2008, and we wanted to assemble an updated work to cover new advancements in this exploding field. If you plot yearly nanosatellite launch rates vs. launch year using a logarithmic scale on the vertical launch rate axis, you will discover that a tsunami-like second wave of nanosatellite launches started in 1997, with exponential growth that doubles every 2.44 years. The graph, shown simplistically on the cover, validates the use of the term "nanosatellite revolution." Note that the 1997 start date was determined by analyzing launch rates through 2022, and this could change by a few years as we add more data each year.

This book is organized into four sections: a section on missions, a section on technologies, a section on policy, and a final section on future perspectives. In reality, nearly every contribution has elements relating to all three sections. Mission investigations show that nanosatellites or CubeSats (synonymous to us) have evolved from serving as technology demonstration testbeds to providing practical and commercially useful data from space. Nanosatellites were never intended to replace large satellites, except when used in constellations. Companies and governments will continue to permeate low Earth orbit (LEO) with small, micro-, and nanosatellites to form mega-constellations, and inadvertently increase the probability of accidental collision between satellites and debris objects. The problem is further exacerbated if a significant number of satellites arrive partially or totally disabled on orbit. We believe that the future of nanosatellites remains positive and that industry in collaboration with government organizations will self-police to ensure safe access and operations in space. One radical approach to actively reduce the density of ∼10-cm scale orbital-debris objects is given in Chapter 24.

Nanosatellites were the first spacecraft the United States attempted to launch in response to the former Soviet Union successfully orbiting the Sputnik-1 and -2 microsatellites (10 to 100 kg mass). Unfortunately, the Vanguard TV-3 and -TSG nanosatellites had launch failures. Explorer-1 became the first U.S satellite, a microsatellite, to reach orbit in 1958, followed by the first U.S. nanosatellite, Vanguard-1. Satellites were launched by government agencies, and the early flight success rate was miserable; only 55% for the Soviet Union and 37% for the United States between October 1957 and April 1960. Emphasis soon shifted to manned spaceflight, and satellite launch masses grew considerably in the 1960s and 1970s as launch vehicles evolved in reliability and throw-weight capability to support manned operations in LEO, and then, in cis-lunar space.

From the start of the Space Age in 1957 through 1994, only 54 active nanosatellites were launched, yielding a miniscule average launch rate of 1.42 nanosatellites per year. More than 500 passive nanosatellites were launched or ejected on orbit, primarily by the Soviet Union, to reflect light or radio waves to calibrate ground-based sensors and to monitor atmospheric density through orbital decay, but these were just structures without any electronic systems (e.g., energy conversion and storage, communications, command, and control, etc.) required by a true satellite. The highest launch rate of eight active nanosatellites per year occurred in 1965 and in 1967. After that, nanosatellite launch rates declined rapidly and dropped to zero per year between 1973 and 1989. Nanosatellites re-emerged in the 1990s with a meager average active nanosatellite launch rate of 1.8 per year. No one noticed the start of the nanosatellite revolution during the 1990s, or even through most of the 2000s (2000–2009) with an average launch rate of only 3.3 per year. The nanosatellite revolution started slowly, fueled by advancements in miniaturized electronics and microelectromechanical systems for the consumer market, small satellite flight experience gained by the Amateur Radio Satellite Corporation (AMSAT, a not-for-profit organization dedicated to amateur radio enthusiasts that had flown more than 45 small satellites, mostly microsatellites, by the year 1997), and access to affordable space launch opportunities using the truly revolutionary CubeSat containerized satellite concept that was born in Silicon Valley. The nanosatellite revolution started in universities and government labs, but then spread to for-profit commercial companies to provide game-changing services in LEO to a variety of civilian and governmental customers. Planet Labs (now Planet) developed the audacious plan of flying hundreds of CubeSats in LEO to provide 5-meter ground resolution imagery, with daily revisit times, to anyone who would buy the data. Entrepreneurs saw a new market, and new launch service providers were born. The availability of launch on an almost monthly basis, from multiple vendors to moderate cost, spurred the development of even more nanosatellite service providers, resulting in hundreds of nanosatellites being launched each year. *Vive la révolution!*

Our nanosatellite revolution started at The Aerospace Corporation when three intrepid researchers (S. W. Janson, E. Y. Robinson, and H. Helvajian) assembled a community of interest to study miniaturization technologies prevailing at the time to reduce satellite mass. One output was the radical concept of the kilogram-mass integrated-silicon nanosatellite formally presented at the 1993 International Astronautics Federation Conference in Graz, Austria. This was followed by four books and technical publications that focused on miniaturization technologies, development of nanosatellite concepts and technologies, and the presentation of results from small-satellite missions—both successful and failed. The last work was an edited book, *Small Satellites: Past, Present, and Future*, containing 24 chapters on small satellites from U.S., Canadian, Japanese, German, Dutch, and British authors. This new fifth work, and likely the last from these editors, continues our tradition by documenting results from selected nanosatellite missions and technologies, and governmental requirements to launch and fly missions. We expanded our international coverage to include Russian, Chinese, and Singaporean authors, and significantly expanded the gender diversity of our chapter authors. Similar to our prior works, this book also reflects on the future to not only identify driving technologies that will propel further advancement, but also to highlight impending issues spawned by the nanosatellite revolution such as a rapid increase in the orbital debris environment.

Nanosatellite and small-satellite capabilities will continue to increase over time due to the continuing advances in radio frequency electronics, microelectromechanical systems, photonics, power management and storage, materials development, and the increasing computational processing and data storage capabilities that can be put into a single square centimeter of silicon. Many successful nanosatellite-based commercial space enterprises like Planet, Spire, and Swarm are established or underway, and more are expected in the near future. Nanosatellites initially enabled university-class researchers to inexpensively build and fly space experiments, and now they also enable entrepreneurs and venture capitalists to expand commercialism into LEO, and beyond. The perseverance of nanosatellite researchers worldwide during the past 30 years has transformed imagination into practical reality. The quote from Jonas Salk in the opening pages of this book serves as a gentle nod to these dedicated researchers.

In conclusion, we make note of additional trends that are worth observation. (1) The increasing sophistication that can be packaged in a nanosatellite bus and the increasing capability of ride-sharing permit use of nanosatellites as robotic probes that can be sent to explore our solar system with far more detail than has been achieved to date, not only to planets, but to moons and asteroids. (2) In a similar vein, nanosatellites can become the mass-producible building blocks for assembling large argosies (a merchant ship or fleet of merchant ships) in space: "the smart brick." In fact, we predict an era of space development that is enabled by self-assembly using smaller, functional units.

Finally, we thank the authors who report in these pages—we thank them for their contributions, their vision, and their perseverance. We know of many more stories that confirm the utility of the nanosatellite as a viable space tool, and we anticipate the next 25 to 30 years to be a watershed for nanosatellite proliferation.

Henry Helvajian
Siegfried Janson
Editors
April 2023

Contents

Chapter 1

Small Spacecraft for In-Situ Plasma Research and Review of Russian Small-Satellite Format

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1.1 Introduction

The modern trend for more affordable spacecraft brings to the forefront the grand idea of spacecraft miniaturization. The definition of "small" spacecraft depends on the application; we define it as: "micro" (less than 100 kg), "nano" (less than 10 kg), and "pico" (below 1 kg) spaceraft. Micro and nano formats are indeed becoming increasingly popular.[1,2,3] On one hand, progress in electronics allows significant reduction of the spacecraft mass. However, on the other hand, physics and mission requirements often dictate the opposite: directivity and sensitivity of sensors (detectors, telescopes, antennas, etc.) depending on their size, and requirements for payload functionality are growing. Thus, "mass reduction" is just one of the aspects in the current development of space technology. For example, the average mass of geostationary spacecraft tends to increase.[4]

Small satellites actually do not directly replace the large ones, they rather fill free niches in the range of applied and fundamental problems that are not occupied by "ordinary" spacecraft for technical or financial reasons.[1,5] An important factor is the possibility of relatively fast and low-cost implementation of small projects, which allows for quick reaction to changes in priorities, and incorporation of enhanced successor missions. As a result, the number of spacecraft launches has increased and the circle of space players has expanded due to involvement of scientific and educational organizations and even small companies.

