AFRL-OSR-VA-TR-2013-0388

RETRODIRECTIVE RADAR CALIBRATION NANOSATELLITE

Wayne A. Shiroma (Principal Investigator); Larry K. Martin (Student Program Manager); Nicholas G. Fisher (Student Systems Engineer)

University of Hawaii

JULY 2013
Final Report

AIR FORCE RESEARCH LABORATORY
AF OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
ARLINGTON, VIRGINIA 22203
AIR FORCE MATERIEL COMMAND

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

1. REPORT DATE *(DD-MM-YYYY)*
13-07-2013

2. REPORT TYPE
FINAL REPORT

3. DATES COVERED *(From - To)*
Apr 2011 - Apr 2013

4. TITLE AND SUBTITLE
RETRODIRECTIVE RADAR CALIBRATION NANOSATELLITE

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-11-1-0051

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Wayne A. Shiroma (Principal Investigator); Larry K. Martin (Student Program Manager); Nicholas G. Fisher (Student Systems Engineer)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Hawaii
Office of Research Services
2440 Campus Road, Box 368

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR
875 N Randolph St
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2013-0388

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION A: APPROVED FOR PUBLIC RELEASE

13. SUPPLEMENTARY NOTES

14. ABSTRACT

For more than eight years, the DMSP F-15 and RADCAL satellites have been operating past their operational lifetimes and are facing imminent failure, leaving the US military without a reliable means for C-Band radar calibration and performance monitoring. To address the need for a quick, reliable, and low-cost solution, a team of University of Hawaii students has developed a nanosatellite solution to supplement these failing satellites, all with a modest $110K budget and two-year schedule. Our satellite's name is Ho`oponopono, or "to make right" in the Hawaiian language. While the RADCAL and Ho`oponopono satellites share several common design features, Ho`oponopono exhibits several notable differences from RADCAL in its design as a direct result of advances in technology. While the most apparent difference is Ho`oponopono's 3U CubeSat form factor, which is a fraction of the size of RADCAL's structure, a not-so-apparent difference is the fact that Ho`oponopono is a student-built nanosatellite, fabricated at a modest price. Ho`oponopono was selected by NASA to be a participant of its CubeSat Launch Initiative and is manife

15. SUBJECT TERMS
Nanosatellite, CubeSat, Radar, Education

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	SAR		Wayne A. Shiroma

19b. TELEPHONE NUMBER *(Include area code)*
808-956-7218

Reset

Reinventing Space Conference
AIAA-RS-2012-3001

Cost-Effective, Rapid Design of a Student-Built Radar Calibration Nanosatellite

Larry K. Martin, Nicholas G. Fisher, Toy Lim,
John G. Furumo, James R. Ah Heong Jr.,
Kelson A. Lau, Cam V. Chau,
Darryl M. McKinley, Andy M. Morishita,
Andy H. N. Pham, and Wayne A. Shiroma
University of Hawaii

Reinventing Space Conference
May 7 – 10, 2012
Los Angeles, CA

AIAA-RS-2012-3001

Cost-Effective, Rapid Design of a Student-Built Radar Calibration Nanosatellite

Larry K. Martin, Nicholas G. Fisher, Toy Lim, John G. Furumo, James R. Ah Heong Jr., Kelson A. Lau,
Cam V. Chau, Darryl M. McKinley, Andy M. Morishita, Andy H. N. Pham, and Wayne A. Shiroma
University of Hawaii
2540 Dole Street, Honolulu, HI 96822; 808-956-7218
larrymar@hawaii.edu

ABSTRACT

For more than eight years, the DMSP F-15 and RADCAL satellites have been operating past their operational lifetimes and are facing imminent failure, leaving the US military without a reliable means for C-band radar calibration and performance monitoring. To address the need for a quick, reliable, and low-cost solution to supplement these failing satellites, a team of University of Hawaii students has developed a nanosatellite named Hoʻoponopono, or "to make right" in the Hawaiian language. While the RADCAL and Hoʻoponopono satellites share several common design features, the most apparent difference is Hoʻoponopono's 3U CubeSat form factor, which is a fraction of the size of RADCAL. A more remarkable difference is the fact that Hoʻoponopono is a student-built nanosatellite, fabricated within a modest $110K budget and two-year schedule. Hoʻoponopono was selected by NASA to be a participant in its CubeSat Launch Initiative and is manifested for a 2013 launch.

