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Abstract.

The Petite Amateur Navy Satellite (PANSAT) was launched aboard the STS-95 *Discovery* Shuttle. The his
flight noted mainly by John Glenn's return to space also marks the Naval Postgraduate School's first sma
space. PANSAT, which is in a circular, low-Earth orbit (LEO), is the culmination of 50 officer studen
theses over approximately a nine-year period. The satellite continues to support the educational mission
will soon provide on-orbit capability of store-and-forward digital communications for the amateur radio
using direct sequence, spread spectrum modulation. The spacecraft includes the communications payloa
power subsystem, digital control subsystem, and structure. This paper describes the overall architecture of th
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 Object

Education

The primary objective for PANSAT is to pro
on educational opportunities for the officer
NPS. The first phase of the program prov
support to the engineering disciplines through
development, integration, and test. A numb
were also related to operations. Now that
operating in space, the emphasis has shift
support education and training in spacecraft
Figure 1 provides a breakdown by disciplin
involvement with PANSAT from a thesis pen
large portion of the work was provided b
engineering students which is not surprising
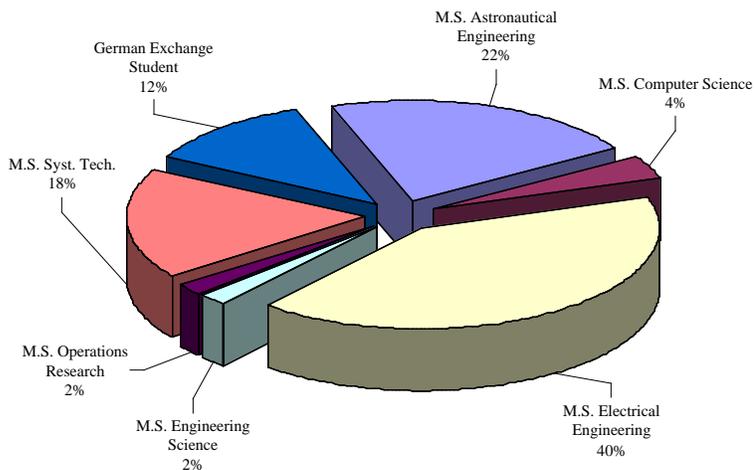the spacecraft is mostly electronics. Spa

Figure 1. Officer Student Involvement by Discipline.

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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

high turnover rate of the student labor. The building hardware was made to maximize t opportunities to provide a learn-by-doing r always, low cost was another driving factor i which further implied a simple design.

A robust, simple design amenable to any num carriers was of primary concern. This is b secondary payload, it is difficult to determi what launch opportunities would be available in order for the design to progress, a launch be selected, or a survey of best-fit options done. PANSAT was designed as a Shuttle payload with the assumption that if the design to qualify as a Hitchhiker ejectable it would l as a secondary payload on an expendable lau as well.

Selection of the Shuttle as the launch carr Hitchhiker program) provided requirements payload envelope, design limit loads, avail options, and safety requirements. These requ outlined in the *Hitchhiker Customer Accommo Requirements Specification* (CARS)[1]. Al Shuttle was selected to provide a baseline desi to be the means of getting PANSAT into spac of additional constraints arise with the use o as the launch carrier. Specifically, safety r have a major impact on the design, more o expense of functionality or reliability. As both the attitude control and propulsion subs removed in the conceptual design phase as safety concerns with hazardous materials. beneficial effect of simplifying the design, bu limited the spacecraft's capability. The design as a Hitchhiker payload is presented in more author[2].

PANSAT Design

PANSAT was designed with neither attitude propulsion. The spacecraft is therefore satellite. Given that no specific orientation is the spacecraft shape was made spherical. Th mainly to narrow the range of solar flux o mounted panels that cover the spacecraft. were designed to be spin-stabilized, a cylin would have been the obvious choice. Given th of the Hitchhiker payload envelope and th shape, the spacecraft configuration was

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configuration with some panels removed to view the interior of the spacecraft.

