Overview of the Naval Postgraduate School Petite Amateur Navy Satellite (PANSAT)

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Abstract.

The Petite Amateur Navy Satellite (PANSAT) was launched aboard the STS-95 *Discovery* Shuttle. The historic Shuttle flight noted mainly by John Glenn's return to space also marks the Naval Postgraduate School's first small satellite in space. PANSAT, which is in a circular, low-Earth orbit (LEO), is the culmination of 50 officer students' graduate theses over approximately a nine-year period. The satellite continues to support the educational mission at NPS and will soon provide on-orbit capability of store-and-forward digital communications for the amateur radio community using direct sequence, spread spectrum modulation. The spacecraft includes the communications payload, electrical power subsystem, digital control subsystem, and structure. This paper describes the overall architecture of the spacecraft bus, a discussion of the NPS command ground station, and some lessons learned.

Introduction

The Space Systems Academic Group at NPS provides direction and a focal point for Naval Postgraduate School (NPS) space research and the space curricula: Space Systems Engineering and Space Systems Operations. The Petite Amateur Navy Satellite (PANSAT) is the first NPS satellite in space. Approximately 50 Master's degree theses were published on the satellite. Officer students played a vital role in the successful development of the satellite and gained invaluable experience through their part in the project. However, it would be more accurate to say that PANSAT played a vital role in providing hands-on opportunities for the officer students in the educational process at NPS. The satellite, itself, is really a byproduct of that educational process.

Mission Requirements and Objectives

Education

The primary objective for PANSAT is to provide hands-on educational opportunities for the officer students at NPS. The first phase of the program provided direct support to the engineering disciplines through subsystems development, integration, and test. A number of theses were also related to operations. Now that PANSAT is operating in space, the emphasis has shifted more to support education and training in spacecraft operations. Figure 1 provides a breakdown by discipline of student involvement with PANSAT from a thesis perspective. A large portion of the work was provided by electrical engineering students which is not surprising given that the spacecraft is mostly electronics. Space Systems

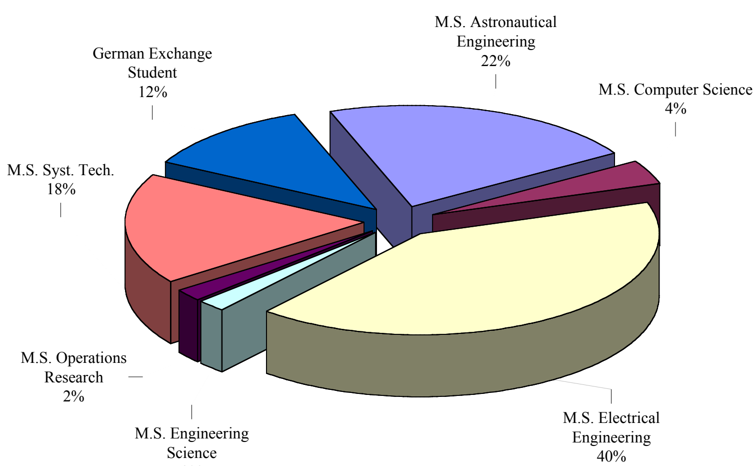

Figure 1. Officer Student Involvement by Discipline.

Operations officer students were also involved in the early part of the program and are shown by those receiving a M.S. in Systems Technology. Many more officer students were involved with PANSAT through laboratory exercises, case studies, and design groups.

Design Requirements

PANSAT requirements are to provide a low-cost, global, digital communications system for message relay in the ultra-high frequency (UHF) band using spread spectrum techniques with a capability of storing thousands of messages. Following are the specifications for the spread spectrum system.

- Operating Center Frequency: 436.5 MHz
- Operational Bandwidth: 2.5 MHz
- Bit-error-rate: 10^{-5}
- Transmission Rate: 9842 bps
- Modulation: Binary Phase-Shift Keying (BPSK)
- Spread Spectrum: Direct Sequence
    - pseudo-noise (PN) code: 7-bit shift register, taps at 7,1
    - PN length: 127 chips
    - One PN sequence length per data bit
- Provide positive link margin
- Use AX.25 link layer protocol
- Near-isotropic antenna radiation pattern
    - minimum antenna gain: -3 dBi
    - circular polarization: axial ratio > 0.42

PANSAT will operate very much like an orbiting mail server. Given the communications availability of the user on the ground, digital messages can be uploaded and downloaded using amateur radio equipment and a spread spectrum modem. When the spacecraft is visible by the ground station, the user would log into the spacecraft and view a directory of messages onboard. The user can then download messages addressed to him/her and upload any messages. Because the communications window is brief, multiple passes may be required to upload (or download) some files. Many of the queries posted to the spacecraft and responses received are dealt with by software control.

