

# Overview of the Naval Postgraduate School Small Satellite, NPSAT1

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The Naval Postgraduate School (NPS) is developing a small satellite as a vehicle for graduate education in Space Systems as well as a platform for experimentation. The NPSAT1 spacecraft is being designed, built, tested, and will be flown by officer students in the Space Systems Academic Group at NPS. This paper provides an overview of the satellite and current status of the project with a perspective on systems engineering. The NPSAT1 mission, conceived and developed by the Naval Postgraduate School (NPS) Space Systems Academic Group (SSAG), is sponsored and executed by the DoD Space Test Program (SMC Det 12).

## I. Introduction

The Space Systems Academic Group (SSAG) at the Naval Postgraduate School (NPS) directs and implements the Space Systems curricula and is the focal point for space research at NPS. Officer students at NPS matriculate into the Space Systems Engineering or Space Systems Operations curriculum for their graduate studies in space. Officer graduates in the Space Systems Engineering curriculum receive a Master of Science in an engineering discipline, such as, electrical and computer engineering, physics, astronautical engineering, or mechanical engineering. Officer graduates in the Space Systems Operations curriculum receive a Master of Science in Space Systems Operations. A Master's Thesis in a space-related field is part of the degree requirements. In addition to the depth of knowledge gained through thesis research in a particular discipline, breadth of knowledge is an objective for graduates with a systems perspective. To address this objective, the Small Satellite Design Program was created.

The Small Satellite Design Program provides opportunities for officer students to work not only on a particular subsystem area, but also to be aware of and work within the influences, or constraints, driven by other disciplines or subsystems. Another advantage of working on an actual satellite project is the exposure to the entire spectrum of issues related to the full life cycle development of a space system, including radio frequency spectrum management issues, ground operations, inter-agency issues, and end-of-life requirements, to name just a few.

The current small satellite project, NPSAT1, is a follow-on project to the PANSAT small satellite, launched aboard the Shuttle, *Discovery*, in October 1998<sup>1,2</sup>. PANSAT was built and operated by NPS SSAG as a digital communications experimental satellite with a two-year mission life. NPSAT1 addresses lessons learned and affords greater capability with three-axis stabilization, higher communications data rates, and more electrical power to support other experiments.

## II. Mission Objectives

The primary objective of NPSAT1 is to provide educational opportunities for the space systems officer students at NPS. This is done mainly through thesis research. The second objective is to provide a platform for small satellite technology proof-of-concept demonstrations, and to provide a platform for space flight experiments. Once in orbit, spacecraft operations performed from NPS will provide another means of officer student involvement.

## B. Space Systems Education

NPSAT1 offers a number of opportunities for thesis research in Space Systems. Each subsystem lends itself to graduate-level research in design, analysis, simulation, and testing in both software and hardware areas. At the time of this writing 15 Master of Science theses were completed with three in-progress. A significant benefit for the graduates is

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the exposure to the myriad system issues, and engineering trades required to bring together a complex space system. This is apparent in the design and development of the spacecraft subsystems as well as the experiments where electronics must interface with the electrical power and command interface, the mechanical housings, and meet the environmental requirements imposed by space flight, including vibrations due to launch, single-event effects (SEE), thermal extremes, and operation in a vacuum.

A common theme raised in the aerospace industry is the need for systems engineers. The systems aspect, including the operation of the spacecraft, is invaluable for NPS space systems graduates as they move forward in their career, many of which will serve the nation in the planning, management, operation, or acquisition of current or future space programs. This is particularly true in light of the era of network-centric warfare. The network, as a weapon system, relies on space; and the real vehicle to obtaining such a network is by means of space-savvy individuals with the knowledge, skills, and abilities to forge the concept to reality.