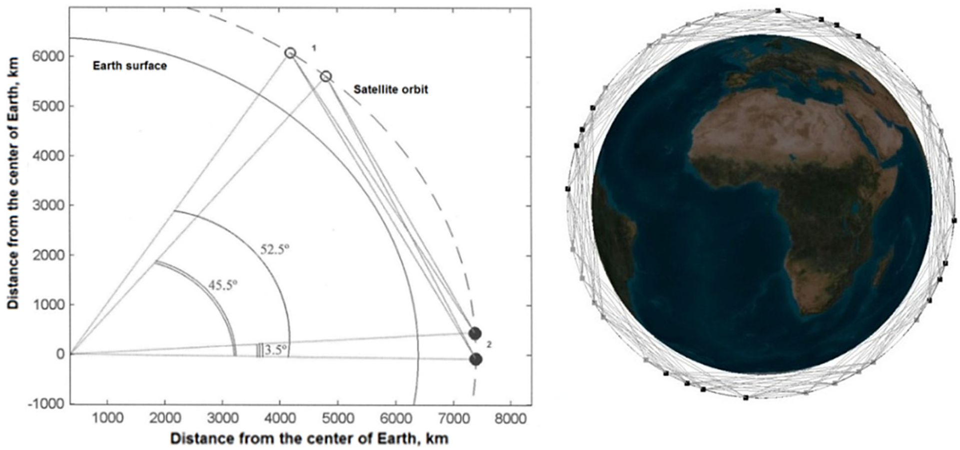

Figure 1-6 Inter-spacecraft tomography scheme. The satellites-transmitters are designated with black circles, and satellites-receivers with grey circles. (Images courtesy of Russian Space Systems.)

approximation. An orbital constellation consisting of 36 small satellites with three frequencies allows a similar reconstruction without any initial assumption (Figure 1-6). To cover the range of spatial scales starting from a few km and larger, the sampling should be not less than one per second.

1.5 Estimating Effectiveness of Scientific Spacecraft

The quality of scientific projects is usually assessed by expert panels. However, it is instructive to consider, primarily for illustration, some formal quantitative indicators. All numbers used hereafter are taken from open sources and are approximate.

For example, one can define a criterion of "information cost"—the ratio of the amount of information received from a spacecraft, in bytes, to the cost of the project. For reference, a NASA scientific project with the largest information return, the SDO solar observatory, transmits about one terabyte of data per day, and its cost is close to a billion USD. Assuming a default three years of primary mission, one gets the cost of one megabyte (MB) of data on the order of 1 USD. Magnetospheric and ionospheric projects generate a smaller information flow (maximum is about a gigabit per day) and are cheaper. The estimates for the high-apogee Van Allen and THEMIS projects are about 100 USD per MB (for three years), and for the low-altitude ionospheric Demeter and "Chibis-M" satellites are about 20 to 50 USD per MB. It should be noted that the real lifetime of "large" satellites is substantially longer, often 10 to 20 years, while the operation costs are much less than the development and launch cost. Therefore, the actual information costs in the long run are much lower.

Chapter 2
The Start of Something Great! How NASA Ames Launched the NASA Biological and Scientific CubeSat Revolution

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2.1 Introduction

This chapter provides a chronological history of the NASA Ames CubeSat and nanosatellite project and mission evolution, starting with a discussion of the background summary of biological research and technology development, and early biological free-flyer projects. The central focus of the chapter is the development and implementation of GeneSat-1, and subsequent 3-unit (U) and 6U nanosatellite projects and missions. Other Ames nanosatellite and small satellite activities are also described, and the chapter concludes with a discussion and summary of the significance and benefits of that initial GeneSat-1 and subsequent missions, along with projections for the future.

The CubeSat scientific and biological revolution started with a blast on December 16, 2006, with the launch of NASA's first CubeSat, GeneSat-1,

2.2.3 Early Biological Free-Flyer Projects

2.2.3.1 ISGEN

In-situ Space Genetic Experiments on Nanosatellites (ISGEN) was a project sponsored by the FSB program office at NASA Headquarters and implemented by the Astrobionics advanced technology development group at NASA ARC. The objective was to develop and demonstrate the autonomous, integrated technologies needed to conduct fundamental in-situ genetics experiments in space. Major elements of requirements assigned to this challenge were: incorporate one or more genetic model organisms as a validation parameter; operate without crew intervention; acquire all data in situ and telemeter to Earth (no sample return); integrate into a small free-flyer platform and launch into space (LEO or other orbit); and lay a solid technology foundation for future autonomous genetics experiments. From this ISGEN exercise arose nanosatellite-targeted biological design-reference experiments, which formed the basis for the subsequent Ames in-situ bioanalytical payloads, instruments, and missions.

2.2.3.2 BioNanosatellite/BioExplorer

BioExplorer was planned as the first in a series of small satellites with biological payloads developed jointly by NASA Ames and Stanford University. BioExplorer was to demonstrate technology that could enable researchers to perform cell-culture-based biological experiments in small satellites. The objective of the first science experiment was to evaluate the influence of microgravity on the growth rate of yeast cells. The satellite would first store the data and then transmit them to a radio station at Stanford University over the course of several days following the mission. Prototypes of both the spacecraft and the science payload were developed and demonstrated, but BioExplorer was never flown due to unavailability of affordable launch possibilities at that time.

These platforms and standards, originally developed for aerospace engineering hands-on learning and academic training, were narrowly viewed at that time by mission and program managers for NASA missions and applications. Nevertheless, these early Biological Free-Flyer Technology development and demonstration efforts led to the recognition of the possibilities and capabilities for scientific utilization of these small platforms.

2.3 NASA Ames Nanosatellite Platforms and Missions

2.3.1 GeneSat-1/GeneBox

2.3.1.1 Mission Description and Outcome

GeneSat-1 was launched as a secondary payload with the Operational Responsive Space TacSat-2 spacecraft aboard a Minotaur-1 in December of

2.4 Summary and Conclusions

2.4.1 NASA Ames Early Nanosatellite Contributions and "Firsts"

This chapter has described eight (8) 3U nanosatellites developed and launched by the NASA Ames nanosatellite mission teams from 2006–2017. These missions were responsible for a number of significant "firsts," as described in Figure 2-34.

2.4.2 NASA Ames Early Biological Science and Technology Contributions

As important as these early nanosatellite spacecraft and mission contributions were, just as significant are the in-situ biological technologies, instruments, and payloads developed and demonstrated in these Ames-developed missions. Table 2-4 summarizes accomplishments and products of these biological missions, much of which has already been discussed earlier in this chapter.

2.5 Conclusions

In this chapter, we have attempted to chronicle the initial development and evolution of NASA's early entry into the nanosatellite ecosystem. Although the primary focus of the Ames nanosatellite efforts was to search for ways to accomplish biological research objectives, there quickly emerged a need and opportunity to utilize these platforms for low-cost technology demonstrations and risk-mitigation missions. The combinations of these capabilities bode well for future in-situ biological, medical, and astrobiology missions, as well as terrestrial, domestic, environmental, and quality of life applications.

In accomplishing our nanosatellite missions, NASA Ames made pioneering breakthroughs and contributions in several important areas including:

- Tailored nanosatellite lifecycle product development and missions, CubeSat bus and payload development, with streamlined review and reporting procedures which are captured in NASA Procedural Requirements (NPR).
- Modification to the CubeSat Standard and P-PODs to accommodate a mass of 2-kg/cube.
- Introduction of the "Tuna Can" extension to the baseline CubeSat standard configuration, and associated modifications to the P-POD, developed by California Polytechnic State University (Poly) to accommodate that change.