Design Philosophy

The primary emphasis on education placed a number of constraints on the design, including the need for a flexible development schedule, a desire to build rather than buy technology, and a need to simplify the design which meant difficult decisions regarding redundancy and reliability. A flexible schedule was required given the guaranteed high turnover rate of the student labor. The emphasis on building hardware was made to maximize the hands-on opportunities to provide a learn-by-doing method. As always, low cost was another driving factor in the design which further implied a simple design.

A robust, simple design amenable to any number of launch carriers was of primary concern. This is because as a secondary payload, it is difficult to determine early on what launch opportunities would be available. However, in order for the design to progress, a launch vehicle must be selected, or a survey of best-fit options needs to be done. PANSAT was designed as a Shuttle Hitchhiker payload with the assumption that if the design is sufficient to qualify as a Hitchhiker ejectable it would be amenable as a secondary payload on an expendable launch vehicle as well.

Selection of the Shuttle as the launch carrier (via the Hitchhiker program) provided requirements such as the payload envelope, design limit loads, available orbital options, and safety requirements. These requirements are outlined in the *Hitchhiker Customer Accommodations and Requirements Specification* (CARS)[1]. Although the Shuttle was selected to provide a baseline design, it proved to be the means of getting PANSAT into space. A number of additional constraints arise with the use of the Shuttle as the launch carrier. Specifically, safety requirements have a major impact on the design, more or less at the expense of functionality or reliability. As an example, both the attitude control and propulsion subsystems were removed in the conceptual design phase as a result of safety concerns with hazardous materials. This had a beneficial effect of simplifying the design, but very much limited the spacecraft's capability. The design of PANSAT as a Hitchhiker payload is presented in more detail by the author[2].

PANSAT Design

PANSAT was designed with neither attitude control nor propulsion. The spacecraft is therefore a tumbling satellite. Given that no specific orientation is guaranteed, the spacecraft shape was made spherical. This was done mainly to narrow the range of solar flux on the body-mounted panels that cover the spacecraft. If PANSAT were designed to be spin-stabilized, a cylindrical shape would have been the obvious choice. Given the constraints of the Hitchhiker payload envelope and the spherical shape, the spacecraft configuration was defined as octagonal in the front, side, and top views. The launch vehicle interface was placed on the bottom square face, with the other square panels providing solar panel mounting surfaces. Figure 2 shows the PANSAT configuration with some panels removed to view the interior of the spacecraft.

The PANSAT block diagram is shown in Figure 3, where the spacecraft is separated into three sections, the communications payload, the digital control subsystem (DCS), and the electrical power subsystem (EPS). The modem, although part of the communications subsystem, is directly connected to the processor board. Some redundancy is furnished through the use of mutually exclusive processor-modem modules. Other modules are