### A. Spacecraft Technology

The NPSAT1 spacecraft will demonstrate technology applicable to current and future space systems. In the area of space power, NPSAT1 will fly as its main battery a lithium-ion battery and experimental triple-junction solar cells. This battery technology offers much higher energy density than nickel-based battery technology. The NPSAT1 lithium-ion battery has a de-rated capacity of 226 Watt-hours, based on expected operation. Fig. 2 shows the battery assembly. The battery will be sealed in order to maintain one atmosphere of pressure.

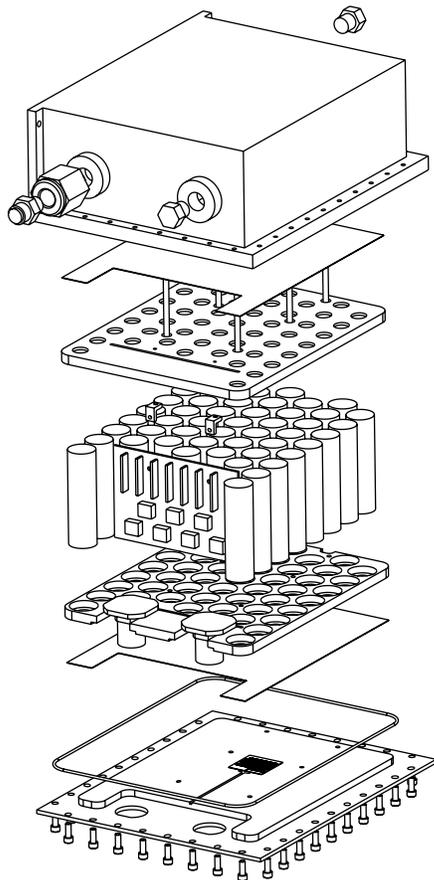


Figure 1. NPSAT1 Battery Assembly.

The NPSAT1 lithium-ion battery cells have undergone a number of tests to characterize their performance as well as vibration testing to ensure they can survive the launch environment. A prototype battery is in the process of being built and will be tested for performance as well as throughout the life of the program as the ground control portion of the experiment.

NPSAT1 will also fly experimental, triple-junction solar cells. Current-versus-voltage (IV) curves will be taken twice each orbit through the life of the satellite and provided to the sponsor for evaluation. The design, simulation, and development of the experiment controller for the solar cell measurement system (SMS), is a substantial undertaking and was the focus of two theses, currently in-progress; one of which was presented by Salmon<sup>3</sup>, and the other in this conference by Lo.<sup>4</sup> A number of the design features of the SMS are leveraged to carry over in the design of the electrical power subsystem (EPS) and attitude control subsystem (ACS). These are similar in architecture to the SMS in that there is a digital board which interfaces with the spacecraft's command and data handler (C&DH) and an analog board.

The attitude control subsystem will demonstrate a very low-cost means of 3-axis attitude control where pointing requirements are on the order of  $\pm 10^\circ$ . This is certainly applicable to low-Earth orbiting communications satellites. The design was presented by Leonard<sup>5</sup> and is currently in the process of being simulated on a 3-axis air bearing to validate the analytical computer models. The basic concept is to use on-board navigational information and a geomagnetic reference model to look up the orientation of the magnetic field in the spacecraft's correct attitude and compare that with measurements from an on-board magnetometer.

Although at any point, if the error were zero, there would still be ambiguity (rotation angle) about that magnetic field vector; but, while the spacecraft is continually driving the error to zero as it orbits, 3-axis attitude control is achieved even though full attitude determination is not. The hardware cost is then very low, since it is the sum of the controller, magnetic torque rods, and a 3-axis magnetometer.

The spacecraft command and data handling (C&DH) subsystem will demonstrate the use of a PC-compatible architecture for space applications. The C&DH is built around the Linux operating system with a Sharp ARM 79520 selected for the processor. The C&DH will incorporate error-detection-and-correction (EDAC) RAM memory to ensure against single event effects (SEE) due to radiation. As a PC-compatible computer running the Linux operating system, it allows for immediate software development utilizing free and robust development tools. Furthermore, many core functions of the operating system can be ported directly to the C&DH hardware platform leveraging on many man-hours of development and resulting in greater capability and higher reliability.