Chapter 3

One Year On-Orbit Operation of a Micropropulsion System Using an Ion Thruster and Cold-Gas Thrusters on the 50-Kg-Class Micro Space Probe, PROCYON

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3.1 Introduction

3.1.1 Micro Space Probe, PROCYON

PRoximate Object Close flY by with Optical Navigation (PROCYON)[1,2] is a 50-kg-class micro–space probe that was developed collaboratively by the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA) (see Fig. 3.1). It was launched on December 3, 2014 and operated for a full year thereafter. The purpose of PROCYON was to show that microspacecraft (spacecraft weighing 100 kg or less) can be used for deep-space exploration in a threefold mission. The nominal mission was to verify bus technology for small space probes and to achieve not only basic functions, such as heat control, attitude control, communication, orbit determination, and electricity generation in deep space, but also constant acceleration provided by the electric propulsion. Next, the advanced portion of the mission was to verify a high-efficiency power amplifier using gallium nitride (GaN),[3] navigation experiments with very long baseline interferometry (VLBI), an Earth swing-by using orbit control via electric propulsion, entry into an asteroid flyby orbit so these operations were implemented extremely carefully. Operation #10 related to the fact that the attitude stability was not really obtainable in the attitude control mode.

Unfortunately, despite the tireless recovery operations of the project team over an approximate two-month period, the high voltage short circuit could not be resolved by the end of April, which was the final deadline, so the Earth swing-by had to be abandoned. Later, the priorities of the PROCYON operations were changed to achieving missions other than asteroid flyby.

3.5 Trajectory Correction Maneuver Test of Cold-Gas Thrusters

3.5.1 Unloading Maneuver by the Cold-Gas Thrusters

After May 2015, when the asteroid flyby was abandoned, the focus of the I-COUPS operation was changed to the CTU. The focus was continuous verification of the cold-gas thrusters for reaction wheel (RW) unloading function and testing of the translational thrust generation intended for use during flyby. As RW unloading is the lifeline of the probe, the significance of accumulating space verification performance is large. In addition, the generation of translational thrust has a high affinity with future rendezvous and docking missions and obtaining orbital operation data about this is highly valuable.

A placement diagram of the cold-gas thrusters is shown in Figure 3-18. CT1–2 are placed on the PZ plane, CT3–4 are placed on the MZ plane, CT5–6 are placed on the PX plane, and CT3–4 are placed on the MX plane. The axis of the thruster nozzle is tilted 20° from the plane-normal in the case of CT1–4 and 15° in the case of CT3–4. By combining the operation of these thrusters, it is possible to provide rotational and translational force in both directions on three axes. The combination of these is given in Table 3-7. It should be noted that torque around the *X* and *Y* axes associates with

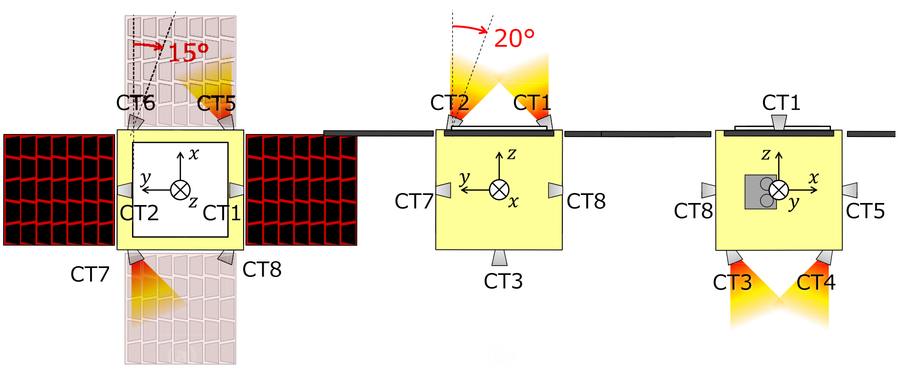

Figure 3-18 Configuration of the cold-gas thrusters.

Chapter 4
Small-Satellite Trending and Reliability 2009–2018

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4.1 Abstract

Once a niche application or a novelty, small satellites ("SmallSats") are becoming increasingly ubiquitous contributors to the civil, military, and commercial space communities. Each new generation of SmallSats has more capable payloads and bus technologies, demonstrating increasingly sophisticated platforms to collect data from space or provide services to terrestrial users. Small satellites have demonstrated miniaturization of existing components as well as improving reliability of previous generations of flight hardware and software. Widespread demand for highly reliable CubeSat-compatible components has allowed operational users to turn to inexpensive SmallSats to perform missions that historically would have required larger satellites and higher costs, while allowing for new missions that previously wouldn't have been possible if the business case didn't close.

This chapter will quantify trends in small-satellite utilization, reliability, and capability using a database of all small satellites (<500 kg) launched from 2009 through 2018. By analyzing the full small-satellite industry over time, this chapter will identify trends in implementation, success rates, and the reasons why some missions have failed. It will also address how to improve future missions to maintain the benefits of the lower cost space element while still achieving complex, multidimensional missions.

This study identified several key trends that illustrate the recent state of the small-satellite industry:

- Overall, 87% of small satellites with completed missions launched in the last decade were successful, including 90% of satellites launched in the last three years.

4.5 Results

4.5.1 Satellite Mass and Size

The initial publication considered just the 244 satellites launched between 2009 and 2013. In the subsequent five years, another 1208 satellites were launched, a six-fold increase that highlights the dramatic growth in the small-satellite industry in a short period of time (Figure 4-1).

Overall there has been a significant rise in launches in recent years, which was anticipated, predicted, and then confirmed by previous studies.[4,6,17] However, there has not been the exponential growth that was anticipated in 2013 and 2014, which was likely due to a series of launch failures, including Orbital ATK's Antares and SpaceX's Falcon 9 launch vehicles in October 2014 and June 2015. The loss of 51 small satellites on these failed launch vehicles alone, coupled with a reduced launch rate while Orbital ATK and SpaceX undertook rigorous fault identification and recovery actions, meant that significantly fewer SmallSats launched to orbit in 2015–2016. While there has been some recovery in 2017–2018, the overall rate is lower than optimists (including the authors) predicted in 2014.

Figure 4-2 shows the distribution of satellite mass, which—as expected-correlates well with satellite size—is shown in Figure 4-3. Most of the satellites

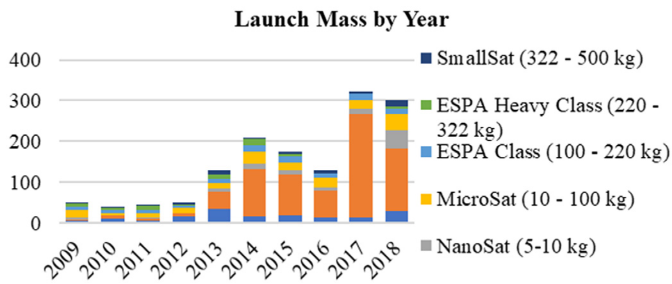

Figure 4-1 Launch mass category by year (2009–2018).

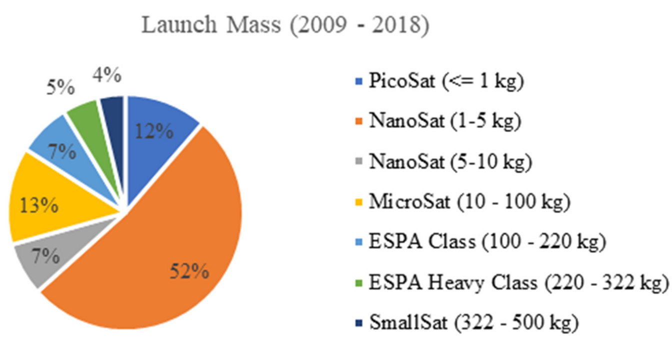

Figure 4-2 Launch mass category summary (2009–2018).