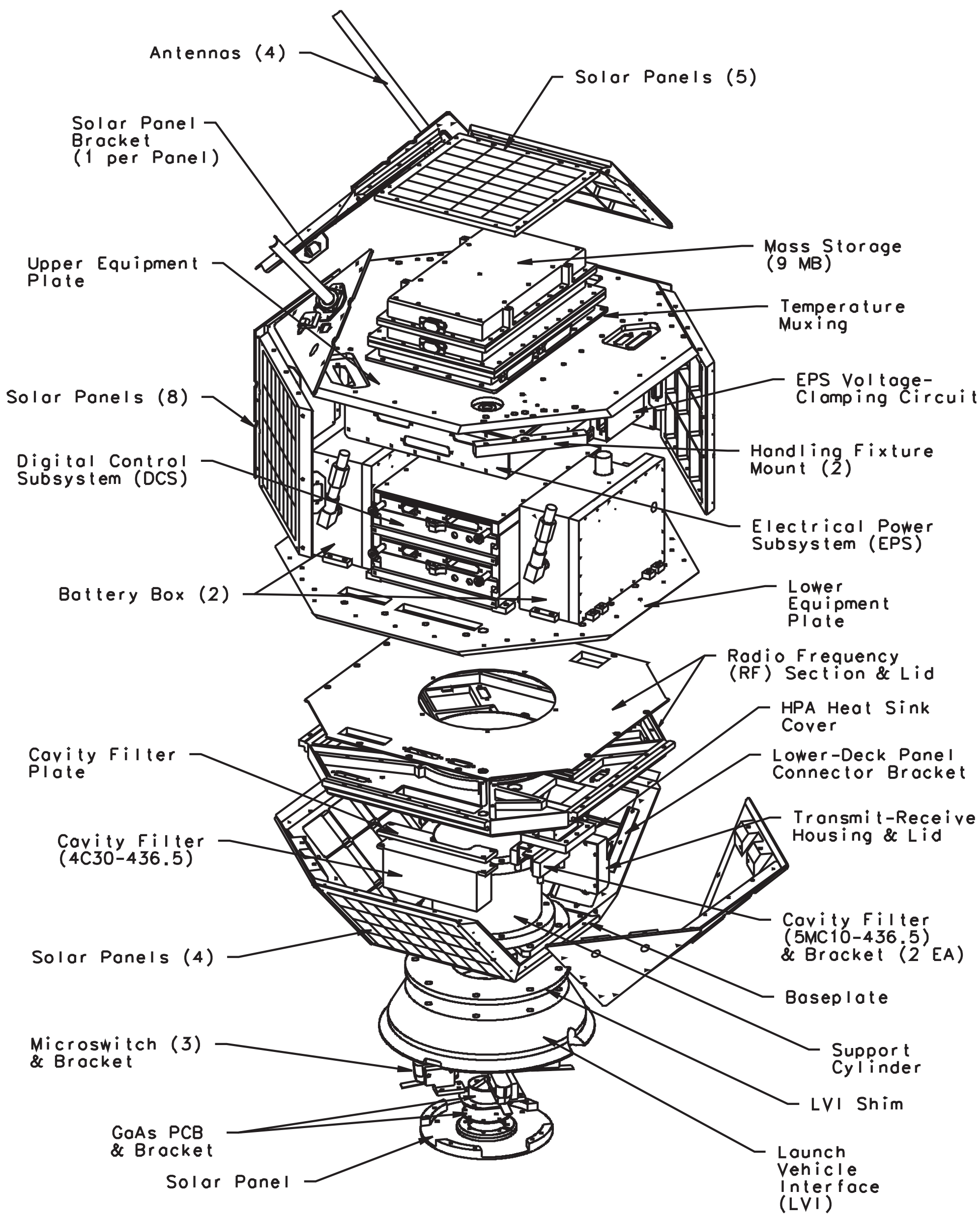

Figure 2. PANSAT Configuration.

paired to provide increased capacity and failure modes where if one module fails, such as the 'mass storage' module used for memory, the other module will provide half the capacity. The peripheral control bus (PCB) provides the means for communication and control of all modules by the active system controller.

a direct digital synthesizer (DDS) for the sampling clock. The PA-100 acquires, tracks, de-spreads, and demodulates the incoming signal and provides a synchronous, serial, TTL output to the SCC. The SCC interrupts the spacecraft processor when messages are received. Redundancy is provided by having two modem/processor modules.

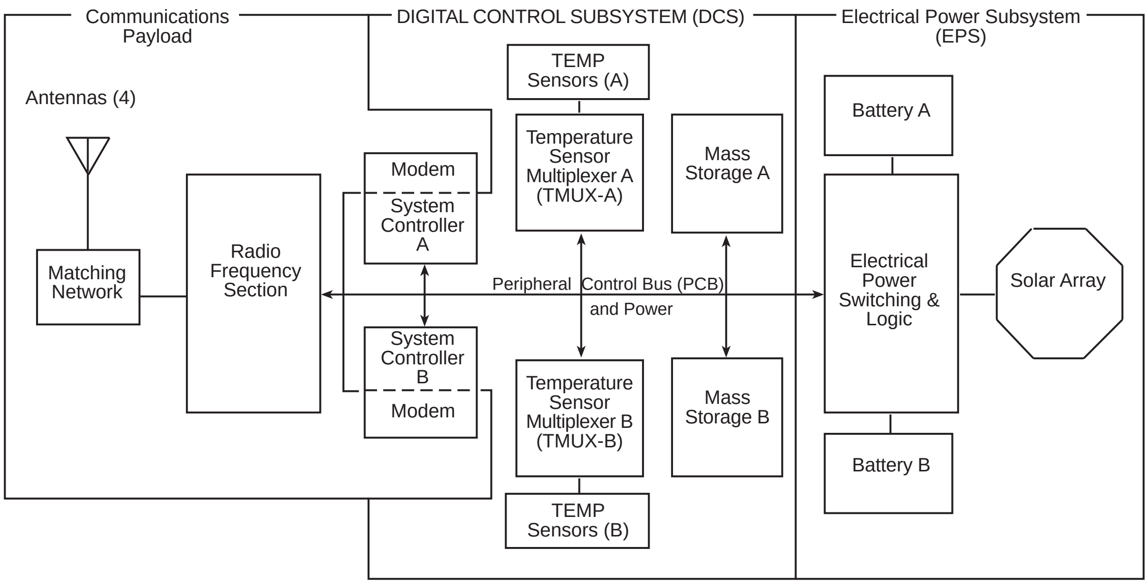

Figure 3. PANSAT System Block Diagram.

Communications Payload

The PANSAT communications payload is a half-duplex system working on the same frequency for both the up-link and down-link. In the spread spectrum mode, PANSAT operates at a 9842 bits per second transmission rate centered at 436.5 MHz with approximately 2.5 MHz of bandwidth. The heart of the communications payload is an Application-Specific Integrated Circuit (ASIC) chip, the Lockheed-Martin PA-100, which provides a digital solution to the acquisition, tracking, and demodulation of the received signal.