modem, although part of the communications is directly connected to the processor bo redundancy is furnished through the use exclusive processor-modem modules. Other
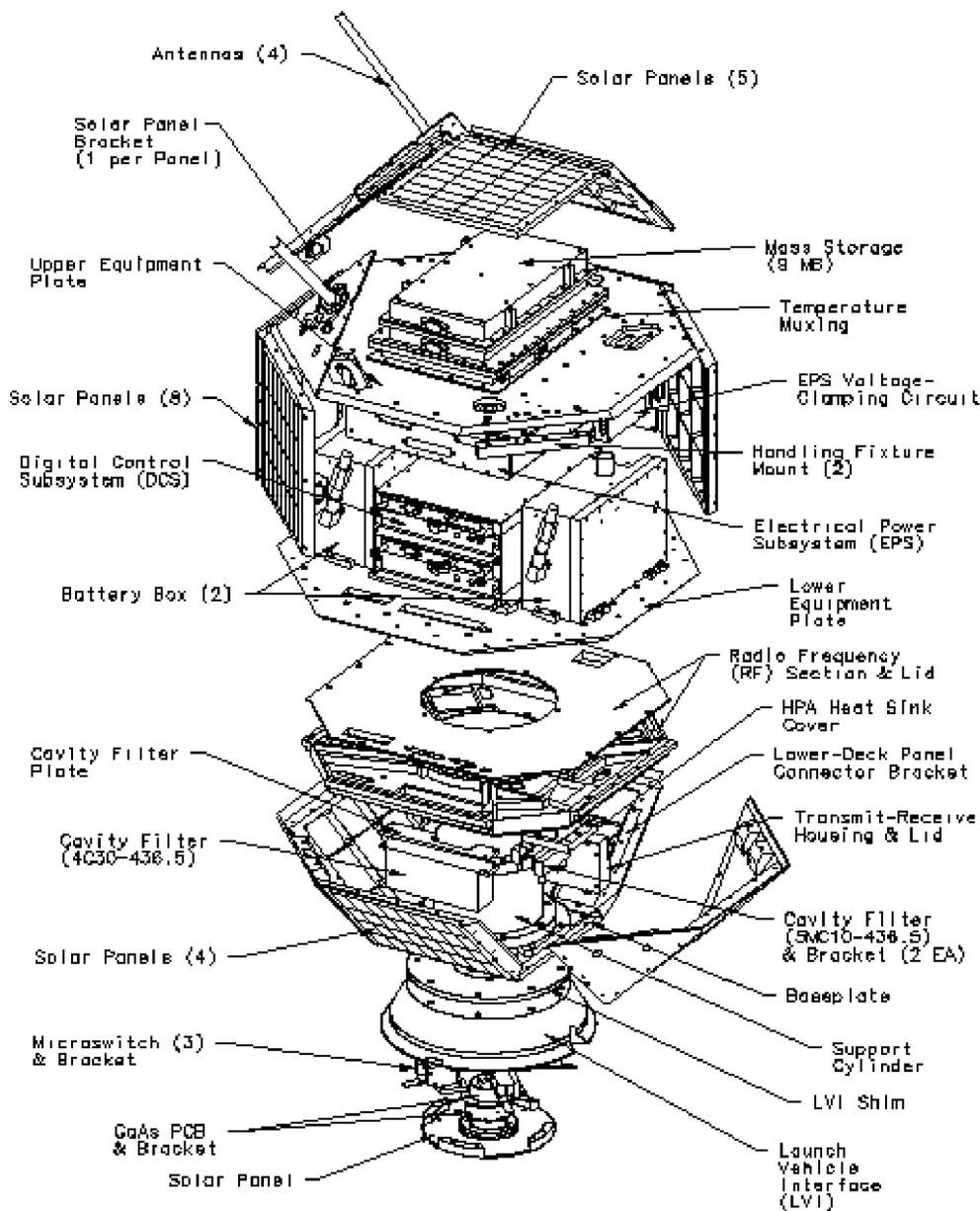
Figure 2. PANSAT Configuration.

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provides the means for communication and control of all modules by the active system controller.

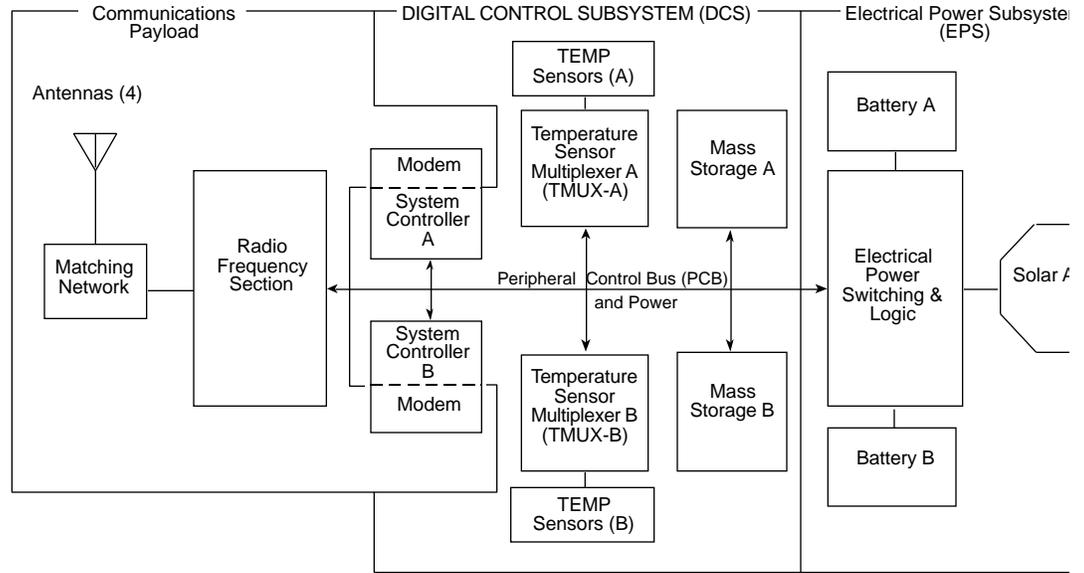processor when messages are received. Re[...] provided by having two modem/processo[...]