Chapter 5
MarCO: Mars Cube One

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5.1 Introduction

Near the end of June, 2003, six small spacecraft launched as secondary payloads onboard a Rockot KS from Plesetsk, Russia.[1] While many small secondary (or tertiary) spacecraft had previously flown, these so-called "CubeSats" adhered to a new standard that simplified the interface to the launch vehicle, minimizing risk to the primary payload.[2] In subsequent years, adoption of these standards by universities, researchers, commercial enterprises, and government agencies led to a surge in low-Earth-orbit (LEO) small spacecraft, greatly enhanced by the availability of amenable launch vehicles. Within several years, the U.S. National Science Foundation recognized the possibility for unique scientific missions and NASA's CubeSat Launch Initiative encouraged further launch opportunities.[3]

The significant expansion of LEO opportunities, along with rapidly advancing technological capabilties, led to questions as to both the suitability and applicability of these CubeSats (or other nanospacecraft) in interplanetary exploration. While a multitude of probes have previously been deployed from larger vehicles, none seemed to match the characteristics of interplanetary nanospacecraft:

- independent spacecraft once deployed—able to survive long enough to accomplish a scientific mission; self-orient, and translate to achieve interplanetary objectives; and communicate directly back to Earth for command and control as well as navigation.

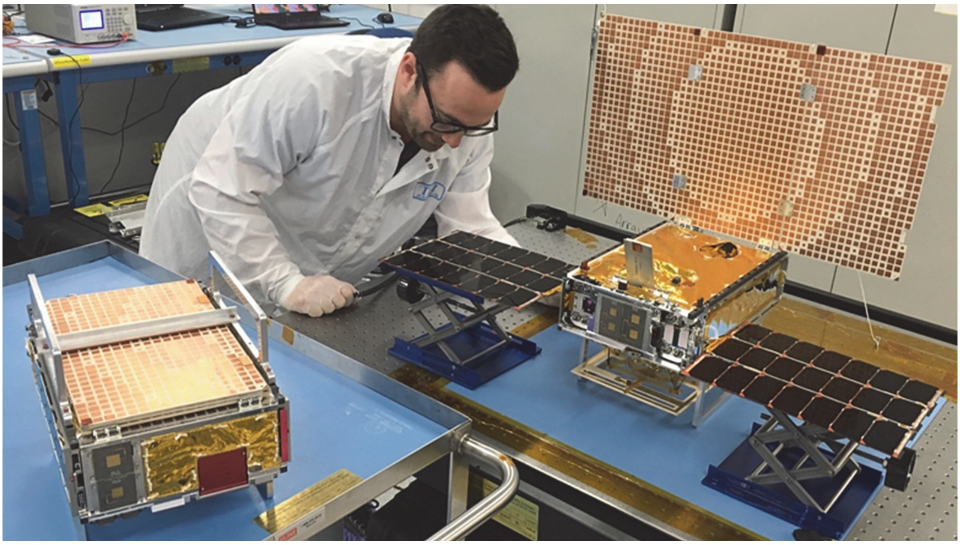

Figure 5-7 MarCO flight spacecraft prior to delivery. MarCO-B in stowed configuration is on the left, while MarCO-B is on the right. Each spacecraft is held by aluminum support brackets for safe handling. Red remove-before-flight covers are in place to protect the deployment switches and star tracker.

The batteries had weathered storage well, beating expected capacity drops in subsequent testing. In the early months of 2018, both spacecraft performed day-in-the-life and long-duration testing. Initial sequences were developed to turn the spacecraft on after launch, and launch day procedures were practiced. Near delivery, FM-2 was determined to have a leak in the propulsion system, and FM-1 had a small leak between the tank and the plenum expansion chamber. Aligning with the schedule-first vs performance-first strategy chosen for the two vehicles, FM-2 had its tank re-opened for seal repair, while the risk was accepted for FM-1. FM-2 underwent final vibration testing, and the vehicles were prepared for flight delivery.

5.4 Flight Readiness

Though launch was scheduled for May 5, 2018, each flight spacecraft was delivered for dispenser integration on March 3rd. Final checkout included verification of dispenser interface requirements, demonstration of deployment switches, and evaluation of the power-on sequence. This also was the final opportunity for software updates and battery charge as each spacecraft would be powered-off until on-orbit deployment.

The power-on sequence of MarCO is triggered by four deployment switches in a two-series-two-parallel (2s2p) configuration. The exposed roller-lever switches are located in each corner on the smallest side of the spacecraft and triggers are connected directly to MOSFET gates. These gates provide essentially the same direction as the received UHF source. This test utilized the broad-beamed Medium Gain Antenna to compensate for the geometry difference.

After several attempts that served to wring out discrepancies in the test setup, the bent-pipe relay was successfully exercised for both MarCO-A and MarCO-B with the UHF signal transmitted from SRI, to the spacecraft, and down to the Canberra DSN station. The InSight GDS team verified that no data was lost during this transmission. The team also exercised a variety of characterization tests, such as reducing signal level, switching to carrier-only, and slightly offsetting the carrier frequency to test UHF locking, autonomous sweep, and range of sweep. This test campaign proved that MarCO had met the primary Technology Demonstration goal of bent-pipe relay, and that the MarCO spacecraft were fully capable of Insight EDL support.

5.5.5 Other Checkout Activities

Additional systems were also checked out within the first month after launch, including evaluating additional data rates, ranging while transmitting at 8 kbps, and even usage of the cameras. One of the first images from MarCO was that of the Earth and Moon, with MarCO-B's HGA and HGA feed in the field of view. The image was primarily used to evaluate the HGA deployment, however the team planned an orientation of the spacecraft to also capture the two celestial bodies. A small model of the spacecraft along with a cell phone light and an attitude determination tool known as TBALL were used to plan the shadow placement of the HGA feed, as well as occlude the Sun from the wide field of view (WFOV) camera. Pictures taken from the NFOV were unfortunately blurry. While MarCO-A also had these two cameras, the NFOV had been disconnected during I&T during late checkout issues, and the WFOV consistently showed blurry images of the HGA.

By the end of checkout, all technology demonstration objectives were complete, save travel to Mars itself.

5.6 Cruise

With checkout complete, the team transitioned to sustaining operations and reduced the JPL workforce from approximately 12 engineers during Launch and Checkout phases to approximately five JPL engineers for the cruise phase, augmented by four Cal Poly students. Each spacecraft was sent commands during approximately three weekly uplink/downlink passes. On days without uplink, each spacecraft made use of multiple-spacecraft-per-aperture opportunities. Generally the spacecraft were programmed to downlink historical telemetry or perform delta differential one-way ranging (ΔDOR) (in conjunction with InSight).

Chapter 6
STU-2: A 3 CubeSat Constellation for Earth Observation and Marine/Air Traffic Monitoring

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6.1 Introduction

In 1999, the CubeSat (Cube Satellite) concept was developed by California Polytechnic State University and Stanford University, which established a set of standards or specifications to help universities worldwide to perform space science and exploration.[1] A CubeSat is a type of miniaturized satellite for space research that comes in unit volumes of one liter (10-cm cube), known as 1U, has a mass of no more than 1.33 kg per 1U volume, and typically uses commercial off-the-shelf (COTS) components for its electronics.[2] Since then, the CubeSat standard has been accepted worldwide and has inspired many universities to develop their own CubeSat projects, missions and technologies. These efforts spun off high-tech companies dedicated to the CubeSat community. CubeSats are scalable along any axis, using 1U increments, meaning that CubeSats such as 2U, 3U, 6U, and 12U CubeSats have been built and launched, or are under development. Subunit sizes such as 1/2U and 1/4U have also flown. The CubeSat standard has brought the small satellite community into the "CubeSat Era."[3,4,5,6]

In 2017, over 300 nano/microsatellites with mass below 50 kg were launched globally, representing an increase of nearly 205% compared to 2016.[3] Among them, more than 280 were nanosatellites based on CubeSat technologies. These numbers prove that after more than a decade's development, CubeSats have evolved from purely educational tools into a

Table 6-14 Power Management of STU-2A/C.

