

WPI Nanosat-3 Final Report

PANSAT - Powder Metallurgy and Navigation Satellite

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The logo for PANSAT is displayed in a stylized, metallic, 3D font. The letters are white with a gradient and a shadow effect, giving them a three-dimensional appearance. The logo is set against a dark, rectangular background.

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Abstract

This document summarizes the activities of the WPI Nanosat-3 (N3) program proposed in response to a BAA by the AFOSR and AIAA (University Nanosat Program, AFOSR BAA 2003-02) . Specifically, we proposed to have WPI undergraduate and graduate student teams under the direct guidance of WPI faculty, develop a nanosat that would be used as a vehicle to investigate;

- a GPS based navigation and orientation determination system
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1. Introduction

This document summarizes the activities of the WPI Nanosat-3 (N3) program proposed in response to a BAA by the AFOSR and AIAA (University Nanosat Program, AFOSR BAA 2003-02) . Specifically, we proposed develop a nanosat that would be used as a vehicle to investigate;

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Original Statement of Objectives

Our specific science, design and implementation objectives for the WPI nanosat were originally as follows.

- i. To design, test and characterize a powder metallurgy (P/M) bus structure that has specific thermal management and instrument/component support properties. The traditional approach for structural/bus design is to use aluminum and to machine the components. The advantages of P/M are that i) P/M material can be designed to exhibit unique and useful material, electrical, and thermal properties, ii) P/M parts require minimal machining and handling, and iii) P/M parts can be designed to be light weight and low cost with a relatively fast design and implementation cycle.
- ii. To develop, test and characterize a GPS navigation system that can provide orientation and geolocation information. GPS is becoming common on satellites, but the use of GPS for satellite orientation, particularly with a short baseline system is unusual.

In the course of addressing these two objects, we proposed to address the following objectives as well.

- iii. To implement a series of optical light intensity and direction sensors that can be used to verify the rate and to some extent the orientation data provided by the GPS navigation system.
- iv. To implement a commercial (Honeywell) magnetometer science instrument to provide field strength data for geolocated orbital positions.
- v. To implement a data down link using commercially available (400-470MHz range) receivers, transmitters and omni directional antennas.
- vi. To maintain an operation envelope with a maximum weight of 20kg (44lbs), and a maximum linear dimension of 45cm (17.7").

The program objectives did not change since the submission of our first performance report (26 September 2003).

2. Status of Effort

Since this report represents our final program report, we will summarize our activities, organization, participation and other activities in terms of final accomplishments.

Organization

The WPI NS3 program was organized around the WPI capstone projects program known as the Major Qualifying Project program¹, or simply MQP. The MQP requires that every student at WPI complete a three course equivalent project that represents a capstone experience in their major area. The NS3 program at WPI blended nicely with the MQP requirement and, as a result, about 50+ students completed their senior project requirement (MQP) as a participant in the WPI NS3 nanosat development program.



SHOT 1 Team

NS3 Activities Participation

Specific activities in which WPI students participated as part of the AF NS3 program included the following.

Safety Exam

Immediately after the student selection process was completed and prior to the end of the last quarter of academic year (AY) 2002-03 (D term), all WPI Nanosat-3 team members were contacted and assigned specific sections of the nanosat Safety Exam. Prof. Robert Labonte' (ECE) coordinated this effort.

SCR Teleconference

Four students were tasked with focusing on the SCR teleconference scheduled in April, 2003. The slides used for the SCR have been made available to the AFOSR Nanosat 3 office.

Shot I - June, 2003

Four students from WPI participated in the SHOT I workshop and three students participated in the SHOT II workshop. The SHOT I the students developed a small payload that included a camera with an electronic triggering mechanism, and a temperature measurement system.



WPI PDR Team

¹ <http://www.wpi.edu/Academics/Projects/information.html>

This payload worked perfectly and was perhaps the only payload that managed to take pictures from the upper regions of the flight where the curvature of the earth and weather patterns could be easily identified.



WPI Team SHOT 1 Balloon Picture

Satellite Design Course - October, 2003

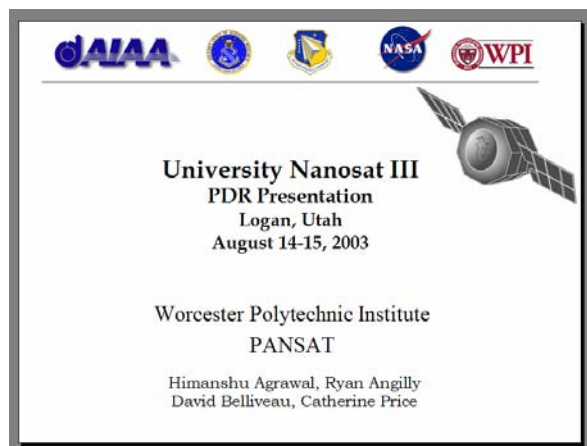
Three WPI students participated in the AF Research Labs satellite design course in the fall of 2004.