Modem

A block diagram of the modem is given in Figure 4. The modem works at a 70 MHz intermediate frequency (IF) and is tightly coupled with the processor through the modem interface. Through this connector, the processor controls the PA-100, information is transferred via the serial communications controller (SCC), and power is provided to the modem board. PANSAT can initiate a low-power mode by powering off the modem which would only occur if batteries were depleted. The PA-100 provides feedback to the automatic gain control (AGC) and drives

These modules are mutually-exclusive. Only one modem-processor pair is active at any one time.

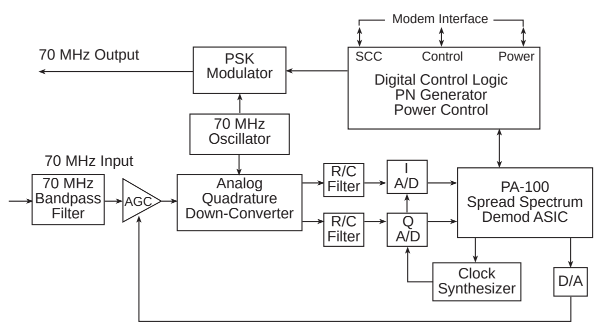

Figure 4. Modem Block Diagram.

Radio Frequency (RF) Section

The radio frequency (RF) section provides the down-conversion from 436.5 MHz to the 70 MHz IF on receive, and the up-conversion on transmit. The block diagram of the RF section is shown in Figure 5. A detailed description of the RF section is given by Lahti[3]. The receive path is shown on the upper half of the block diagram. Some redundancy is built into the RF section providing multiple paths for the incoming and outgoing signals, including a backup local oscillator (LO). Because there are redundant modems, separate paths are provided, shown at the right of the figure, for each of the transmit and receive inputs to the respective modems. The RF section, however, is not fully redundant. Each of the pin-diode switches and mechanical relays constitute a single-point of failure.

The redundancy scheme incorporated in the PANSAT design posed a number of questions on how software control could handle a possible failure. Determination of a failure in the RF section for the receive path can only be inferred by lack of any communication from the ground; whereas, a transmit path failure would be indicated by repeated requests from the ground after having received commands. In either case, the spacecraft would not be able to determine the cause of the failure indication should the problem actually occur in the ground segment. Different signal paths for both transmit and receive were defined as states in the RF section and the amount of time allotted prior to switching to the next state was then defined. Additionally, after exhausting the different states in the RF section, the next course of action would be to try the alternate modem. This last recourse meant resetting the spacecraft in order to switch processors. Rather than try and maintain incoming commands for repeated transmissions from the ground, a simple timer was used which would be reset by certain commands or by ground station control.

A 15-second timer was added as a safety inhibit in the RF section to remove the possibility of inadvertent RF transmissions after separation from the Shuttle. The 15-second RF timer lies in-line with the power and control to the mechanical relay used to switch between transmit and receive. Because PANSAT is normally in a receive-only mode, the timer must expire before any transmissions through the antenna can occur. This feature was only necessary for the very short period from Shuttle ejection and the time that PANSAT reached a safe distance from the Shuttle of 3.44 meters. The 15-second RF timer also constituted a single-point of failure.

Antennas

The lack of attitude control for the spacecraft required that the antennas be omnidirectional. Design of the antenna configuration was performed by Ellrick[4] and Karapinar[5] using the *Naval Electromagnetic Code (NEC)* to yield an isotropic radiation pattern with nulls no deeper than -3 dB. The configuration uses four 1/4-wavelength monopole elements in a tangential turnstile. The top view yields a pin-wheel shape, and the front and side views show the antennas canted at 45°. Each element is driven 90° in phase from the adjacent element, thus resulting in a 0°, 90°, 180°, and 270° phase differential, respectively. Figure 6 shows a block diagram of the antenna design. The hybrid junction in the lower portion of the diagram performs a power divide as well as a phase difference of the outputs by 180°. The quad hybrids perform a 90° phase difference of the outputs as well as impedance matching. The unused terminals of the quad hybrids are terminated.