Payload/Instrument	Design Index	In-Orbit Results	Switch Control
AX100@3.3V	0 ~ 950 mA	886 mA (STU-2A) 866 mA (STU-2C)	OK
OBC@3.3V	0 ~ 250 mA	116 mA (STU-2A) 107 mA (STU-2C)	OK
HUB@3.3V	0 ~ 60 mA	48 mA (STU-2A) 53 mA (STU-2C)	OK
GPS/BD2@3.3V	0 ~ 200 mA	134 mA (STU-2A) 138 mA (STU-2C)	OK
Camera@5V	0 ~ 2000 mA	1576 mA	OK
Micropropulsion@16.6V	0 ~ 2000 mA	190 mA	OK
Star Tracker@3.3V	0 ~ 300 mA	199 mA	OK
Reaction Wheels@3.3V	0 ~ 500 mA	431 mA	OK
S-band Tx@16.6V	0 ~ 2000 mA	750 mA	OK

6.8 Ground- and Space-based ADS-B Data Fusion Analysis

In this section, the implementation and integration progress of ADS-B payload in STU-2C will be introduced and some experiment results in space will be compared with the ground ADS-B data.

6.8.1 System Overview

A limiting factor for the space experiment is the line-of-sight range to any aircraft. A radio link between ADS-B-aircraft and the satellite should be considered at the very first. All calculations and assumptions are listed in Table 6-15.

Table 6-15 Link Budget for Space-Based ADS-B Reception.

Parameter	Value	Unit
TX Power	24 / 250	dBW/W
TX Antenna Gain	1	dBi
Line Loss	2	dB
TX Bit Rate	1.04	Mb/s
EIRP	23	dBW
Atmospheric Loss	2.5	dB
Polarization Loss	6	dB
RX Antenna Gain	5	dBi
RX Sensitivity	–103	dBm
Max Range	925	km

Chapter 7
The AeroCube-6 Mission

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AeroCube-6 was a 1U (10 cm) CubeSat-class nanosatellite that separated, on command, into two ½U satellites on orbit. The primary payload on each 850-gram 0.5U CubeSat was a trio of micro-dosimeters designed to monitor space radiation levels. These satellites were spin-stabilized with their solar arrays facing the sun and flown in tandem at different ranges from 100 to 800 km. Differential drag was used to establish and maintain the desired spacing between them. The AeroCube-6 mission provided the first example of spatially separated dosimeters on CubeSats flying in unison to study the dynamics of the space weather radiation. It launched on a DNEPR in June of 2014 into a 700 km, 98-deg inclination orbit. It was hosted inside the UniSat-6 satellite, built by G.A.U.S.S. Srl in Rome, Italy. UniSat-6 deployed AeroCube-6 and three other CubeSats after a few days. The secondary payload was a solar cell monitoring experiment that measured current-voltage curves for a second set of solar cells. Development of AeroCube-6 was funded by the USAF SMC Advanced Plans program office.

7.1 Mission Genesis and Benefits

The original concept of AeroCube-6 (AC6) was to take advantage of an anticipated surplus in deployer volume during the development of our AeroCube-5 (AC-5) satellites. Each of the two AC-5 spacecraft was expected to be slightly longer than a single CubeSat "Unit" of ten centimeters, so that it appeared that a volume of 0.4 CubeSat Units ($\sim 10 \times 10 \times 4$ cm) would be available for a single additional satellite—enough volume to fly a simple, tumbling space weather experiment. As the AC-5 design matured, the anticipated surplus volume evaporated, and the initial flight opportunity was, fortuitously, lost. Instead, the possibility of a tandem pair was proposed. When the science team was asked whether two identical satellites replacing the

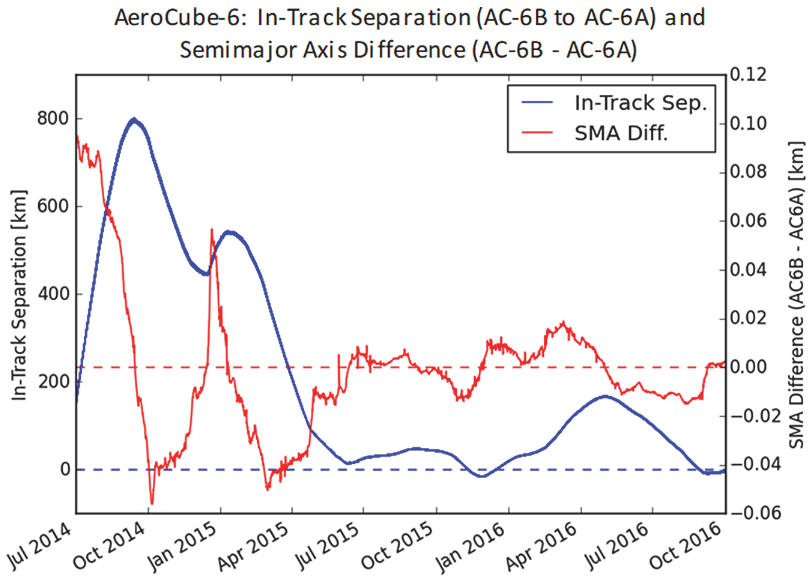

Figure 7-10 Evolution of AC6 spacecraft separation. The differential drag technique allows operators to adjust the rate of change in the semi-major axis (SMA). The SMA difference between the two vehicles determines the separation/closure rate.

allowed the separation rate to change by 0.03 km/day^2 at the flight altitude, but faster acceleration could be achieved when solar and geomagnetic activity inflated the neutral atmosphere, enhancing the drag.

7.3 Science Results

In the early years of satellite-based radiation-belt research, convolution of spatial and temporal variations in the observations led to significant uncertainties in their interpretation. If statistically significant variations are seen in the run of data, are they due to temporal or spatial variations in the ambient particle population?

The velocity of AC6-A and AC6-B, a pair of LEO satellites, initially put into a 613×700 km sun-synchronous orbit, is ~7.5 km/s, whereas the gyro radius of a radiation-belt electron at LEO altitudes in the energy range of interest, 10 keV to a few MeV, is about 1–10 m. Thus, spatial structures could exist that would be passed through in milliseconds. Further complexity is engendered by the fact that radiation-belt particles in general are not isotropic; therefore, given the usual directional sensitivity of satellite sensors, the instantaneous satellite attitude is important.