Shot II - June, 2004

The students on the SHOT II workshop flew our GPS receiver system along with temperature and pressure sensors. Because of balloon launch failures the system was only partially successful. Regardless, the data returned to us was sufficient to show that our designs would likely work and that we were doing a reasonably good job on our technology development.

PDR - August 2004

The culmination of the summer student work was the preparation of the slides and presentation for the Preliminary Design Review. Four WPI students participated in the NS3 PDR in August, 2003 in Logan Utah. An overview of our program organization, planned developments and technology development were presented at this conference.



PDR Slide Presentation Introduction

SDR - January, 2004

Five students presented at the January 2004 System Design Review at Dulles, VA. WPI was well represented by the PANSAT team members present. All team members spent significant time representing the WPI designs to visiting professionals, as well as visiting with and closely examining the designs of other colleges.

Representative comments by numerous review representatives included the following.

- WPI students did a good job in analyzing the link margins, and making good choices for up and down link frequencies and communication data rates.
- WPI appears to be the only college that has seriously considered up and down link power levels.
- One of the two strongest areas for WPI was our insistence on students clearly understanding the analytical aspects of our satellite design. This resulted in many positive comments from reviewers. WPI students could talk intelligently and often eloquently about various PANSAT design issues and choices.
- Our thermal design and analysis was well ahead of other colleges, and our students had a much better understanding of the orbital environment.
- WPI was one of only a few teams that seemed to understand the need for SEU tolerant designs
- WPI had a good plan and approach for sensor development. We were the only college to directly address H&S on a large scale.
- WPI was the only college to use circular polarization (very good) or to undertake the development of patch antennas (very good), to understand and compute antenna patterns and ground coverage and track, and the only college to perform path calculations



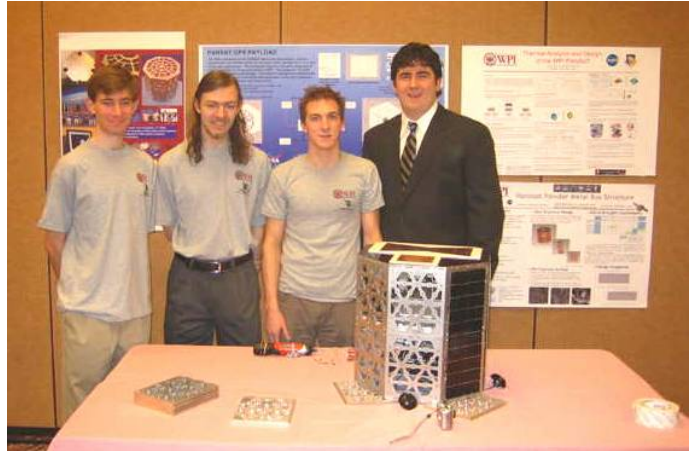
WPI SDR Team with AMSAT Representative and program coordinator Professor F. Looft (right).

Final Competition

Four WPI students represented the WPI PANSAT program in Reno NV during the final presentations and payload flight selection. While we were of course disappointed in not being selected, we recognize that as a new participant in the NS competition it would have been unrealistic to expect full satellite development when one considers that many other colleges have been in the program for multiple program competitions and, thus, could reuse or capitalize on many of their previously developed technology solutions.

Regardless, WPI students and faculty had many reasons to celebrate, notably including the following that stood out in our opinion as outstanding achievements.

- The only university to have developed a fully functional, useful and accurate orbital model of our satellite, based on a model that was previously developed as part of a project for the Goddard Space Flight Center Space Technology 5 (ST5) satellite.
- The only university to undertake the development of a custom, high performance, open source triple modular redundant (TMR) satellite computer system.
- The prototype of the custom designed TMR voter system for the TMR processor earned Mr. Ryan Angilly first prize in the 12th Annual Frank J. Redd Student Scholarship Competition. Angilly presented a paper that described an FPGA multiple processor architecture that uses hardware



WPI final competition team in Reno NV in January, 2005.
Mr. Ryan Angilly is on the right.

redundancy to guard against processor faults due to the radiation environment found in Low Earth Orbit (LEO). Angilly's paper was entitled: TREMOR: A TRIPLE MODULAR REDUNDANT FLIGHT COMPUTER AND FAULT-TOLERANCE TESTBED FOR THE WPI PANSAT NANOSATELLITE. TREMOR uses an architecture known as Triple Modular Redundancy to achieve radiation and high energy particle logic upset tolerance. Angilly discussed the TREMOR FPGA system and how it will be used to synchronize the processors and ensure that no erroneous data propagates to the system bus. Angilly also discussed how the flexibility of this design will allow TREMOR to become a new test bed for various implementations of the TMR architecture.