## B. Program Elements

### 1. Schedule

The NPSAT1 spacecraft is manifested on the STP-1 mission due to launch in September 2006 on an Atlas V Evolved Expendable Launch Vehicle (EELV). NPSAT1 mates to the Atlas V via the EELV Secondary Payload Adapter (ESPA) as one of five secondary payloads. A majority of the spacecraft is being built at NPS by officer students, faculty and staff. This includes electronic circuit boards, mechanical housings and components, and integration of the spacecraft. Of course major components such as the torque rods, magnetometers, and sun sensors are procured. Most of the environmental testing at the subsystem level will be done at NPS.

System-level testing will be performed off-site of NPS because of the facilities required. Testing is planned to take place at the Naval Research Laboratory for all structural verification testing on the flight unit as well as a structural engineering development unit (EDU). EDU testing includes static loads testing, random vibration testing, and may include shock testing, and is planned for October 2004. The flight unit acceptance testing will include similar structural testing as well as thermal-vacuum cycling tests, mass measurements, and magnetics testing. Deployment tests are planned during the thermal-vacuum tests at both temperature extremes. System-level acceptance testing is planned for November 2005. Fig. 2 shows a schedule of milestones for the NPSAT1 program.

### 2. Risk and Reliability

NPSAT1 is designed as a Class D spacecraft per DOD-HDBK-343.<sup>6</sup> The mission life of the spacecraft is two years; however, a six-month life would be the acceptable minimum for experimenters to obtain sufficient data to process results. The NPSAT1 design basically accepts higher risk in order to maintain lower costs. In a university environment, keeping costs low is mandatory. Therefore, a number of single-points-of-failure in the design exist. Certain risk mitigation measures were taken in the conceptual phase and further measures were taken as the design matured and action was deemed appropriate. At the outset of the design, the decision was made to use body-mounted solar cells, as opposed to deployable panels, to remove the possibility of a mechanism failure. One design feature that was defined early was to implement EDAC memory for the processor. Although the mission orbit is fairly radiation-benign, experience with PANSAT has shown that bit errors are inevitable.<sup>1</sup>

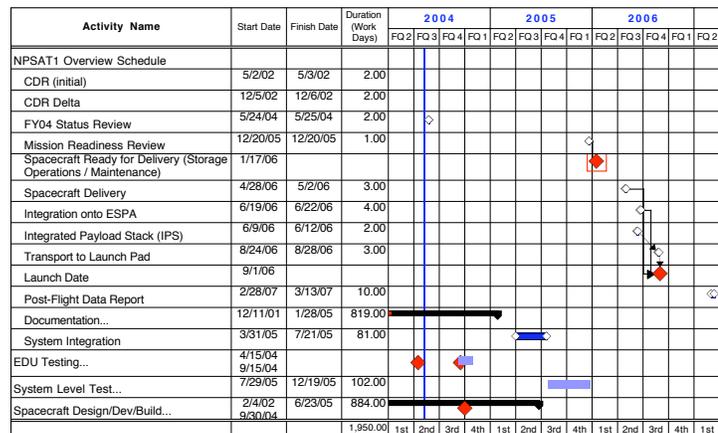


Figure 2. NPSAT1 Schedule Milestones.

Little redundancy is apparent in the overall spacecraft design. Areas where redundancy were implemented can be seen in the core subsystems of EPS, ACS, and communications. Redundant antennas were included early in the design to ensure that should the ACS suffer an anomaly, a means would be available to communicate with the spacecraft. Since the ACS design is itself experimental, a momentum wheel was added to ensure its functionality. The EPS consists of experimental triple-junction solar cells. In order to mitigate the risk of these cells failing, commercial triple-junction solar cells were added which have flight heritage. Although NPSAT1 has only one battery to support its mission, the battery design consists of seven cells in series and seven of these strings connected in parallel. If a cell does fail, the worst case situation would be that the string with the failed cell would be separated from the battery, since historically, lithium-ion cells fail in an open circuit.