While many of the observations made in LEO are of particles destined to enter the atmosphere, the temporal and spatial structures of these particles are indicative of physical processes happening at higher altitudes, up to and including the equatorial magnetosphere. These equatorial processes include

Chapter 8

Design, Integration, Test, Launch and In-Orbit Test of NUS' First Nanosatellite – Galassia

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8.1 Introduction

The Galassia journey began in August 2011, when the National University of Singapore (NUS) department of Electrical and Computer Engineering (ECE) took in five students who were interested in building an unmanned system that goes into space. The concept of using a 2U CubeSat measuring $10\,\text{cm} \times 10\,\text{cm} \times 20\,\text{cm}$ and leveraging on the use of commercial off-the-shelf (COTS) parts to build and launch a scientific space mission was conceived. Not long after, in October 2012, NUS embarked on the Aerospace Systems Initiative as part of its Design Centric Program (DCP, now known as the innovation and design program, iDP) which has a pedagogical approach using hands-on multi-disciplinary aerospace projects (e.g., CubeSat) to train a pipeline of engineering students over four years of their undergraduate education at NUS. It is envisaged that students educated in this way will be

Figure 8-22 Antenna mast and mission control station of Galassia.

to a maximum height of about 13 m to overcome the obstructions from adjacent buildings in the NUS campus and it holds a UHF antenna as well as a VHF antenna. The UHF antenna is for the Telemetry, Tracking and Communication of the ground stations with Galassia. This UHF antenna system is also used to receive payload data stored in the OBC of Galassia. As for the mission control room, it includes two desktop workstations and two monitors. The concept of the mission control center design is that one set of desktop station and monitor is meant for performing mission control and operations of the Galassia, whereas the other set of desktop station and monitor is primarily used to look at the payload data received by the ground station. Figure 8-22 shows the physical set up of the antenna mast as well as the mission control for the Galassia mission.

8.6.1 Ground Segment Architecture

Figure 8-23 shows a block diagram of the Galassia ground station hardware (radio, antennas, rotator, and desktop computers).

8.6.2 Ground Control Software

The ground station software was developed in order to have an intuitive and easy-to-use platform for the Galassia mission (Figure 8-24). It was also intended to provide the framework for future missions so that future ground stations need not be developed from scratch.

8.7 Launch and Early Orbit Phase Launch Campaign

The launch campaign for the Galassia FM took several weeks (from November 14, 2015 to December 8, 2015) and it involved two research staff members from the NUS. Careful scheduling was used to ensure that enough schedule margin was built into the activities. This is crucial to combat unforeseen circumstances occurring during the launch campaign.

Chapter 9

Space-Based AIS with a Norwegian Small-Satellite Constellation

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9.1 Introduction

In recent decades, small satellites have become capable of increasingly valuable missions to demonstrate emerging technology and applications. Together with shorter development cycles, the reduction of launch costs, and operational resiliency in the event of failure, small-satellite constellations offer an attractive way of establishing national expertise in space technology. The Norwegian Automatic Identification System (AIS) small-satellite constellation was initiated based on national needs for better monitoring of ocean areas under Norwegian jurisdiction, which amounts to more than two million square kilometers.[1] With this goal in mind, the first satellite, AISSat-1, was initiated in 2007 and subsequently launched in July 2010 as a service demonstrator.[2] It is a nanosatellite designed by the Space Flight Laboratory (SFL) and carries an AIS receiver for collecting transmissions from vessels, containing information such as identity, position and heading, on dedicated frequencies in the maritime VHF band (156.025–162.025 MHz).

Chapter 10

IceCube: Submillimeter-Wave Technology Development for Future Science on a CubeSat

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10.1 Introduction

Clouds play important roles in Earth's climate and weather systems through interactions with atmospheric processes in radiation, dynamics, latent heat release, and precipitation in a wide range of spatiotemporal scales. Clouds are the leading source of uncertainties in climate/weather prediction.[1,2,3] Ice clouds, in particular, have been used as a tuning parameter in global circulation models (GCMs) to achieve model agreement with observations at the top of the atmosphere for radiation budget and at the bottom for precipitation. Clouds in the GCMs have been less realistically represented, largely because of inaccurate ice cloud measurements and poorly constrained cloud processes in the model. As a result, there is a wide spread in the cloud ice amount simulated from GCMs.[4,5,6]

Submillimeter-wave remote sensing at 200–1000 GHz is capable of penetrating clouds to measure cloud ice mass and microphysical properties in the middle-to-upper troposphere, filling the sensitivity gap not covered by visible (VIS)/infrared (IR) and low-frequency microwave (MW) sensors (10–183 GHz). However, risks and potentially high costs remain as an obstacle for enabling future science missions for high-frequency receivers. For decades NASA has made a significant effort to advance submillimeter-wave technologies and the development of spaceflight systems for science applications. The IceCube project is the latest of NASA's effort to advance

Chapter 11

Meeting the Challenge of More-Capable NanoSat Missions

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11.1 Introduction

NanoSat capabilities have advanced rapidly over the past decade, allowing them to address missions once thought to be too challenging, given the performance of early NanoSat systems and components. Early NanoSats, used for educational purposes, focused on training students in systems engineering, space science, and project management on development cycles suitable for university programs. These early NanoSats, characterized by low-power, low-data-rate communications, and coarse pointing, had limited potential for addressing many operational missions. Their primary focus was on training the next generation of space scientists, engineers, and leaders, with less emphasis on pushing the state of the art in high-performance miniature platforms. Early perceptions of NanoSats were that they were toys and inadequate for most mission areas. However, those perceptions have been slowly changing as more NanoSats perform more-advanced space and Earth science, Earth imagery, and communications missions.

NanoSats are primarily characterized by their small size and mass. This presents both challenges and benefits. There are many logistical advantages of being small, including ease of transport, use of smaller facilities for integration and test, and the ability to launch in quantity at relatively low cost. This has the secondary effect of shrinking required floor space, simplifying integration support equipment, and reducing capital equipment costs. This lowers the barrier to entry into the NanoSat market and has been especially advantageous for small companies just starting up.

Chapter 12
What Is the Right Look for a Constellation of Small Satellites?

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12.1 Introduction

Small satellites, in their many varied forms, shapes, and looks, have become a key part of the modern space industry. The advent of micro- and nanosatellites, with their low individual cost, opened the door for constellations of many satellites, which in turn opened the door for a whole new range of applications that single satellites could not undertake. Probably the best-known example is large-scale, fast imaging of the Earth's surface: currently this is only achievable at "reasonable" resolutions using constellations of satellites in low Earth orbit (LEO). Similar requirements led to the development of constellations to collect automated identification of ships (AIS) signals or constellations to sound the atmosphere by looking at the variations in global navigation satellite signals. These are applications where physics drives the choice of a constellation solution over a single satellite solution. Additionally, there are other applications that increasingly rely on constellations to deliver them, but for which there are clear single-satellite alternatives: in these cases, the fact that the constellation offers a critical advantage to the users drives its choice. This is the case for many of the broadband constellation systems currently being developed that rely on an "edge" performance advantage of LEO constellations and low-communication latency as the reasoning behind the selection of a constellation configuration.

Constellations will look very different depending on what their final purpose is, and the trade-offs that will need to be considered are equally different. This chapter does not address the detailed design of constellations, as there are plenty of texts and papers addressing that aspect in quite some

Chapter 15
Innovative and Unique Launch Opportunity for Small Satellites from Kibo/ISS

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15.1 Introduction

In recent years, a growing number of universities and companies around the world have been developing small satellites, mainly CubeSats.[1] CubeSats are attracting much attention not only for their short-term and low-cost development but also for their ability to perform various types of difficult missions, such as Earth observation, technology demonstration, and planetary exploration. At the beginning of the CubeSat history, the method of transporting a satellite into orbit was as a secoundary "piggyback" payload carried aboard a launch vehicle, and launch opportunities were limited by the willingness of the launch vehicle owner to accept the risk of carrying an additional payload.

The Japan Aerospace Exploration Agency (JAXA) developed a unique system called the JEM Small Satellite Orbital Deployer (J-SSOD) to deploy and inject satellites into orbit from the Japanese experiment module (JEM) known as "Kibo" on the International Space Station (ISS). Kibo is a unique module that incorporates both the JEM-Airlock (JEM AL) and the JEM-Remote Manipulator System (JEMRMS), a special kind of robotic arm.[2,3,4,5] Figure 15-1 shows a photograph of Kibo.

Small satellites are delivered to Kibo/ISS as cargo carried by resupply vehicles such as the Japanese H-II transfer vehicle (HTV) known as "Kounotori" (shown in Figure 15-2), the SpaceX Dragon, and the Orbital-ATK Cygnus. CubeSats can now be sent to the ISS using standard resupply launches and deployed by Kibo.