KEYWORDS: CubeSat, radar calibration

INTRODUCTION

Today's radar calibration satellites serve a large number of beneficiaries including NASA, 13 tri-service agencies, over 80 user programs, and over 100 radar stations distributed over 23 geographic locations[1]. Access to this critically important calibration capability will soon come to end, however. The Radar Calibration (RADCAL) and DMSP F-15 satellites are the only two radar performance monitoring satellites still in orbit of the five that have launched since 1969, and both are operating over 18 and 8 years past their operational lifetimes, respectively.

This paper presents the first CubeSat solution designed and developed to address the imminent, operational need to supplement the RADCAL satellite. Designed and built by a team of undergraduate and graduate students at the University of Hawaii (UH), this CubeSat is named Hoʻoponopono ("to make right" in the Hawaiian language), an appropriate name for a calibration mission.

The project is funded and administered by the AFRL/AFOSR/AIAA University Nanosatellite Program (UNP)[2], and is in its final phase of development in preparation for a 2013 NASA launch.

RADCAL SATELLITE

RADCAL (Figure 1) was designed with the primary mission of supporting the calibration of C-band radar stations operated by the US Space Launch Range. It was developed and delivered within an aggressive one-year schedule through a $10 million contract (including launch) administered by the US Air Force Space Test Program[3]. RADCAL was launched from a Scout rocket on June 25, 1993 into a near-circular orbit at an altitude of 815 km x 765 km and 89.5° inclination, with a mission life designed for minimum and nominal durations of 1 and 3-5 years, respectively[4].

RADCAL carried three experimental payloads: (1) a communications system that exhibited store-and-forward and bent-pipe features, (2) a peak power tracker to control the charging process of one of its on-board batteries, and (3) a pair of GPS receivers to help validate the feasibility of GPS as an accurate and reliable means of orbit determination[5-6].

RADCAL consequently became the first satellite to successfully show that GPS could be used as a reliable means for attitude determination[7]. Power consumption issues, however, limited the amount of time that the GPS hardware could operate before the satellite experienced overloading issues and reboots.

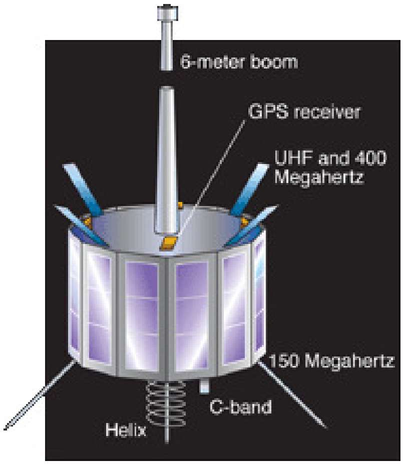

Figure 1. RADCAL satellite[5].

All orbit determination for satellites in the years preceding RADCAL was carried out using Doppler beaconing. In fact, since RADCAL's GPS payload was purely experimental, Doppler beaconing is still its primary source for orbital determination, requiring a network of tracking stations to monitor the satellite. All tracking information is then sent to one or more processing sites where the orbits are determined. In RADCAL's case, the GPS Division of the National Geospatial-Intelligence Agency (NGA) uses 21 Doppler tracking stations to produce daily ephemerides of RADCAL[8]. It is also through Doppler beaconing that RADCAL is able to meet its stringent 5-m accuracy of orbit determination.

Now over 18 years past its operational lifetime, RADCAL has repeatedly failed on several occasions before being brought back online. Permanent failure is therefore imminent for this well-established source of calibration for radar systems around the world.

HO'OPONOPONO CUBESAT

The most attractive feature of UH's Hoʻoponopono CubeSat (Figure 2) is that it was designed to carry out the same basic function as its RADCAL counterpart, but at a fraction in size and cost.

As participants of the sixth iteration of the UNP, our team of undergraduate and graduate students worked under a $110K budget and two-year timeline to develop Hoʻoponopono. As with any CubeSat design, one of the largest obstacles was fitting the various hardware components into a form factor that is about the size of a loaf of bread.