No rigorous failure modes and effects analysis has been done, or is planned for NPSAT1 because of the time and resources needed. At each design phase, however, a critical look is taken and risks are catalogued and followed. This is done internally, as well as through periodic program reviews attended by personnel from outside agencies and sponsoring agencies. Additionally, the NPSAT1 project team has embraced a philosophy with emphasis on subsystem testing where possible to ‘flush out’ potential problems. One example is the testing of the shutter for the VISIM camera, discussed later.

### III. Spacecraft Bus

#### A. Electrical

Fig. 1 shows the block diagram of the NPSAT1 spacecraft electronics. The EPS, ACS, and SMS, as alluded to earlier, are similar in design with a digital logic board and analog board. The analog boards differ based on their respective sensor inputs or actuators, but having a common core facilitates the design, test and build of these three modules. Recent changes to the initial design of this common core are the migration from a 80C196 micro-controller to a field-programmable gate array (FPGA). This simplifies the design and assists software control in the implementation of a state machine.

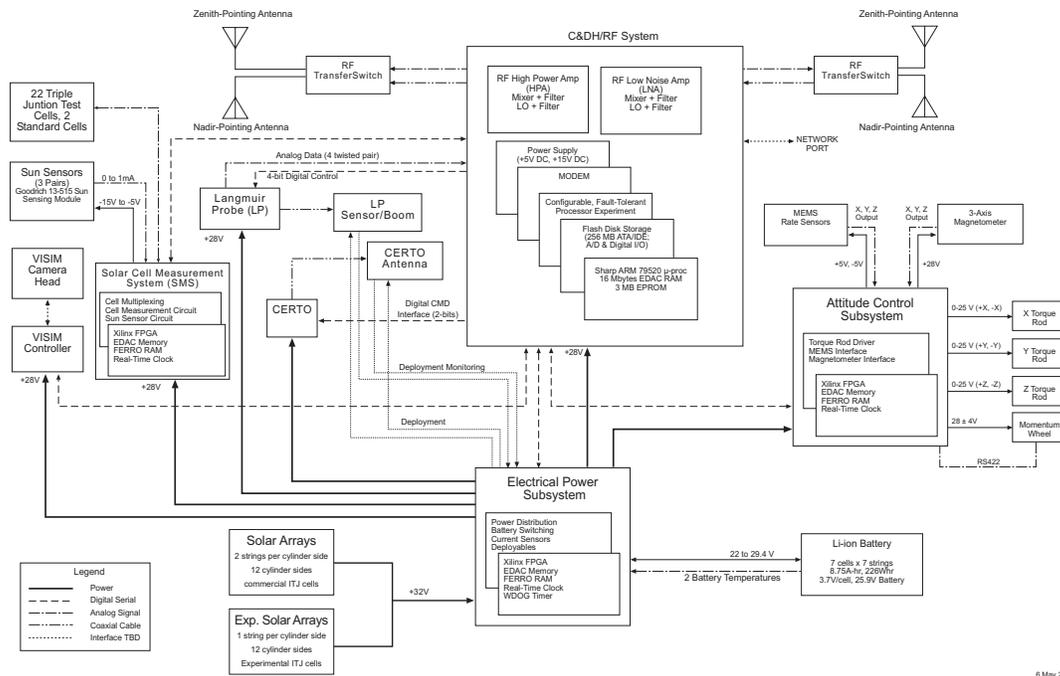


Figure 3. NPSAT1 Block Diagram.

The C&DH and radio frequency (RF) system are tightly coupled in order to allow throughput of the transmitted data and processor control of the modem. In addition to the EDAC memory, mass storage memory is provided by non-volatile FLASH memory. The mass storage memory is co-located with the analog-to-digital (A/D) and digital input/output (I/O) devices. Also attached to the C&DH is the configurable, fault-tolerant processor experiment (CFPE), described later. The CFPE is connected to the processor board via a PC-104 bus, incorporated in the C&DH architecture.