Chapter 16
Multi-Aspect Cosmic Ray Ion Detectors for Deep-Space CubeSats

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16.1 Introduction

Understanding the interactions of the sun, Earth, and other natural and manmade objects in the solar system with the space radiation environment is crucial for improving activities of humans on Earth and in space. In order to provide a complete understanding of how energetic processes internal and external to the solar system shape magnetospheres, atmospheres, and surfaces, in-situ particle observations should include measurements of solar energetic protons (SEPs) and galactic cosmic rays (GCRs), along with solar wind and plasma. Missions to achieve these measurements would include flexible path orbiters, probes, landers, or rovers beyond low Earth orbit (LEO).

Nanosatellites with masses of 10 kg and less (such as CubeSats) are seen to be low-cost, nimble platforms ideal for conducting this range of observations either solo or in multiple locations as a swarm. However, current detector technology limits the measurement capability by restrictions of size, power, and thermal stability of the nanosatellite platform.

To meet these challenges, NASA Glenn Research Center (GRC) is developing a suite of CubeSat-based radiation detectors based on wide-bandgap (WBG) semiconductors to study solar and cosmic ray ions in lunar orbit or deep space. These WBG semiconductors have the benefit of high thermal stability, low noise, and tolerance to radiation damage that allows fabrication of compact detectors that are easily configurable for a nanosatellite platform.

Chapter 18
Nanosatellite Communications

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18.1 Overview

Over 560 nanosatellites currently operate in low Earth orbit. See Figure 18-1, which is a picture of nanosatellites being deployed from the International Space Station (ISS). The satellites were built and operated by Planet Labs, Inc., to take images of Earth from space.[1] Higher data rate nanosatellites are transitioning away from amateur radio bands to higher frequency bands. The NASA Goddard Space Flight Center (GSFC) has studied methods to optimize future space-to-ground nanosatellite communication.

The NASA Near Earth Network (NEN) project consists of globally distributed tracking stations, including NASA, commercial, and partner ground stations, that are strategically located to maximize the coverage provided to a variety of orbital and suborbital missions, including those in low Earth orbit (LEO), geostationary Earth orbit (GEO), highly elliptical orbit (HEO), lunar orbit and Lagrange point L1/L2 orbits. Analyses involving the NEN have applicability to other ground station networks. Our studies addressed nanosatellite direct-to-ground communication and nanosatellite constellations with a mother-ship direct-to-ground communication.

We simulated architectures and identified technologies to develop optimum communication concepts for nanosatellite communications. This chapter will present details of the simulations and analyses that include

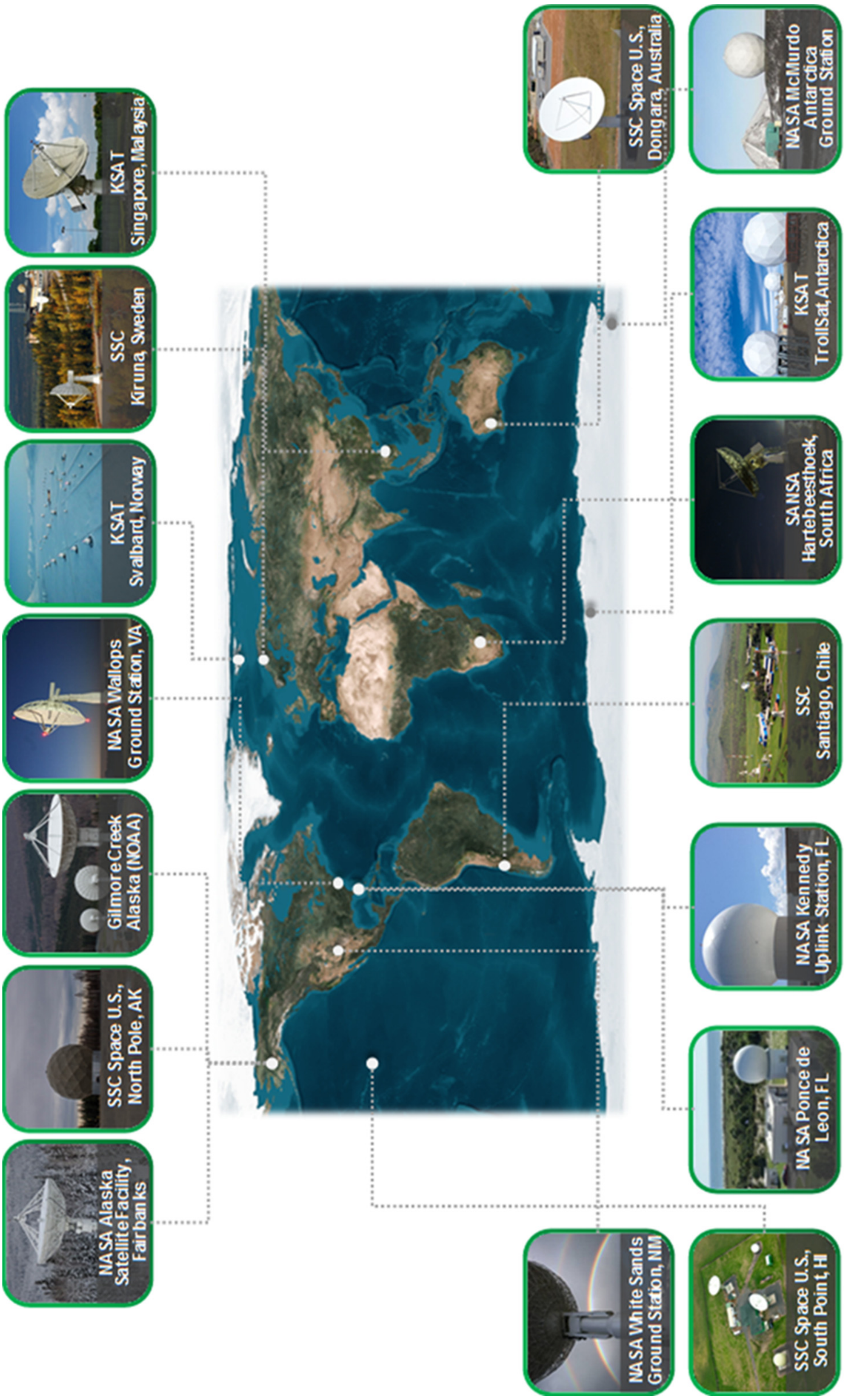

Figure 18-2 NASA NEN.

Chapter 19

SASSI^2, a CubeSat Sensor Platform for Atmospheric Entry Aerothermodynamics

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19.1 Introduction

Thermal protection systems (TPS) on atmospheric entry vehicles are currently designed with significant margins due to uncertainties in hypersonic flow properties, TPS material response, and the resultant nonequilibrium chemically reacting flow. One of the largest uncertainties in a reentry flow is the rate at which different types of chemical reactions occur. The TPS margin associated with uncertainty substantially increases cost and mass for atmospheric entry missions. Comprehensive ground-based testing of TPS in this high-enthalpy, low-density flow is not possible with current technology. As a result, the only method for obtaining data in this regime is through flight testing. While past missions have attempted to obtain this information, none of these missions have successfully provided chemical-reaction data uncontaminated by an ablative-heat shield for a vehicle traveling at orbital velocities through the upper atmosphere. The Student Aerothermal Spectrometer Satellite of Illinois and Indiana (SASSI^2), shown in its final assembled form in Figure 19-1, will demonstrate the ability of a 3U CubeSat to determine constituent flow species and their number densities, as well as bulk-flow properties. SASSI^2 will collect these data during reentry into the atmosphere using its instrument payload and will communicate using the Globalstar network to ensure that the data are transferred without dependence on

Chapter 21
Navigating the U.S. Policy Compliance Roadmap

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21.1 Introduction

Small satellites, like large satellites, must comply with all applicable laws and policies for operating in space. Unlike large satellites, however, small satellites are more likely to be built by organizations new to space, or to be the product of a partnership of many different organizations. Small satellites also have short development cycles, and licensing processes appropriate for large satellites with long development cycles can sometimes take longer than it takes to build a small satellite. In some cases, policy approval and licensing processes have not kept pace with the proliferation of small satellites and the increasing democratization of space.