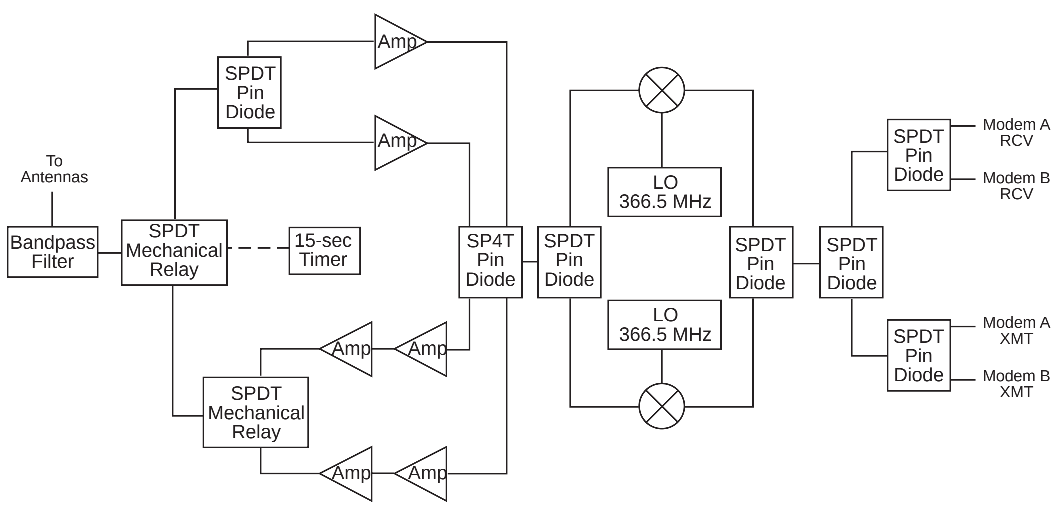

Figure 5. Radio Frequency (RF) Section.

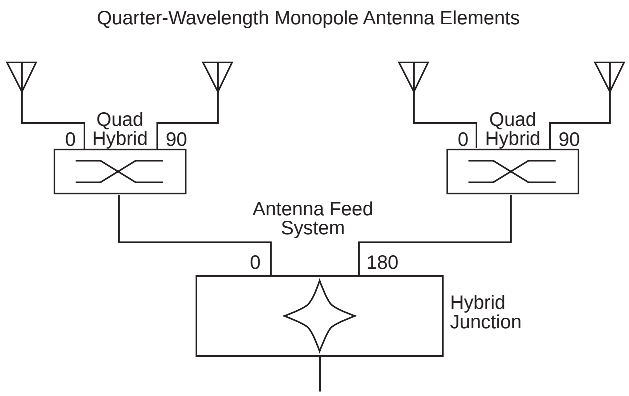

Figure 6. Antenna Block Diagram.

Field testing of the antennas was done to verify the analysis. A detailed discussion of the antenna testing and modifications to the antenna model are given by Smilowitz[6]. The final antenna design showed a worst-case null of -8 dB located at the top of the satellite with as much as 5 dB of gain on the opposite side of the spacecraft. This design included an antenna deployment mechanism to avoid contact of the antennas with the Hitchhiker canister while attached to the Shuttle. However, the deployment mechanism was removed because of NASA safety concerns that the antennas may inadvertently deploy. The spacecraft structure was modified for additional height, but a dimensional error resulted in the antennas contacting the interior of the canister which became evident during integration at NASA/GSFC. In order to avoid contact with the Hitchhiker canister and to stay within the user envelope, the antennas were bent. Analysis performed after the modification suggests the antenna pattern to have become exaggerated; that the nulls may have become deeper and positive gains slightly larger.

Command and Data Handling

PANSAT command and data handling is performed by the digital control subsystem (DCS). The DCS is composed of the processor board or system controller, the peripheral control bus (PCB), the mass storage units (MSU), and the temperature sensor multiplexer (TMUX) modules. There are two system controllers which are redundant and mutually exclusive. Each system controller has an Intel M80C186XL microprocessor. This is the military version of the 80C186 operating at 7.3 MHz. The M80C186XL was selected because of its proven architecture, radiation tolerance, low power consumption, availability of development tools, and its capability of supporting a multi-tasking environment. The system uses an error-correction-and-detection (EDAC) controller (Harris ACS630MS) with RAM for system memory[7], read-only memory (ROM) for the boot kernel, a four-channel analog-to-digital (A/D) converter, a serial communications controller (SCC) chip, and a programmable peripheral interface (PPI) chip for control of the PCB. Figure 7 shows the block diagram of the system controller.

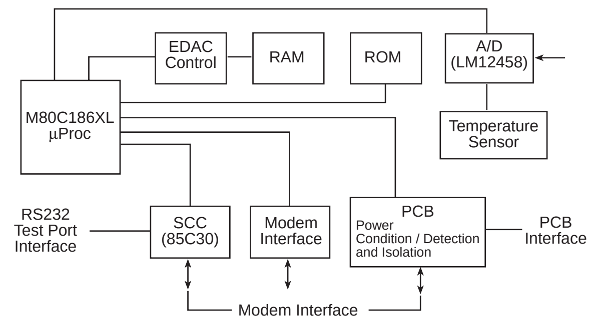

Figure 7. System Controller Block Diagram.

Two mass storage units (MSU) provide memory storage of messages and telemetry. Each MSU has a capacity of 4.5 megabytes, of which 512 kbytes is non-volatile Flash memory. The Flash memory is reserved for telemetry data which can hold almost two days of data based on the boot-ROM software telemetry collection. The MSUs can be operated at the same time to provide for a total capacity of 9 megabytes of which 1 megabyte would be Flash memory. Each MSU is low-power using only 250 mW during access and 100 mW at standby.