#### B. Mechanical

NPSAT1 mechanical systems include the spacecraft structure, mechanisms, and spacecraft thermal control subsystem. The spacecraft structure is made of aluminum 6061-T6. The majority of the structure is heritage equipment from a canceled Navy small satellite project. An additional superstructure was added to accommodate additional solar cells, handling points, the retention mechanisms, and the zenith-pointing antennas. The structure design is very robust with a margin-of-safety greater than 5.0 for combined loads of 12 g in each axis.

NPSAT1 mechanisms include a deployable antenna and boom, retention mechanisms, and microswitches. The deployable appendages are for the experiments provided by the Naval Research Laboratory (NRL). These include a three-frequency antenna and a boom for a Langmuir probe. Likewise, the retention mechanisms are to restrain the deployable items during launch and release them on command from the ground. Both the deployable items and the retention mechanisms are provided by NRL. The only other mechanisms are the microswitches that are attached to the separation system. Four microswitches provide safety inhibits for the spacecraft while attached to the launch vehicle.

A detailed thermal analysis of the NPSAT1 spacecraft was performed by Gruhlke<sup>8</sup> showing that temperatures for all the components can be held within the required operating temperatures. Internal temperatures of the electronics ranged from -14°C in the cold case to about +13°C for the hot case. Batteries were kept within operating temperatures by means of a thermostatically-controlled heater. Further simulations will be needed following the on-going battery tests to address optimal temperature ranges for the battery and the expected energy required for heating.

## IV. Experiments

### A. NRL Experiments

The deployable antenna is part of the coherent electromagnetic radio tomography (CERTO) experiment. The CERTO experiment is a radio beacon that transmits at 150, 400 and 1067 MHz. Working with a network of ground receivers, the CERTO beacon will be used to measure the integrated electron density of the ionosphere in the plane of observation. CERTO will also be used to develop and test tomographic algorithms for reconstruction of ionospheric irregularities; to provide a database for global models of the ionosphere; to characterize the ionosphere for geolocation; and to perform scintillation studies of the ionosphere. The Langmuir probe will be operated to collect on four separate 12-bit A/D channels at sample rates between 1 and 1000 samples per second. The Langmuir probe provides in-situ measurements at the spacecraft altitude where the data can be processed for correlation with the ground observations of the CERTO beacon.

### B. NPS Experiments

NPSAT1 will fly three space flight experiments of NPS origin in addition to the lithium-ion battery, triple-junction solar cells, ACS, and C&DH technology demonstrations mentioned earlier. These experiments are the configurable, fault-tolerant processor (CFTP) experiment, a micro-electromechanical systems (MEMS) rate sensor, and a visible wavelength imager (VISIM). The CFTP experiment will test the use of a FPGA-based processor board to implement a flexible, triple-modular, redundant (TMR) computer architecture for reliable computing for space applications. Single event effects (SEE) within the processing are detected and corrected through voting logic without the need to reboot the processor. The CFTP experiment is described in greater detail by Ebert, et al.<sup>9</sup>

The MEMS rate sensor is intended to gain flight data on a commercial, off-the-shelf (COTS) MEMS device that has potential for space applications. MEMS devices offer low-cost, lower power, and small size. The current technology of these devices ( $\pm 5^\circ/\text{sec}$ ) are not at the working range for orbital rates, however. During normal operation by the ACS, the MEMS rate sensor will be working more or less in the noise. It may be useful at launch vehicle separation, though, where tip-off rates can be higher. The experiment will focus more on the on-orbit performance of these devices looking at parameters such as bias drift and duty cycling.