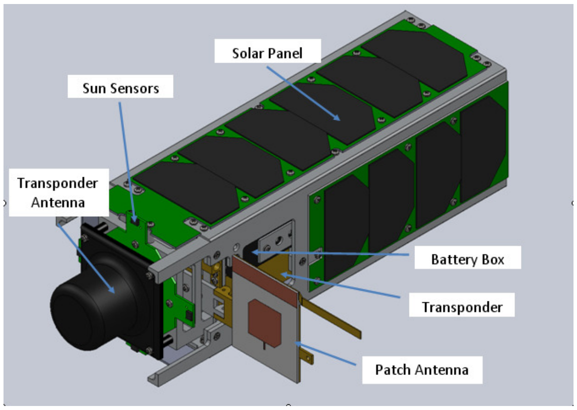

Figure 2. Hoʻoponopono CubeSat.

Typical of most satellites, Hoʻoponopono's functionality is modularized into power, communications, command and data handling, payload, structural, and attitude and control subsystems. At the heart of each active subsystem is a Microchip dsPIC33F microcontroller. More extensive design details can be found elsewhere[9], but here we summarize the main points as well as provide updated information.

Power is generated through the use of 22 Spectrolab Ultra Triple Junction solar cells with 28.3% efficiency. Power is regulated and distributed using various Maxim and Texas Instrument (TI) components such as DC/DC converters, variable resistors, and linear battery chargers. A Tenergy battery pack is used for power storage capabilities, and inhibit schemes are incorporated to prevent any prelaunch electrical activity.

To uplink and downlink mission-critical GPS data, along with various state-of-health data, Hoʻoponopono makes use of the Microhard MHX-2420 and AstroDev Lithium-1 radios. Microstrip patch and dipole antennas are used and designed to operate in the S and UHF bands for these two radios, respectively.

Hoʻoponopono hosts several payload instruments to carry out its mission. On its nadir-facing side is an Antenna Development Corporation quadrifilar helix antenna used for receiving and transmitting RF pulse signals to and from various radar ground stations. After receiving an interrogation signal from one of these radar stations, the Herley MD2000-C1 transponder unit acts as a microwave repeater to regenerate an amplified version of the received signal and retransmits directly back with a shift in frequency. The zenith face features an Antcom 1.9G1215A-XSO-2 Active L1/L2 antenna to collect GPS data using a NovAtel OEMV-1DF-L1L2 GPS unit.

As a consequence of the pointing requirements for the payload instrument antennas, a relatively stable orientation is needed for successful mission operations. To accomplish this, a 5-m gravity gradient (GG) boom is designed to extend from the zenith side of Ho‘oponopono (Figure 3). At the end of the boom is an 80-g aluminum end mass.

The GG boom is designed to deploy after Ho‘oponopono’s three hysteresis rods dampen the satellite’s oscillation while detumbling. These rods are developed by the Magnetic Shield Corporation and each placed along the *x*, *y*, and *z* axes. If the GG boom deploys in the wrong conditions and stabilization is oriented in reverse polarization, an on-board reaction wheel will actively turn the satellite about its axes to achieve the correct orientation.

To determine its attitude, Ho‘oponopono implements a three-axis gyro, a magnetometer, and six carefully placed photodiodes manufactured by Invensense, Honeywell, and OSI Optoelectronics, respectively.

For command and data handling (CDH), Ho‘oponopono incorporates UH’s CubeSat Stackable Interface (CSI) architecture[10-11]. This design, which uses the PCI-104 standard and fits within a 1000 cm^3 volume, distributes standard voltages across a common bus to the stack of printed circuit boards (PCBs) for each subsystem, and also allows for placement of addressable I/O expanders on each PCB that can be accessed by an I^{2}C bus, permitting remote access to various I/O through the system.

Aside from the Microchip dsPIC33F microcontroller, which is common among all active subsystems, CDH’s integrated circuitry includes the TI TCA9539 I/O expander and TI SN65HVD233 CAN driver. The Microchip SST25VF032B flash memory is also used for data storage.

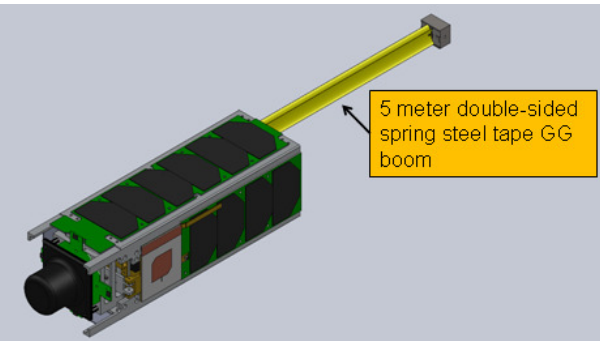

Figure 3. Gravity Gradient Boom (not fully extended).