As small satellites have become more plentiful, so too have missions with large numbers of satellites on one rocket. Often the satellites come from multiple different organizations and also contain payloads from different organizations hosted on satellites owned by yet another organization. In this new pardigm, the launch integration manager is faced with the challenging task of understanding the space policy requirements for a diverse set of agencies and guiding its mission partners through the approval process. Small satellites are quicker and cheaper to build than large satellites; rideshare launches allow these satellites access to space at a fraction of the cost of procuring a dedicated rocket. All of this has had a democratizing effect on the space enterprise. As small satellites and rideshares have lowered the barriers to space access, we see an increase in the number of satellites navigating the approval quagmire, and also in mission managers of multipayload rideshare missions who wish to smooth the path to launch approval.

Chapter 25
HIVE: A New Architecture for Space

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25.1 Introduction

It is a foregone conclusion that in the near future both space architecture and the systems that inhabit it will change. We foresee routine on-orbit servicing, repair, and assembly of space systems, the development of large (argosy-class) constructs and the increased use of nanosatellite-class spacecraft as sentinels, inspectors, or probes for solar system exploration and debris monitoring. These anticipated developments can be linked to the maturing of the aerospace industry and the increasing number of space-faring nations and companies. These developments are buttressed by the following technology advancements: the miniaturization of electronics and photonics, the trend toward integrated systems, and the advancement of robotics. The advances in technology are further supported by manufacturing advancements. These include the precision scale of current manufacturing processes that derive an increase in reliability and the development of new materials with multifunctional properties. Finally, the information flow and processing are changing, with significant progress in distributed-computing architectures, "containerized" computing, and the expanding field of artificial intelligence (AI). Having been an active participant throughout the "space age era," The Aerospace Corporation assembled a team of technical experts and started from a clean slate to develop a new space architecture concept and the types of systems that could reside therein. HIVE (not an acronym) is one such product. It receives its inspiration from nature, namely, atomic chemistry, molecular chemistry, and cellular biology. This chapter presents a snapshot of the concept, which is supported by engineering analysis. It describes some of the critical elements to standing up a space architecture that is adaptable, highly resilient, and continually upgradeable.

Chapter 26
Enabling High-Resolution Imaging and Spectroscopy of an Exoplanet by Use of the Solar Gravity Lens

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cooler, M-type stars at much closer range that may not be habitable due to tidally locked rotation rates and highly variable particle radiation environments due to much closer proximity to stellar flares. Additional and closer (to us) Earth-like exoplanets orbiting sun-like stars should be discovered in the coming years as more observational data are obtained and data-analysis routines improve.

The occurrence rate of Earth-sized terrestrial planets in the habitable zones (HZ) of sun-like (types F, G, and K) stars remains a debated quantity.[2] Estimates range from 2% to 22%.[3,4,5] The SIMBAD database lists 1688 F stars, 5309 G stars, and 8589 K stars within 30 pc.[6] Taking the lowest estimates, we expect $\sim$280 terrestrial planets in the HZ of a star within 30 pc to be detected in the near future. When such a planet is discovered, significant observational resources will be devoted to studying it.

Once a very good Earth-like planet is discovered, the next question will be "Does it have a nitrogen/oxygen atmosphere indicative of life as we know it?" This can be answered by spectroscopic analysis of light reflected and emitted by the exoplanet. If the answer is "Yes," the next immediate questions will be "What does the planet look like? Does it have oceans, clouds, and significant continents?" and, finally, "Are there signs of intelligent life, like large artificial structures and glowing cities at night?" Answering the last three questions for Earth-like exoplanets requires radically new tools and techniques.

26.3 The Solar Gravitational Lens

Direct detection of light reflected by a small, distant object moving in close proximity to its parent star is a formidable undertaking.[7] The angular size of an exoplanet is extremely small, requiring very large apertures or interferometric baselines, and light received from the exoplanet is also extremely faint. An Earth-like planet at 30 pc (97.8 light-years), for example, has an angular diameter of 13.8 prad (0.5 nanoarcsec). This would be equivalent to seeing 5-μm-diameter objects on the surface of the moon. For an Earth-like exoplanet orbiting a G-type star like the sun at 1 AU, the maximum reflected light flux we would receive at a 30-pc range would be only 5×10^{-21} W/m^2, which is about 1 photon per square meter every 40 s. Unfortunately, the host star will be about 10^{16} times brighter. Advanced coronagraphic techniques are required to block the starlight.[8,9] Reflected light from the planet rides on a noisy background, thus detecting it requires excessively long integration times together with exquisite pointing stability. We would need a telescope aperture of $\sim$90 km with an aggressive coronagraph to image our Earth from the distance of 30 pc with a modern diffraction-limited telescope.[10] Using a $\sim$100-km-diameter array of multiple telescopes, each with apertures of several tens of meters could provide the required angular resolution, but it would also require integration times of several-hundred-million years to reach a reasonable signal-to-noise ratio (SNR) of approximately seven. Direct light (EBL), (2) measurements of the cosmic IR background (CIB), and (3) tests of the gravitational $1/r^2$ law up to 100 AU and beyond.

26.9 Applications

These demonstrations would develop and test technologies to drive down weight, risk, and cost. We anticipate that developments in the next ten years will increase battery density (J/kg) by factors of two to four, removing about 5 to 7 kg of mass per SGL spacecraft. Chip-scale atomic clocks should see a factor of 100 improvement to 33 years for 1-Hz drift (0.1 ppm). Star trackers with high-resolution data from the Gaia mission should reach 1-μarcsec angular resolution.

The concurrent development of long-lived SmallSats and solar sails suggests a fusion of these two technologies to create a new space-exploration building block: the light-sailing micro- or nanospacecraft for rapid, affordable exploration of our solar system and beyond by a trajectory that spirals towards the sun and accelerates outward at perihelion. We envision 3U to 6U sized CubeSats equipped with a solar sail, capable of exploration anywhere in the solar system and beyond. All locations within the solar system become accessible, including locations out of the ecliptic. Light-sailing SmallSats could act as Discovery mission "scouts" to pave the way for more targeted but costlier medium-sized and larger flagship missions. The NASA 2003 report[63] argues for a more balanced exploratory approach regarding solar-system exploration, and we believe that light-sailing SmallSats are a viable alternative in need of further study. The challenges to feasibility scales with the mass of the spacecraft. A solar-sail surface-area-to-mass ratio (m^2/kg) of 70:1 is viable today if the spacecraft mass is on the order of 10 kg, but is significantly less viable when the mass is 100 kg. Continued sailcraft flight demonstrations and missions will help to increase practical A/m to 400:1 and higher for sailcraft in the 10- to 100-kg-mass range, over the coming decades.

The CONOPS of such a mission can be partially standardized. Speeds of 10 to 25 AU/year appear possible. Target costs of 5 to 10 million USD for a spacecraft plus payload and shared launch costs make this approach financially attractive. Total time from concept to launch of two years makes the quest for scientific and technology experiments much more rapid than previous concepts.

26.10 Summary and Recommendations

Imaging of an exoplanet at 100×100-pixel resolution, or greater, may finally answer one of Humanity's most enduring questions: Are we alone? The string-of-pearls architecture, with multiple micro- and nanospacecraft per pearl, meets the science requirements of enabling flights to one or more exo–solar