The VISIM is simply a CCD camera that will be used primarily as a data generator for ground operations by officer students and on-orbit processing by the CFTP. The VISIM hardware is COTS equipment consisting of a PC-104 single-board computer, camera controller board, and camera head and optics. A shutter was considered early in the design to mitigate the risk of inadvertently looking directly at the sun either after separation while the ACS is in the acquisition mode or in the event of an anomaly in the ACS functionality. However, thermal-vacuum testing of the selected shutter system indicated that the reliability of the shutter, itself, was questionable for the life of the mission. The risk of damage from overexposure from the sun was traded with the expected life cycle of the shutter system, especially in light of the narrow field-of-view of the VISIM camera optics.

## V. System Safety

System safety is an important part of any space system. This is particularly true for NPSAT1 as a secondary payload on the first flight of an ESPA complement of payloads. System safety was one of the driving requirements in the conceptual design. Much of the safety design was based on experience with PANSAT as a Shuttle ejectable payload,<sup>10</sup> al-

though differences are apparent for NPSAT1 as an unmanned launch vehicle payload. The safety design began by identifying potential hazards and employing safety inhibits in the design to adequately address those hazards. Some of the obvious hazards deal with failure of structural integrity, inadvertent release of any stored energy, such as in the battery, inadvertent radio frequency emissions, and inadvertent deployment of the CERTO antenna or Langmuir probe. Because of the stored energy in a battery, a critical look at such things as leakage, pressure due to overheating or overcharging, and potential for electrical short circuits is required. Safety hazards are not only confined to the launch phase, but on ground operations as well, including integration and testing.

Safety hazards are categorized for their criticality once identified. Guidance on both the hazards and criticality are provided by the EWR 127-1 document.<sup>11</sup> NPSAT1 safety features that address a majority of the potential hazards include a no-power bus concept, a highly robust structure, and the use of relays as additional inhibits. The no-power bus concept describes the NPSAT1 configuration while attached to the launch vehicle where, by means of microswitches in the launch interface, no electrical power is provided to the EPS until the spacecraft separates from the launch vehicle and the microswitches change state. Two of the four microswitches are wired in parallel and break the circuit of the solar panel power to the EPS. Although the battery is fully charged, it is kept off-line from the power bus by a relay, denoted as the 'K2' relay. Once the EPS receives power from the solar panels it will boot up and can then switch the K2 relay to put the battery on-line.

Another relay, denoted as the 'K1' relay, is used as an inhibit to avoid inadvertent RF emissions or deployment. This relay is controlled by the C&DH with the control line passing through the other two microswitches. This pair of microswitches is also connected in parallel for reliability. All potential hazards requiring power through this K1 relay are disabled by three independent inhibits: 1.) the microswitches; 2.) the K1 relay; and 3.) software command.

Structural integrity is verified by analysis and structural verification testing, described earlier. Other safety items will be performed either by procedure during integration, such as the state of the K1 and K2 relays, or by other analysis and testing. One example is the lithium-ion battery. The specific cell used in the NPSAT1 lithium-ion battery has been tested by Underwriters Laboratory. It is also considered a dry cell because of the very small amount of electrolyte in the cell. Therefore, leakage of the electrolyte is not a credible hazard. Another area where analysis and testing will ensure safety is in the ground support equipment, specifically the NPSAT1 handling equipment where analysis shows sufficient strength and proof testing will adequately verify the load capability of the equipment.

Table 1 shows a summary of the NPSAT1 safety assessment, including hazard mitigation methods.<sup>12</sup> Probability and severity are defined in EWR 127-1, Table 1-1.<sup>11</sup> The categories of severity are: I - catastrophic, which may cause death or over \$1M in equipment loss; II - critical, which may cause severe injury or illness or equipment loss between \$1M and \$200K; III - marginal, which may cause minor injury or illness or equipment loss between \$200K and \$10K; and IV - negligible, which causes no injury or illness and less than \$10K in equipment loss. The likelihood that the event will occur are give in the 'Probability' column as: A – frequent; B – reasonably probable; C – occasional; D – remote and E – extremely improbable.