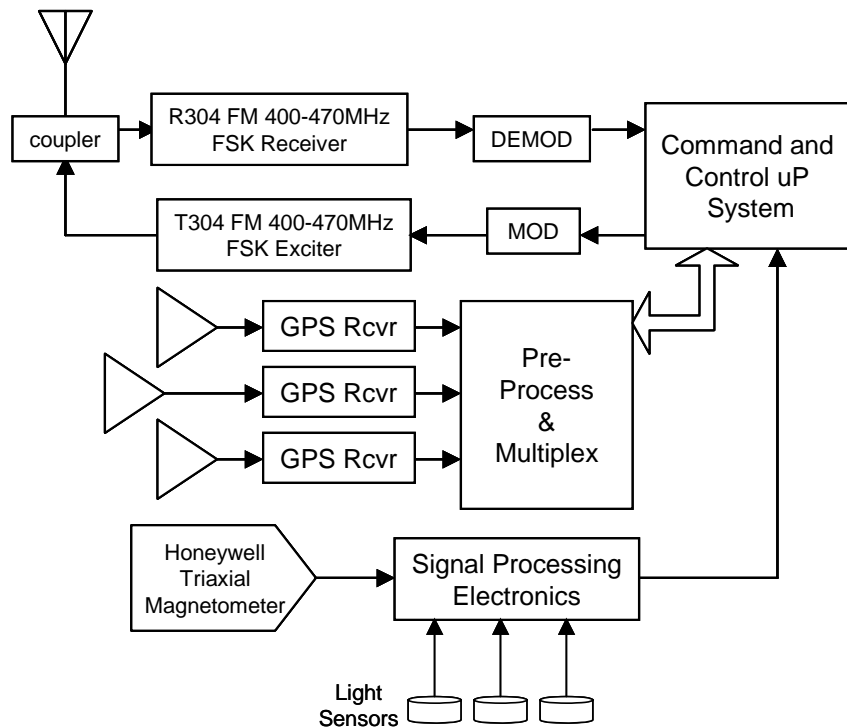
- We were the only competitor to consider or develop a bus structure based on materials other than the traditional aircraft aluminum (6061 T6 and its variants). We successfully created both a modular satellite design that was easily expanded on according to the needs of the mission for payload space and solar cell area and successfully created modular components based on powder metallurgy design principles.
- We successfully implemented a comprehensive and highly capable health and safety data collection system. This system was designed to support nearly 100 temperature and voltage measurement points throughout the satellite.
- We performed an exhaustive and comprehensive satellite stability system analysis. Based on our location in Massachusetts and a thorough understanding of the gravitational field in LEO, we were able to conclusively demonstrate through modeling and analysis that a fully passive satellite stability system that employed strong magnets strategically placed within the satellite would provide the desired level of satellite stability and support appropriate orientations that would facilitate antenna pointing for communications and control.

- We successfully developed a very short baseline GPS receiver and antenna system that, based on MATLAB modeling and Kalman filtering analysis, proved to be capable of determining satellite attitude using very short baseline (9") antenna separation and complex phase analysis of the received GPS signals.
- We designed a custom SEPIC based power management and conversion system that was both highly efficient and reliable. The design managed the power flow from 7 solar arrays and a NiCad battery pack to insure proper circuit power availability, battery charging and dark-side power delivery, all at about a 90% efficiency level.
- Prior to AF involvement, we independently negotiated the donation of thermal analysis software and then, in conjunction with a detailed and thorough analytical analysis, developed LEO models of the thermal environment for the satellite including predictions of internal and external temperatures based on estimated internal power levels, surface reflectivity, and other satellite parameters.

3. Accomplishments

General Design

The original system design for the WPI Pansat was detailed in our proposal and shown in the following system diagram. With only slight variations, the original system design concept was in fact implemented



Original System Design for Command, Control and Communications

with only slight changes to the overall structure of the system.

Based on the proposed system design, student teams were recruited to work on specific aspects of the satellite development. In particular, over the two year period of the program student teams were organized according to following research and development tasks.