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 [...] processor pair is active at any one time.
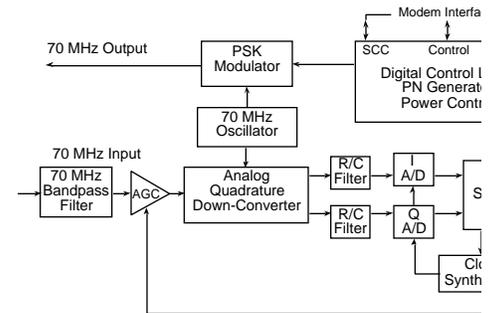

Figure 4. Modem Block Diagram

Radio Frequency (RF) Section

The radio frequency (RF) section provides [...] conversion from 436.5 MHz to the 70 MHz I[...] and the up-conversion on transmit. The bl[...] of the RF section is shown in Figure 5. [...] description of the RF section is given by [...] receive path is shown on the upper half [...] diagram. Some redundancy is built into the [...]

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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.

to the mechanical relay used to switch betwe
and receive. Because PANSAT is normally i
only mode, the timer must expire before any tr
through the antenna can occur. This featur
necessary for the very short period from Shu
and the time that PANSAT reached a safe di
the Shuttle of 3.44 meters. The 15-second R
constituted a single-point of failure.

Antennas

The lack of attitude control for the spacecr
that the antennas be omnidirectional. De
antenna configuration was performed by I
Karapinar[5] using the *Naval Electromagnetic*
to yield an isotropic radiation pattern with nul
than -3 dB. The configuration uses four 1/4-
monopole elements in a tangential turnstile. T
yields a pin-wheel shape, and the front and
show the antennas canted at 45°. Each eleme
90° in phase from the adjacent element, thus
a 0°, 90°, 180°, and 270° phase differential, n
Figure 6 shows a block diagram of the ante
The hybrid junction in the lower portion of
performs a power divide as well as a phase c
the outputs by 180°. The quad hybrids pe
phase difference of the outputs as well as
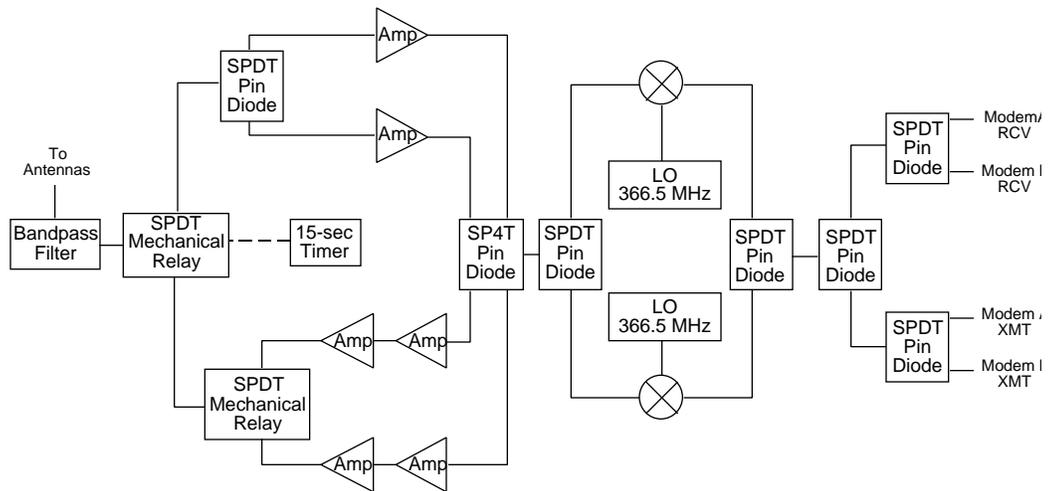matching. The unused terminals of the quad
terminated.