The temperature multiplexer (TMUX) modules are two separate multiplexers located on the same printed circuit board as mirror images. Each TMUX has 32 channels. One channel is used for calibration and critical temperatures are redundant. The TMUX is also a low-power module, consuming approximately 600 mW. The TMUX has a duty cycle of 100%. Analog signals are input to the A/D converter on the system controller.

Resetting of the microprocessor board is handled by a watchdog timer located in the electrical power subsystem (EPS). The processor periodically resets the watchdog timer during its normal operations. If the watchdog timer expires, the EPS switches power from the active system controller to the alternate system controller. Another means of selecting the redundant processor is if software control logic determines that the modem has failed. This is defined by another timer which is described in the RF section. Finally, the system controller may be reset or toggled to the inactive processor by ground station control. This is necessary as a means of transferring control from the boot-ROM software to new uploaded software.

The DCS operation is much like that of a desktop PC in that upon powering, the processor boots from the on-board ROM. The boot-ROM kernel performs all the hardware initialization and a minimal set of software commands and functionality. As a PC would load the operating system from a hard disk, so too is the operating system uploaded to the spacecraft processor, except that the source is from the ground. The PANSAT operating system is uploaded in stages, however, allowing more sophisticated tools to be available within each upload. Finally, software tasks, or applications, are uploaded to provide for additional functionality and for user services such as the digital messaging service. Unfortunately, should the processor reset at any time, the spacecraft reverts to its boot-ROM software while erasing any stored messages in MSU RAM areas.

Electrical Power

The electrical power subsystem (EPS) consists of 17 silicon solar panels and one gallium-arsenide (GaAs) panel, two nickel-cadmium batteries, and the power distribution electronics. The EPS is controlled by the active system controller via the PCB. However, the EPS module is first to power up at startup. The EPS also contains the watchdog timer which is used to reset from the active system controller to the alternate system controller should a processor failure occur.

The EPS provides a battery-dominated bus with a range of 9 V to 16 V. The bus is clamped at 16 V by the voltage clamping circuit, a Darlington transistor and diode. Battery maintenance includes efficient battery charging by minimizing the number of charge/discharge cycles, trickle charging discharged batteries, and reconditioning batteries. Batteries are discharged to 40% depth-of-discharge (DOD) before charging. With two batteries, one battery can be charged over multiple orbits for a single charge cycle. This reduces the number of charge/discharge cycles if one battery were charged every sunlit portion of an orbit and then discharged in eclipse. With careful battery operation and optimization of the battery charge algorithm following analysis of on-orbit operation, a mission life of at least four years is expected for PANSAT.

The battery itself was designed and built at NPS using commercial, off-the-shelf (COTS) nickel cadmium battery cells. Although selection and matching of the individual cells was contracted, the housing, wiring, and integration of the batteries was done at NPS. The batteries were designed in full compliance with NASA safety requirements. To satisfy some of the Shuttle safety concerns, the batteries were fully discharged prior to integration with the Hitchhiker canister.

Three microswitches were implemented in the design for Shuttle safety. Two microswitches on the power line and one microswitch on the return line between the solar panel power and the EPS electronics were used to ensure that PANSAT would not operate while attached to the Shuttle. The microswitches were located at the base of the spacecraft and were kept in the open-circuit position by the Hitchhiker ejection system (HES) pusher plate. Upon separation, the microswitches close and the spacecraft is capable of powering up. It should be noted, however, that each of the microswitches constitutes a potential single-point of failure.

Spacecraft Structure

The PANSAT structure was designed to be amenable as either a Shuttle secondary payload or a payload on an expendable launch vehicle. For this reason, the structure was designed with a goal of high margins of safety. Design factors for the development of the PANSAT structure included the launch vehicle payload envelope, structural loads expected during launch, issues related to manufacturing, and compatibility issues related to the space environment and the Shuttle. The latter pertains particularly to materials selection for safety-related issues, such as low-outgassing materials, stress-corrosion cracking resistance, and reliability of components.

The configuration, shown earlier (Fig. 2), has an octagonal profile in the top view, and an octagonal profile plus the launch vehicle interface (LVI) in both the front and side views. Internal to the spacecraft are two equipment plates and a thin-shell support cylinder. The load-bearing structure is composed of 13 of the solar panel substrates, the internal equipment plates, an internal cylindrical support, and the LVI. Five of the solar panel substrates are merely cover panels, and attach to the main structure by threaded fasteners. Figure 8 shows the load-bearing structure of the satellite.

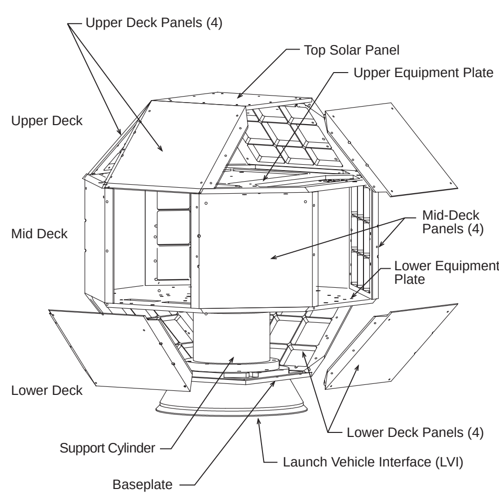

Figure 8. PANSAT Load-Bearing Structure.