<ul style="list-style-type: none"> • LEO Satellite Model • Thermal Analysis • Stability Systems & Analysis • Power Control & Management • Health and Safety Systems 	<ul style="list-style-type: none"> • Magnetometer Instrumentation • Magnetometer Boom System • Satellite Comm. Systems • Ground Based Comm. Systems • Ground Tracking Antenna 	<ul style="list-style-type: none"> • Powder Metals Bus Structure • Structure Vibration Analysis • Satellite Patch Antennas • GPS Navigation and Orientation System Design
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Below, each of these student team based program projects will be described in more detail.

Project Designs and Accomplishments

LEO Satellite Model

The purpose of this project was to create an orbital simulation of a satellite which could be used as an aid in the preliminary design process of PANSAT.

The first step was to create an orbital model using Satellite Tool Kit (STK). This program simulated the satellite in orbit, given its classical orbital elements. Numerous reports were then generated by STK that described the satellite's orbit and parameters associated with the orbit. The reports related to the orbital model dealt with position acquisition in terms of latitude and longitude as well as ground station azimuth and elevation angles. This model also generated other useful reports that influenced the design of the power and communication subsystem design.

The power model addressed the generation, storage, and distribution of PANSAT's power system. Solar cells were modeled for power generation and secondary batteries for energy storage. A power budget was generated based on the proposed electrical components for the satellite. Based on orbital model results that determined the maximum eclipse and sunlight durations, calculations were performed to determine the required area and efficiency of the solar cells.

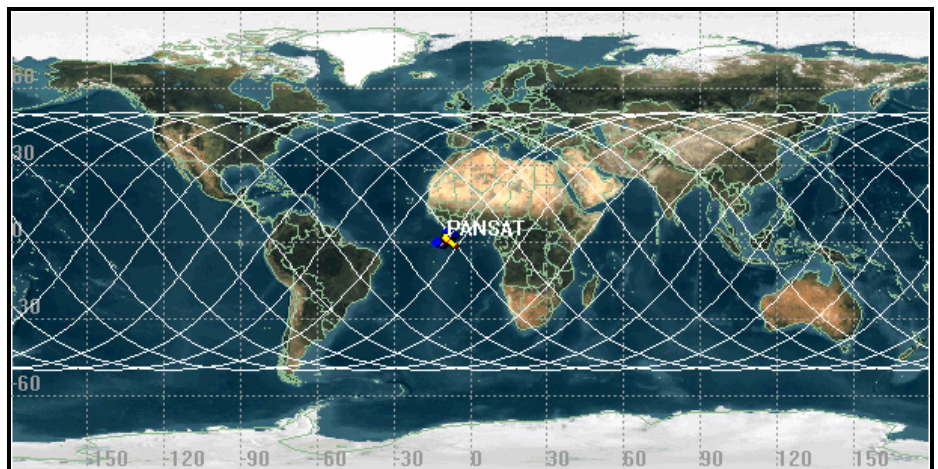
For the data transmission model ground station view time durations were obtained from the orbital model to determine the amount of time that would be required to transmit data to Earth. The satellite was modeled for a period of one month and gave reports that determined the minimum, maximum, and mean in-view time durations of the satellite from a particular point on the surface of the Earth. A bit generation chart was also created that tallied the amount of the data that would be collected for the maximum time that the satellite was out-of-view from the ground station, which was used to determine the amount of onboard memory necessary for this data collection.

The resultant model also allowed the user to generate two dimensional ground tracks of the satellites.

Based on the calculations that were performed, it was determined that the solar cells would provide sufficient power for power supply and battery recharge.

Summary

The PANSAT orbital model proved to be an extremely useful and flexible tool in the initial design stage of the satellite. The orbital model was easy to use and provided numerous mission scenario




PANSAT Ground Track Model Prediction

reports. The results of this model helped estimate power requirements and ground station communication parameters for PANSAT. Subsequent models helped establish related top-level constraints for the communication and power subsystems of the satellite.

Thermal Analysis



The goal of the thermal analysis team was to perform a comprehensive thermal analysis on all components, systems and integrated PANSAT structures. Accomplishments of this team (see poster, below) included the following.