The software for Ho‘oponopono is divided into four levels of programming: 1) core features, 2) protocols, 3) drivers, and 4) applications.

All internal hardware is enclosed in an aluminum structure designed to provide strength and support while limiting the overall mass and balance of the spacecraft.

One of UH’s previous CubeSats, “Ho‘okele”[12], was used as the basis for designing Ho‘oponopono’s structure, however several modifications were necessary to accommodate the placement and sizing of the hardware. For example, mounting locations were customized, along with ensuring adequate room for a battery box that had a sufficient number of venting holes, per UNP requirements.

All structural design and FEA analyses were performed in SolidWorks. The majority of structural components were milled out of 6061-T6 aluminum using a CNC machine. The cradle hinge for the patch antenna, however, was machined out of brass due to its solderability.

RADAR CALIBRATION SEQUENCE

Ho‘oponopono’s radar calibration sequence begins with a radar range submitting a request for calibration. After receiving the request, the RADCAL coordinators at Vandenberg Air Force Base create an interrogation schedule which is uplinked to Ho‘oponopono via a ground station. In the following pass, Ho‘oponopono’s nadir-facing transponder unit is interrogated by the radar range with a two-pulse RF signal. The transponder’s interrogation response is immediately sent back, and an estimate can then be made as to where Ho‘oponopono is in orbit. GPS data is simultaneously collected from Ho‘oponopono’s GPS antenna and soon thereafter downlinked and forwarded to the NGA for processing. An orbital model is made from processing this GPS data, which is then made available to all RADCAL users, including the original range requesting calibration. By comparing their own estimates to those of the more accurate GPS data, the range can then determine how close their radar system is at pinpointing Ho‘oponopono’s orbital location and make adjustments as needed.

RADCAL – HO‘OPONOPONO COMPARISON

While the RADCAL and Ho‘oponopono satellites share several design features such as C-band transponders for the radar interrogations and GG booms for nadir- and zenith-facing transponder and GPS antennas, respectively, advances in technology since the time of RAD-

CAL's development in the early 1990s have allowed for other features to mature.

RADCAL's two redundant Trimble TANS Quadrex GPS receivers, for example, which were added purely for experimental purposes, helped RADCAL become the first satellite to successfully demonstrate that low-cost GPS receivers could be used to generate highly precise orbital data. Today, companies such as NovAtel, Inc., have specialized in developing a complete product line of GPS receivers that meet a wide range of accuracies[13]. The higher performance of these newer GPS receivers also allows for processing data from a larger amount of GPS satellites at a given time (the maximum of 6 GPS satellites that RADCAL's Trimble GPS receivers were capable of simultaneously processing data from is tripled to 18 with the NovAtel OEMV-1DF-L1L2 unit that Ho'oponopono employs)[14-15]. The same holds true for the GPS antenna industry, as a number of specially designed antennas are now available that feature 3-dB beamwidths over 100 degrees to collect GPS data from large amounts of GPS satellites at a given time[16]. This eliminates the need to manually switch between several patch antennas as the attitude of the satellite varies, as RADCAL was designed to do, thus reducing the amount of on-board antennas.

The fact that Ho'oponopono plans to utilize its on-board GPS receiver for self-orbit determination also eliminates the logistical and manpower requirements that RADCAL uses for its Doppler beacon tracking.

On a much broader level, Ho'oponopono implements a wide array of commercial off-the-shelf microelectronics and integrated circuitry that exhibit higher performance ratings, lower costs, and smaller form factors than what's featured on RADCAL's nearly 20-year-old bus. Consider as an example Ho'oponopono's 8-MB flash memory IC which doubles the 4 MB available on RADCAL. It was by implementing these newer, smaller (and oftentimes better-performing) technologies that our team was able to contrive a novel RADCAL satellite that fits within a 3U CubeSat structure.