The PANSAT structure is made almost exclusively of aluminum 6061-T6. Approximately, 90% of the structure was fabricated at NPS. The solar panels were designed with modularity in mind to ease fabrication and assembly, as well as to allow easy replacement with a spare panel. Five different kinds of solar panels allowed the purchase of only five spare panels along with the 18 required for flight. Some optimization was performed to reduce structural weight. This proved to be unnecessary because of the 68 kg (150 lbs.) limit as a Hitchhiker payload. Ballast was actually added to increase the ballistic coefficient to maximize orbital lifetime. The final spacecraft weight was 57 kg (125.5 lbs.).

Structural integrity was shown to be sufficient for PANSAT as a Shuttle Hitchhiker payload[2]. Analysis was performed using the design limit loads given in Tables 1 and 2, applying factors of safety of 2.0 for yield and 2.6 for ultimate. These factors of safety were used for verification by analysis alone, however, system vibration testing is still a requirement. Finite element analysis (FEA) was employed using the Structural Dynamics Research Corp. (SDRC) I-deas® software. The FEA model was verified by modal testing of a prototype structure with correlation of the fundamental frequency within 6%[8]. In addition to FEA of the load bearing structure, detailed analysis of the fasteners was performed. Each structural component was also classified for fracture control.

Table 1. Hitchhiker Design Limit Loads[1].

Payload/Instrument structure					
Load Factor, (g)			Angular Acceleration (rad/sec^2)		
NX	NY	NZ	R_X	R_Y	R_Z
±11.0	±11.0	±11.0	± 85	± 85	± 85

Table 2. Shuttle HH Tertiary Assembly/Component Design Load Factors[1].

Tertiary Assembly/Component	
Weight, (lbs)	Load Factor, (g)
<20	40
20 – 50	31
50 – 100	22

Spacecraft Testing

Spacecraft testing can be divided into functional testing, environmental testing, and testing required for Shuttle safety and interface control compliance. The design philosophy emphasized designing to test. This was extremely important since the development was performed in a university laboratory and development was handed over from one student to the next. Continuity in testing from the board level to an integrated system served in minimizing the unnecessary redesign of tests and test procedures which would prove costly in time. Testing for integration at NASA/GSFC was done with a minimum of test equipment, including two laptops, a programmable power supply, and a brief-case sized modem for testing through the air. A detailed discussion of the functional testing and tools used from development to Hitchhiker integration is given by Horning[9].

Environmental testing was emphasized on the subsystem level to try to discover any workmanship problems early. Testing included random vibration to at least acceptance testing levels, and thermal-vacuum cycling. Overstreet[10] provides a discussion of the subsystem environmental testing performed as part of the PANSAT test plan. Because of the compressed schedule prior to delivery to NASA/GSFC, very little system-level testing was done. All system level testing was performed as part of the Shuttle safety and interface requirements. Random vibration was done on the integrated spacecraft at NASA/GSFC. In addition, a mass measurement was performed to verify that the spacecraft center-of-gravity (C.G.) was within the prescribed envelope for a Hitchhiker ejectable payload.

NPS Ground Station

The NPS ground station is a low-cost solution for LEO satellites. The major components are COTS items available through amateur radio mail-order catalogs. The ground station provides for automatic two-line element (TLE) set updates, control of antenna rotors for azimuth and elevation pointing, automatic spacecraft access determination and scheduling, and the availability of manual or scripted communication with PANSAT. The ground station is also responsible for Doppler compensation while communicating with the spacecraft.

Hardware

The ground station block diagram is shown in Fig. 9 and a photograph of the ground station controller and antenna are shown in Fig. 10. PANSAT-specific hardware is required for spread spectrum modulation. The ground station controller is a PC running the Linux operating system. The controller provides communication to a plug-in serial communications controller (SCC) board. The SCC board outputs a TTL signal which is modulated directly to 436.5 MHz and amplified. Frequency mixing and Doppler compensation is provided by two frequency synthesizers which are controlled by the ground station controller through an IEEE-488 (GPIB) connection. The NPS ground station antenna is circularly polarized with 15.2 dB of gain and a beamwidth of 25°. Mounted near the antenna on the tower is a low-noise amplifier and band pass filter. Azimuth and elevation pointing is performed through a YAESU G-5400B controller and two antenna rotors connected to the ground station controller through a RS-232 serial interface box. Antenna pointing calibration is provided by a low-cost solution popular in the amateur radio satellite community. The solution uses a photo-resistor attached inside one end of a short, closed, delrin cylinder. The other end has a cap with a small hole to act as a collimator. By tracking the sun using the same ground tracking software and reading the resistance, the error in antenna pointing can be determined.