- developed AutoCAD model of structure
- added Thermal Desktop to AutoCAD (procured separate from NS 3 program as a donation)
- added solar array thermal and structural models to PANSAT model
- successfully modeled the thermal response of the satellite in LEO, with various orbital parameters, sun and shadow times, albedo and satellite spin rates, and initial launch conditions
- predicted the full temperature range that could be expected in orbit for different orbits and a range of satellite orientations
- developed a detailed and complete mathematical thermal model of the satellite
- demonstrated results equivalence between the AutoCad-Thermal Desktop results and the analytically derived thermal model



Thermal Analysis and Design of the WPI PANSAT

Kyle Fuller and Sidharth Rupani
Advisor: Prof. Fred Looff

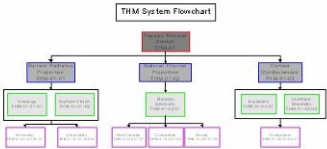



Abstract

The purpose of the project was to create a thermal model of the WPI PANSAT to be used in the configuration of subsystem thermal properties. The PANSAT is WPI's entry in the AFRL University Nanosat student satellite design competition. A finite element model of the satellite structure and subsystems was created and the thermal behavior of the satellite was quantified using the software tools Thermal Desktop, AutoCAD, and SINDA. The results from our model were then used to make recommendations for the selection of material thermal properties and future analysis.

Subsystem Characterization

Passive thermal control of the PANSAT was selected for its simplicity and ease of modeling and implementation. This was recommended by Charles Corban, a thermal engineer from AFRL, in his teleconference with special participants on September 1, 2003.



Thermal Modeling

- Data is increasing fidelity from steady state and transient lumped heat capacity math models to reduced and then multiple node finite element models.
- Goal is to satisfy requirements for flight from the AFRL, as indicated in the Internal Cargo Unit User's Guide (UN6001), to states:

"The University shall quantify the heat transfer within the internal and by the external environment (ICU or space). Thermal models of the satellite shall be capable to AFRL and at a minimum will include a simplified model that includes nodes for each of the temperature critical components."

Steady State and Transient Bulk Temperature

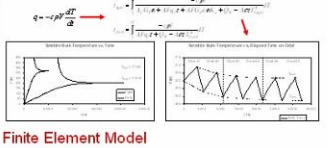
- Steady state thermal model first constructed to define the upper and lower limits of satellite bulk temperature.
- Would show whether or not the component temperature ranges fall within their respective thermal limits, taking the reduced thermal resistance of the satellite.
- Achieved using equations derived for the heat flux of a spherical satellite in the presence of Solar, Albedo, and Earth IR thermal radiation.

$$q = A \sigma (T_{sun}^4 - T_{earth}^4)$$

Component	Min (K)	Max (K)
Antenna	210.0	310.0
Antenna Boom	210.0	310.0
Antenna Support	210.0	310.0
Antenna Base	210.0	310.0
Antenna Mount	210.0	310.0
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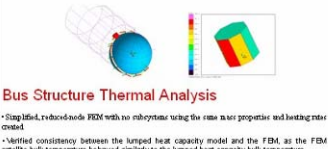
Finite Element Model

- Most detailed thermal model.
- Includes thermal analysis of components with multiple material and optical properties.
- Also accounts for dynamic satellite attitude and orbital inclination.
- Software selected for finite element modeling included SINDA, Thermal Desktop™, and AutoCAD™. Thermal Desktop and AutoCAD are plug-ins for AutoCAD and create the finite element model and its inputs for solving in SINDA.



Bus Structure Thermal Analysis

- Single-level, reduced-node FEM with no subsystem using the same near propeller radiating into void.
- Verified consistency between the lumped heat capacity model and the FEM, as the FEM satellite bulk temperature behaved similarly to the lumped heat capacity bulk temperature.
- FEM panel temperatures varied depending on satellite attitude.



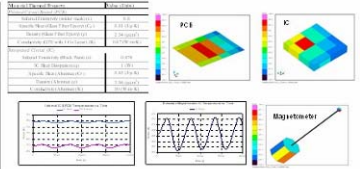
Generic Subsystem Thermal Analysis

Electronic subsystems modeled as a printed circuit board (PCB) with a non-attached integrated circuit (IC).

These subsystems were exposed to the radiation environment within the satellite and simulated with internal power dissipation.

The idea being that the temperature of the components would be between the maximum temperature experienced at the node where the power was being dissipated and the point on the circuit board furthest from that effect, exposed only to internal radiation effects.

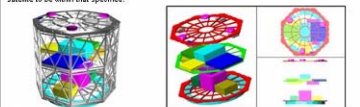
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Antenna Base Support Mount Support	210.0	310.0
Antenna Base Support Mount Support Support	210.0	310.0



Subsystem Configuration and Mass Properties

A preliminary 3D CAD model was created of the satellite bus structure and estimated subsystem components to verify that the mass properties of the satellite would conform to competition mass property specifications.

The model showed that the designed bus structure and planned shoving arrangement would provide more than enough room for all subsystem components and for the center of gravity of the satellite to be within that specified.