<b>Inhibit/Mitigation</b>	S1, S2	S3, S4	K1	K2	S/W CMD	Analysis	Verification Test	Procedure	Severity	Probability
Structural failure						√	√		I	E
Boom deployment		√	√		√		√		IV	E
No-power bus	√			√				√	III	E
Inadvertent RF emissions		√	√		√				IV	E
Battery leak/rupture						√	√	√	III	E
<b>GSE</b>										
Battery charging								√	III	D
Electrical shock						√		√	IV	D
Inadvertent RF emissions					√			√	IV	E
Lifting fixture						√	√	√	I	E
Dolly failure/tip-over						√	√	√	I	E
Sharp corners/edges/pinch pts								√	IV	D
Damage/injury by tool operation								√	III	D

Table 1. NPSAT1 Safety Summary.

## VI. Conclusions

NPS is continuing its progress in the development of its second small satellite, NPSAT1. The educational objectives of NPSAT1 are being successfully met with each graduating officer student. The development phase of NPSAT1 also provides the systems perspective for the officer students. Once in orbit, NPSAT1 has the potential of adding to the knowledge base of science and space technology while still meeting educational objectives through ground operations by officer students and as a laboratory above the sky.

## VII. References

- <sup>1</sup>D. Sakoda, R. Phelps, J. Horning, D. Rigmaiden, and J. Damerou, "Naval Postgraduate School PANSAT: Lessons Learned," AIAA Space 2001 Conference and Exposition, Albuquerque, NM, August 28-30, 2001.
- <sup>2</sup>D. Sakoda, "Overview of the Naval Postgraduate School Petite Amateur Navy Satellite (PANSAT)," Paper SSC99-I-5, Thirteenth Annual AIAA/Utah State University Conference on Small Satellites, Logan, Utah, Aug. 1999.
- <sup>3</sup>J. Salmon, et al., "Solar Cell Measurement System for NPS Spacecraft Architecture and Technology Demonstration Satellite, NPSAT1," Paper SSC03-X-4, 17th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, Aug. 2003.
- <sup>4</sup>ENS. Benson Lo, USNR, et al., "Evaluation and Testing of the Solar Cell Measurement System Onboard the Naval Postgraduate School Satellite NPSAT1," 22<sup>nd</sup> AIAA International Communications Satellite Systems Conference & Exhibit 2004, Monterey, California, May 2004.
- <sup>5</sup>B. Leonard, "NPSAT1 Magnetic Attitude Control System," Paper SSC02-V-7, 16th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, Aug. 2002.
- <sup>6</sup>Design, Construction, and Testing Requirements for One of a Kind Space Equipment, DOD-HDBK-343, Feb. 1986, USAF.
- <sup>7</sup>D. Sakoda and J. Horning, "Overview of the NPS Spacecraft Architecture and Technology Demonstration Satellite, NPSAT1," Paper SSC02-I-4, 16th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, Aug. 2002.
- <sup>8</sup>M. Gruhlke, "Computer Aided Thermal Analysis of a Technology Demonstration Satellite (NPSAT1)," Naval Postgraduate School Technical Report, NPS-SP-03-001, Monterey, California, May 2003.
- <sup>9</sup>D. Ebert, et al., "Configurable Fault-Tolerant Processor (CFTP) for Space Based Applications," Paper SSC03-XI-5, 17th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, Aug. 2003.
- <sup>10</sup>D. Sakoda, "The Petite Amateur Navy Satellite (PANSAT) Hitchhiker Ejectable," Shuttle Small Payloads Symposium, U.S. Naval Academy, Annapolis, MD. Sept. 13-15, 1999.
- <sup>11</sup>Eastern and Western Range 127-1, Range Safety Requirements, Patrick AFB Range Safety Office, December 1999.
- <sup>12</sup>CPT. Gary Prater, US Army, "NPSAT1 Missile System Pre-launch Safety Package (MSPSP)," Naval Postgraduate School Master's Thesis, Monterey, California, June 2004 (to be published).