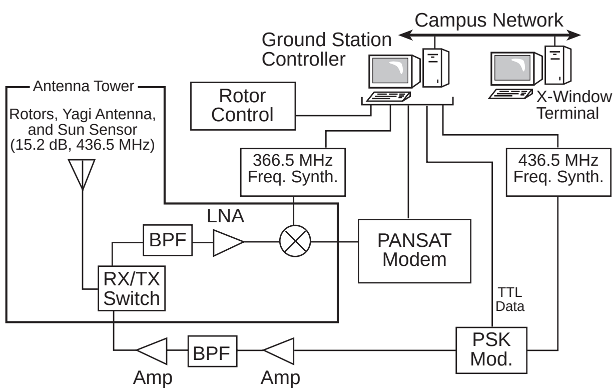

Figure 9. NPS Ground Station Block Diagram.

Figure 10. Ground Station Controller, Terminal, and Antenna.

Software

Software for the ground station controller consists of the PANSAT command and control software, software drivers for control of peripheral equipment, such as the antenna rotors and frequency synthesizers, ground track software, and various customized scripts. The ground track software is an open-source program called, SatTrack. Because of the availability of the source code, SatTrack was amenable to customization for such things as updating TLEs, exporting a schedule of PANSAT access times, and launching scripts based on those access times. The SatTrack program is also used to provide information on azimuth and elevation angles for antenna rotor control, and Doppler frequencies for both the up-link and down-link.

Ground Station Operations

Different scripts are used for satellite command and control. These scripts allow an automated flow of logic for the various tasks necessary for PANSAT operations, such as downloading spacecraft telemetry or uploading a new operating system. The scripts can determine whether the spacecraft is operating on uploaded software; or has reset and is working from the boot-ROM software. Uploads and downloads can also be performed over multiple passes. Following downloads of telemetry, the spacecraft is generally commanded to clear its telemetry storage. Although not absolutely necessary, clearing spacecraft telemetry allows for easier ground operations as on-board telemetry will eventually overwrite itself, and continue to do so until it is cleared.

Other ground station activities outside of direct communications with PANSAT are automated as well. The Naval Space Command provides daily updates of PANSAT ephemeris through the publication of PANSAT TLEs on their bulletin board system. The NPS ground station routinely downloads the new TLEs, publishes them on the NPS Space Systems Academic Group web site[†], and re-propagates PANSAT's orbit to determine more accurate access times. The access times, along with downloaded telemetry information and the recent log of satellite communication sessions, are also posted to the web site. Telemetry data is presented on the web site in both textual and graphical formats.

[†] PANSAT Web URL: http://www.sp.nps.navy.mil/pansat/

On-Orbit Performance

PANSAT was deployed from the Shuttle on Friday, 30 October 1998 at 10:46 A.M. (PST). The spacecraft started up nominally and began charging batteries. Unfortunately, as the satellite flew within view of the NPS ground station, no contact was made. It took two days before any signal from the satellite could be received. Because of the small staff devoted to the project, all of the attention was devoted to the spacecraft prior to returning from integration at NASA/GSFC. The ground segment, although considered ready at the time, had not gone through any rigorous testing. Antenna pointing calibration had not been resolved, and greater losses and noise were apparent in the system than initially conceived. Some of these problems could be explained by the bending of the spacecraft antennas, however, most of the issues were related to deficiencies in the ground equipment and operations.

Communications are currently occurring on a daily basis with the satellite, and software uploads were done successfully for new kernel operating systems. Although the ground station still offers some room for improvement, the satellite appears to be operating as designed. Resets do occur with PANSAT, but the satellite has never failed to reboot from its initial on-board instruction set. One of the reasons for PANSAT to reset is in the decision-making of using the redundancy in the RF section. The initial time limit, coded in ROM, of 12 hours between transferring from one RF state to the next proved to be too brief. This is because PANSAT is within view of NPS three or four times a day in consecutive passes (over a period between about five hours and six hours). This means that for the following 18 hours no contact with NPS is made. The error was simply an oversight since NPS accesses with PANSAT were predicted well before launch, and the information was available when the time period was finally decided. This problem is easily overcome either by uploaded software, or by ground command to reset to the initial RF state.

Conclusions

The PANSAT project is another example of successful spacecraft development in the increasing arena of university-built hardware in space. Through development of individual subsystems down to the component level, invaluable experience was gained in those specific disciplines. A system level purview with emphasis on systems engineering was achieved when dealing with the realities and challenges of designing and actually building, integrating, testing, and operating PANSAT. This could never be accomplished through a curriculum built exclusively around formal lectures and laboratory instruction. Educational objectives continue to be met as NPS officer students are exposed to PANSAT day-to-day operations. The PANSAT project promises even further opportunities for education when the spread spectrum messaging system becomes available in the very near future.

Figure 11. PANSAT Deployment from the *Discovery* Shuttle[‡].

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