Conclusions and Recommendations

- The various thermal models are useful and flexible tools in the design stage of the satellite.
- The temperature ranges predicted by the thermal models at all levels were compatible with the operating temperature ranges of those components that we checked.
- The results of these models can be used to select and apply appropriate thermal control methods in subsequent work.
- The CAD model showed that the center of gravity of the satellite with all components included can easily be made to lie within the area specified by the ICU.
- Overall, the thermal model demonstrated the effectiveness of the software tools we used as modeling tools for thermal and structural space mission design.

Acknowledgements

Our gratitude is extended to all of the people and organizations that contributed time, money and resources to make our project and the University Nanosat project possible. Thanks, especially, to CAR Technologies, for the donation of their software to the project and Prof. Looff for his guidance and encouragement.



Thermal Analysis Design Presentation Poster. This poster won first prize in the WPI Mechanical Engineering senior project capstone competition.

Stability Systems & Analysis

The goal of the stability system design teams was to develop a low power, low mass, low cost and reliable system that could be used to stabilize PANSAT. Specific accomplishments of the various teams that worked on this project included the following.

- reviewed numerous methods for satellite stabilization
- developed a strategy and methodology for comparing and assigning *cost functions* to the various stabilization methods
- after extensive design analysis, MATLAB modeling and a detailed review of candidate stabilization methods, selected a magnetic method that was totally passive
- developed a detailed MATLAB model of the magnetic stabilization method to determine optimum magnet location for desired on-orbit satellite orientation and antenna pointing characteristics
- purchased and tested appropriate magnets for the satellite
- model and select optimal magnet placement in prototype bus structure, mount and test
- verified MATLAB modeling of satellite attitude control expectations

Stabilization Systems

Passive control systems were studied because they would provide stability without the use of mechanisms that require moving parts or power. The lack of complex mechanisms and power to operate functionally make passive control systems very reliable as there are no moving parts to break and power failure will not affect the system. The sacrifice made with high reliability is a lack of pointing accuracy compared to the more complex active systems.

- Gravity gradient stabilization is a method commonly used for low earth orbit (LEO) satellites. This method of passive stabilization takes advantage of the Earth's gravitational field and the gravity gradient torques it exerts. In order for the gravity gradient torques to have an effect on a satellite, the mass moment of inertia about one of the primary axes of the spacecraft must be significantly smaller than the mass moments of inertia about the other two primary axes. The most common method of accomplishing this is through the use of a long boom with a point mass attached at the end.
- Just as gravity gradient stabilization took advantage of the Earth's gravitational field, passive magnetic stabilization utilizes the Earth's magnetic field to align the satellite. Passive magnetic stabilization use one or more permanent magnets placed on the inside of a satellite's bus structure.
- Spin stabilization is defined as the directional stability of a projectile obtained by the action of gyroscopic forces that result from spinning of the body about its axis of symmetry. This method of attitude control is one of the simplest methods of controlling the position and orientation of a spacecraft. There are some basic requirements for spin stabilization to make it work effectively. These are: 1. deployment and spin up, 2. Sun/Earth acquisition, 3. Spin and nutation control, and 4. Vehicle attitude control. Initial deployment is usually achieved with axial separation from the deploying spacecraft using springs.

Active control systems provide attitude control through the use of mechanisms. These mechanisms usually have moving parts and require power and some kind of computer intelligence to operate them. Active control systems, though complex and very sensitive, boast the ability to control spacecraft attitude and positioning to a very fine degree, usually to within 1 degree or less. Active systems are usually desired in spacecraft that require a constant pointing direction and accuracy to enable the use of some onboard equipment.