By downscaling the RADCAL satellite to a 3U CubeSat, a significant reduction in cost is realized by comparing the $10M allocated for RADCAL's development and launch to Ho'oponopono's $110K budget from the UNP – a nearly hundredfold reduction in cost!

The next benefit realized through switching to a 3U CubeSat is a more streamlined fabrication process. Although Ho'oponopono was designed and built over the course of a two-year period through our participation in the UNP, duplicating a future version, even with slight revisions, could be done very quickly. This works in favor for our team as our 2013 launch is meant to serve as a "lessons learned" opportunity to prove the functionality of our satellite. Moreover, it presents the opportunity for rapid-response deployments in the event of on-orbit failures.

The most obvious benefit in switching to the CubeSat form factor is a drastic reduction in size. A side-by-side comparison shows that the 89-kg RADCAL, with a diameter of ~76 cm and a height of ~43 cm, is over 65 times larger in size and 25 times larger in mass than Ho'oponopono!

Though switching to a CubeSat structure was highly advantageous in our case, we were also faced with a few drawbacks, one of which was a lack of redundancy in our system due to the limited real estate within our structure (RADCAL features duplicate GPS receivers, Doppler transmitters, and C-band transponders while Ho'oponopono is a single-string system).

It is worth mentioning that, despite their superficial differences, Ho'oponopono was designed to meet many of the core mission objectives of RADCAL, such as the requirement for RADCAL to complete a full radar calibration sequence in five days (which includes all aspects of the radar interrogation and ephemeris data collection and data processing turnaround from the NGA).

Table 1 summarizes additional RADCAL vs. Ho'oponopono features.

Table 1. RADCAL vs. Ho'oponopono Comparison

Parameter	**RADCAL**	**Ho'oponopono**
Mass (kg)	~89	~3.5
Volume (m^3)	0.197	0.003
Cost	$10M	$110K
On-board memory (MB)	4	8
GG boom length (m)	6.096	5
Number of antennas	10	4
Primary orbit determination mechanism	Doppler beaconing	GPS data
Total duration for C-band radar calibration, spanning from interrogation to receiving processed GPS data	5 days	5 days
Single string?	No	Yes

UNP PARTICIPATION, UPCOMING LAUNCH

As participants in the sixth iteration of the UNP competition, our team competed against ten other universities from across the nation through a number of reviews that spanned from the conceptual stages of identifying mission objectives to presenting a flight-ready satellite. At the conclusion of UNP-6, our team was awarded with the Third Place and Most Improved Awards for producing an engineering model of the Ho'oponopono CubeSat.

The Ho'oponopono CubeSat was also consequently selected by NASA to be a participant of its CubeSat Launch Initiative in February 2011 and is tentatively manifested for a 2013 launch on-board a SpaceX Falcon 9 rocket as a part of the Commercial Resupply Services 3 payload. The tentative orbital parameters include a 325-km, elliptical orbit with a 51° ± 2° inclination[17].

PRACTICAL EXPERIENCE

Our team has worked under the auspices of various organizations, but most directly with the UNP, InDyne/WROCI, and the Northrop Grumman Corporation, gaining practical leadership and engineering skills along the way.

By participating on a project of this caliber, our students are exposed to real engineering design criteria with real mission requirements, which allow us to develop the practical and hands-on skills that matter most in today's workforce.

CONCLUSIONS

This paper presented an experimental 3U CubeSat designed to supplement the failing RADCAL satellite. The background and high-level comparison of their design features were discussed. Our team of undergraduate and graduate students has gained a great deal of practical engineering experience throughout the duration of this project, and will move one step closer to providing the government with a fully-functional radar calibration CubeSat following our NASA-sponsored 2013 launch.

Acknowledgements

The authors are grateful to the following persons and organizations for their support over the span of this project:

- Air Force University Nanosatellite Program for providing our student team with the opportunity to design, build, and test our CubeSat, specifically David Voss, Amanda Pietruszewski, Kelly Alexander, Kent Miller, Jared Clements, Abbie Stovall, and the rest of the UNP reviewers.
- NASA Educational Launch of Nanosatellites Program (especially Garrett Skrobot) for sponsoring our 2013 launch.
- Martin Prochazka, Adam Krebs, Bill Sherrill, and the rest of the team at InDyne WROCI for payload- and mission-related support.
- Vandenberg Air Force Base, 30th Space Wing, and the Naval Postgraduate School for supplying our team with various government-furnished equipment and supplies.
- Nolan Tanaka and the members of his team at Northrop Grumman, Rick Wagner (formerly of Northrop Grumman), Roland Coelho and Jordi Puig-Suari of Cal Poly San Luis Obispo, James Cutler of the University of Michigan, and Gerry Shaw of SRI International, who have given up their personal time to provide valuable support in a number of areas.
- RT Logic (Steve Williams) and the Aerospace Corporation (Petras Karuza and David Hinkley) for providing valuable support with various technical issues and simulation hardware.
- Northrop Grumman, Boeing, and the UH College of Engineering for providing financial support.
- Byron Wolfe, Jason Akagi, Lance Yoneshige, Monte Watanabe, Justin Akagi, Alex Zamora, Tyler Chun, Bao Jun Lei, and Wade Tonaki – all past students of our UH Small-Satellite Program - for mentoring the current students in our program;
- Jason Axelson, Shantel Hunt, Joseph Longhi, and the dozens of past and present team members who have contributed to Ho'oponopono's success.

References

1. Prochazka, M., RADCAL Coordinator at Vandenberg Air Force Base, personal communication.
2. http://www.universitynanosat.net/
3. Langer, J. V., W. A. Feess, K. M. Hanington, M. R. Bacigalupi, M. A. Cardoza, R. G. Mach, and P. A. M. Abusali. 1994. "RADCAL: Precision Orbit Determination with a Commercial Grade GPS Receiver," *Proceedings of the 1994 National Technical Meeting of The Institute of Navigation,* San Diego, CA, pp. 421-431.
4. Kramer, H. J., *Observation of the Earth and its Environment – Survey of Missions and Sensors*, 2nd ed., Springer-Verlag, pp. 1102, 2002.
5. Langer, J., T. Powell, and J. Cox, 2007. "Orbit Determination and Satellite Navigation," Aerospace Corporation Website, May 11, 2007.

6. Martin, D. H. *Communication Satellites: Fourth Edition*. El Segundo: The Aerospace Press, pp. 200, 2000.
7. Purivigraipong, S., S. Hodgart, M. Unwin, and S. Kuntanapreeda, 2010. “Resolving Integer Ambiguity of GPS Carrier Phase Difference,” *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 46, No. 2, pp. 832-847, Apr. 2010.
8. https://www1.nga.mil/PRODUCTSSERVICES/GEODESYANDGEOPHYSICS/GPSPRECISE-EPHEMERIS/Pages/default.aspx
9. Martin, L.K., N. G. Fisher, W. H. Jones, J. G. Furumo, J. R. Ah Heong Jr., M. M. L. Umeda, and W. A. Shiroma, 2011. “Hoʻoponopono: A Radar Calibration CubeSat,” in *Proceedings of the 25th Annual AIAA/Utah State University Conference on Small Satellites*, Logan, UT, paper SSC11-VI-7, Aug. 2011.
10. Fujimoto, A., T. Kikugawa, and T. Lim. 2008. “CubeSat Stackable Interface,” *EE 496 Report, 1st ed.*, Univ. of Hawaii, Spring 2008.
11. Fujimoto, A., J. Axelson, and K. Ishida, 2008. “CubeSat Stackable Interface,” *EE 496 Report, 2nd ed.*, Univ. of Hawaii, Fall 2008.
12. Akagi, J. M., T. N. Tamashiro, R. T. Iwami, J. M. Cardenas, J. T. Akagi, and W. A. Shiroma, 2008. “CubeSat-Based Disaster Detection and Monitoring Systems,” in *6th Responsive Space Conference*, Los Angeles, CA, paper AIAA-RS6-2008-2006, Apr. 2008.
13. http://www.novatel.com/about-us/company-overview/
14. http://navtechgps2.intuitwebsites.com/OEMV-1_Series.pdf
15. http://www.ion.org/search/view_abstract.cfm?jp=p&idno=4399
16. http://www.antcom.com/documents/catalogs/L1L2GPSAntennas.pdf
17. Skrobot, G., NASA Launch Services Program, 2011. “ELaNa – Educational Launch of Nanosatellite (ELaNa) Project Status,” presented at the *8th Annual CubeSat Developers’ Workshop*, San Luis Obispo, CA, Apr. 21, 2011.