Figure 5. Radio Frequency (RF) Section.

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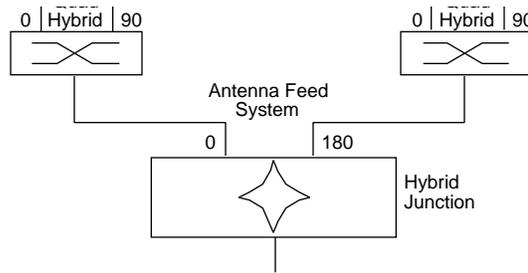
Figure 6. Antenna Block Diagram.

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-
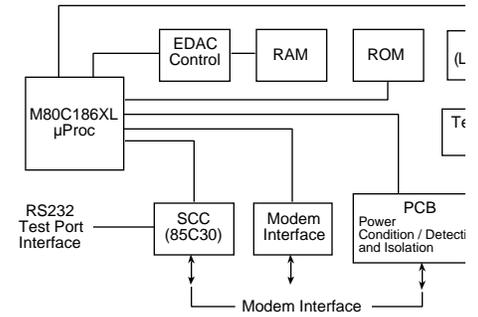
system controller.

Figure 7. System Controller Block Di:

Two mass storage units (MSU) provide men of messages and telemetry. Each MSU has 4.5 megabytes, of which 512 kbytes is non-v memory. The Flash memory is reserved f data which can hold almost two days of data boot-ROM software telemetry collection. Th be operated at the same time to provide for a t of 9 megabytes of which 1 megabyte wou memory. Each MSU is low-power using or during access and 100 mW at standby.

The temperature multiplexer (TMUX) mod separate multiplexers located on the same pi board as mirror images. Each TMUX has ; One channel is used for calibration a temperatures are redundant. The TMUX is power module, consuming approximately 6(TMUX has a duty cycle of 100%. Analog input to the A/D converter on the system co:

Resetting of the microprocessor board is h watchdog timer located in the electrical powe (EPS). The processor periodically resets th timer during its normal operations. If the wat expires, the EPS switches power from the ac controller to the alternate system controlle means of selecting the redundant processor i control logic determines that the modem has is defined by another timer which is describe section. Finally, the system controller may toggled to the inactive processor by ground sta This is necessary as a means of transferring (the boot-ROM software to new uploaded sol

The DCS operation is much like that of a de that upon powering, the processor boots from ROM. The boot-ROM kernel performs all tl

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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

spacecraft and were kept in the open-circuit [...] the Hitchhiker ejection system (HES) pusher [...] separation, the microswitches close and the s[...] capable of powering up. It should be note[...] that each of the microswitches constitutes [...] single-point of failure.

Spacecraft Structure

The PANSAT structure was designed to be [...] either a Shuttle secondary payload or a pay[...] expendable launch vehicle. For this reason, [...] was designed with a goal of high margins of sa[...] factors for the development of the PANSA[...] included the launch vehicle payload envelo[...] loads expected during launch, issues [...] manufacturing, and compatibility issues re[...] space environment and the Shuttle. The la[...] particularly to materials selection for safety-re[...] such as low-outgassing materials, stress[...] cracking resistance, and reliability of compo[...]

The configuration, shown earlier (Fig. 2), has [...] profile in the top view, and an octagonal pro[...] launch vehicle interface (LVI) in both the fr[...] views. Internal to the spacecraft are two equip[...] and a thin-shell support cylinder. The l[...] structure is composed of 13 of the solar pane[...] the internal equipment plates, an internal [...] support, and the LVI. Five of the solar pane[...] are merely cover panels, and attach to the m[...] by threaded fasteners. Figure 8 shows the l[...] structure of the satellite.
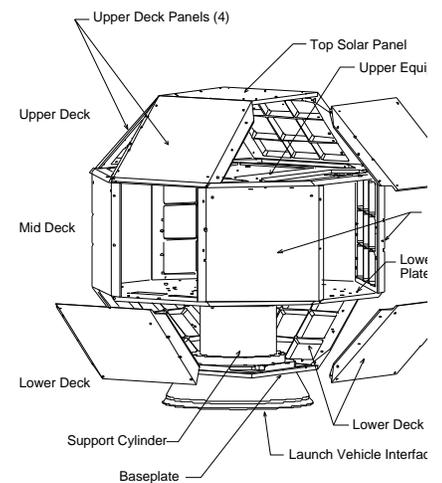

Figure 8. PANSAT Load-Bearing Stru[...]