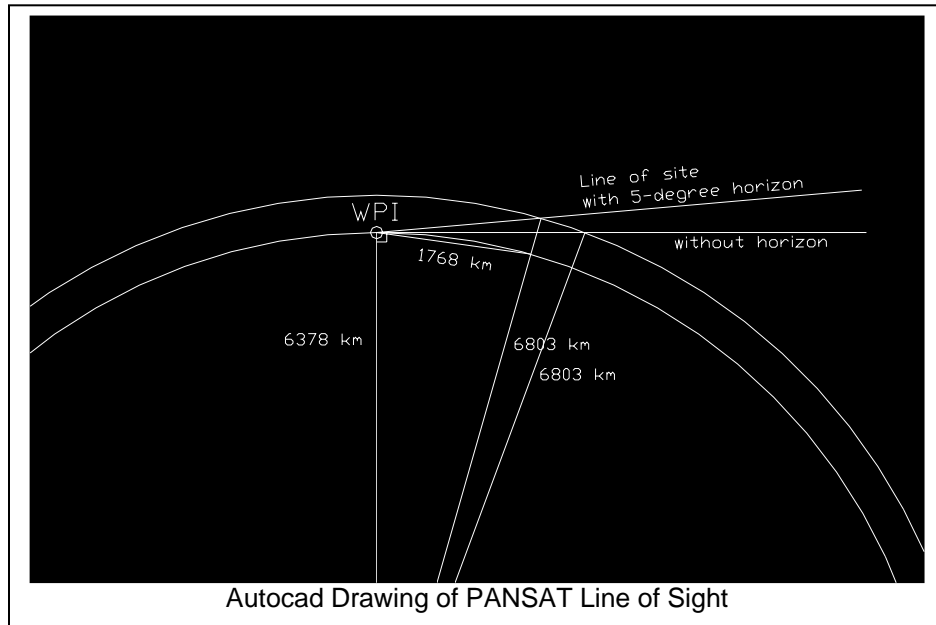
- Known as momentum exchange systems, when spinning, momentum and reaction wheels absorb angular momentum that they create and transfer it to the spacecraft, allowing for attitude and positioning control. Momentum exchange systems allow for very accurate and efficient attitude control. Momentum/reaction wheels, essentially specialized flywheels, operate by spinning at high rates around bearings, which are mounted on the main axis/axes of the spacecraft
- Another way of creating a magnetic torque on the spacecraft by use of the geomagnetic field includes the use of torque rods to create a magnetic moment about the satellite. These torque rods, also known as magnetorquers, are often used as magnetic attitude control actuators for relatively small satellites. A torque rod is an electromagnet that is energized to create a desired magnetic moment by running a current through it.

A value analysis table (below) was developed to compare the different stability control systems.

Stabilization Method	Concept Complexity	Calc. Complexity	Implem.	Power	Cost	Accuracy	Totals
Spin	4.0	2.0	3.0	5.0	4.0	3.0	21.0
Gravity Gradient	4.0	1.0	4.0	5.0	3.5	2.5	20.0
Passive Magnetic	3.5	3.0	5.0	5.0	5.0	4.0	25.5
Momentum Wheel	2.5	1.0	1.0	2.0	1.0	4.0	11.5
Magnetic Torquers	2.5	1.0	3.0	2.0	2.0	4.0	14.5

The method that was chosen for the stabilization of PANSAT was permanent magnet stabilization. This method required a number of permanent magnets to be attached in parallel on the bus structure of the satellite. These permanent magnets interact with the magnetic field of the Earth and force PANSAT to align its z-axis with the geomagnetic field at all times and point the communications antenna towards magnetic north.

In order to determine how close PANSAT will be pointing to the WPI ground station, a number of steps were taken. The first step was to determine the exact view window of PANSAT in terms of Longitude and Latitude. From the summer PANSAT report, it was found that the view window is a circle around WPI with radius 2375 km.



It was discovered by the ACS team that this radius was calculated without considering the 5 degree offset needed to account for the horizon (trees, mountains, etc). Using Autocad and relatively simple geometry, the radius of the view window was determined while taking into account this 5 degree offset. The radius turned out to be $R=1768$ km. Figure 8 shows an example of the Autocad drawings used to help simulate the window.

Using this radius as well as the longitude and latitude coordinates of WPI (42.2N, 71.8W), with the help of an online coordinate/distance calculator, the longitude and latitude of 32 points on the view window perimeter was deduced. The longitude and latitude of 32 points around the perimeters of 4 other circles within the view window were also found (total of 160 points). These circles were also centered at WPI and had radii of $\frac{3}{4}R$, $\frac{1}{2}R$, $\frac{3}{8}R$ and $\frac{1}{4}R$.

The second step in determining PANSAT's pointing accuracy to the ground station was to determine the magnetic field unit vector at the 160 chosen points throughout the window. An online geomagnetic field calculator was used to measure the field 400 km above the Earth's surface at all of these points. The data from this calculator is given in terms of *Inclination* and *Declination* of the field vector. Inclination (**I**) is the number of degrees from the North-East (**X-Y**) Plane that the magnetic field is. The declination (**D**) is the number of degrees East of North the magnetic field is. MathCAD code was written in order to input these two parameters, **D** and **I**, and output the Unit Vector of the magnetic field at any point. The reference frame used for all of the vector calculations is as follows: **X** is geographically northward from any point, **Y** is Eastward from any point, and **Z** is upwards (perpendicular to the Earth's surface) from any point. This MathCAD code also determines the unit vector that is directed from the satellite at a given point towards the WPI ground station, called the Ground Station unit vector.