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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/sec²)		
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

safety and interface control compliance. philosophy emphasized designing to test. extremely important since the development wa in a university laboratory and development over from one student to the next. Continui from the board level to an integrated syste: minimizing the unnecessary redesign of te procedures which would prove costly in ti: for integration at NASA/GSFC was done with of test equipment, including two laptops, a pr power supply, and a brief-case sized moder through the air. A detailed discussion of th testing and tools used from development to integration is given by Horning[9].

Environmental testing was emphasized on th level to try to discover any workmanship pro Testing included random vibration to at leas testing levels, and thermal-vacuum cycling. provides a discussion of the subsystem en testing performed as part of the PANSA Because of the compressed schedule prior to NASA/GSFC, very little system-level testin All system level testing was performed as Shuttle safety and interface requirements vibration was done on the integrated spacecra GSFC. In addition, a mass measurement wa to verify that the spacecraft center-of-gravit within the prescribed envelope for a Hitchhi payload.

NPS Ground Station

The NPS ground station is a low-cost soluti satellites. The major components are C available through amateur radio mail-order ca ground station provides for automatic two-l (TLE) set updates, control of antenna rotors and elevation pointing, automatic spacec determination and scheduling, and the av: manual or scripted communication with PA ground station is also responsible fo compensation while communicating with the

Hardware

The ground station block diagram is shown i a photograph of the ground station controller are shown in Fig. 10. PANSAT-specific l required for spread spectrum modulation.

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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.
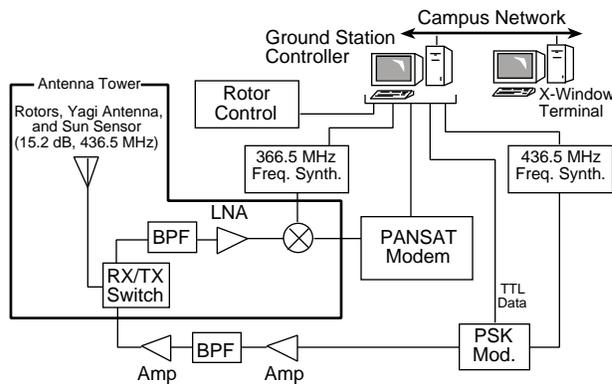

Figure 9. NPS Ground Station Block Diagram.

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

for control of peripheral equipment, such as rotors and frequency synthesizers, ground tra and various customized scripts. The ground tr is an open-source program called, SatTrack. the availability of the source code, SatTrack w to customization for such things as upda exporting a schedule of PANSAT access launching scripts based on those access t SatTrack program is also used to provide inf azimuth and elevation angles for antenna r and Doppler frequencies for both the up-link link.

Ground Station Operations

Different scripts are used for satellite co control. These scripts allow an automated f for the various tasks necessary for PANSAT such as downloading spacecraft telemetry or new operating system. The scripts can determ the spacecraft is operating on uploaded softv reset and is working from the boot-ROM Uploads and downloads can also be perfe multiple passes. Following downloads of te spacecraft is generally commanded to clear i storage. Although not absolutely necessa spacecraft telemetry allows for easier ground as on-board telemetry will eventually overwri continue to do so until it is cleared.

Other ground station activities outside communications with PANSAT are automa

The Naval Space Command pr updates of PANSAT ephemeris publication of PANSAT TL bulletin board system. The N station routinely downloads the publishes them on the NPS Sp Academic Group web site propagates PANSAT's orbit to more accurate access times. times, along with downloade information and the recent log communication sessions, are al the web site. Telemetry data on the web site in both textual a formats.

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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
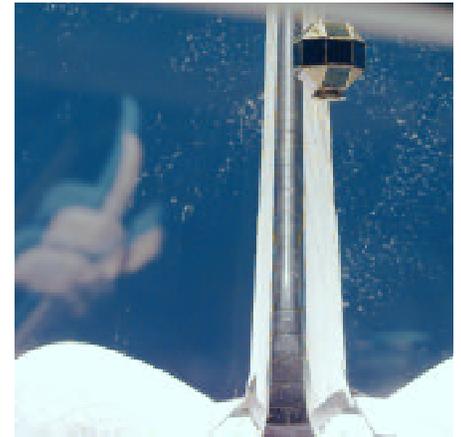

Figure 11. PANSAT Deployment from the Shuttle [‡].

exclusively around formal lectures and instruction. Educational objectives continue NPS officer students are exposed to PANSAT operations. The PANSAT project promises opportunities for education when the spre messaging system becomes available in th future.

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