Finally, the MathCAD code determines the angle, θ , between the magnetic field unit vector and the Ground Station unit vector at each point. This angle, θ , is PANSAT's ground station pointing angle. In addition, the code calculates the angle (ϕ) between the magnetic field unit vector from the Earth's center unit vector (unit vector from PANSAT to center of Earth – always $[0, 0, -1]$). Figure 10 shows the places within the view window that the pointing angle, θ , is 55 degrees, 60 degrees, 65 degrees, 70 and 75 degrees.

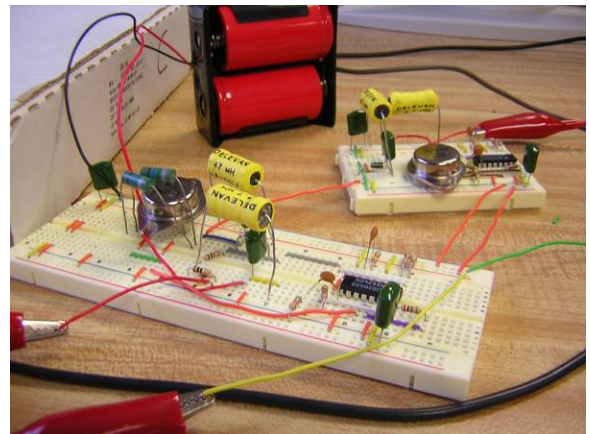
Power Control & Management

The final design of the satellite was a hexagon shaped structure with antennas and sensors on the top and bottom surfaces. It was decided that solar cells would be mounted on each of the six nanosat sides. These cells will be commercially available cells and generate about 5 watts of power on the side that is directly facing the sun (24cm wide x 20cm high area for cell placement, power output de-rated about 30% for off-axis alignment, antenna shadowing, Earth albedo of about 0.3 solar constant, solar constant of $\approx 1358 \text{ W/M}^2 = 0.13\text{W/cm}^2$, $\rightarrow 62\text{W}$ on a hexagonal face, assume 15% cell efficiency and de-rate output, results in about 5W and so forth).

The operation of the nanosat systems will be cycled to manage the state of charge of the batteries. For example, except for mission critical health and safety components all components were designed so that they can be powered down to a minimal current drain state or turned completely off. Also, the communications system was designed to continuously listen for up-link beacons and data while the down-link transmitter can be powered only when a direct and reliable communications path has been established and when sufficient power is available to operate the electronics.

A charging system was designed to insure that the batteries are in their maximum state of charge as long as possible. Further, the charging system was designed to provide both state-of-charge as well as solar efficiency information to the H&S system for power management purposes.

As of January, 2006, a student team is continuing to work on the power system design in an effort to continue to maximize system efficiency, reduce complexity and size, improve reliability and maximize the ability of the system to manage power surges, power control, and system instabilities.



Bench top SEPIC power system
critical component testing



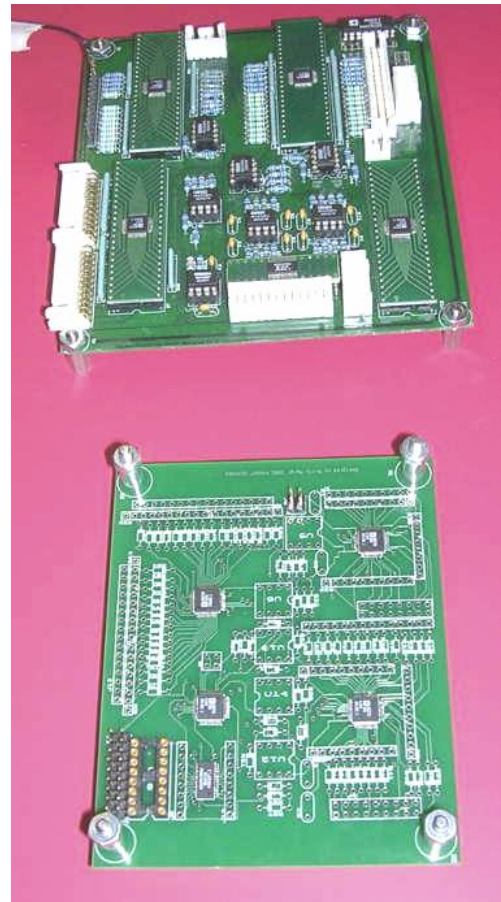
Student team member working on PCB
layout for final power system design.

Health and Safety Systems

The Health and Safety (H&S) system for the WPI Pansat was designed to provide feedback to ground operations concerning both the health of the satellite, as well as whether it was operating in a safe and controllable mode. The system was designed to multiple up to 80 analog sense points representing system voltages (batteries, power systems, solar output, charging system), system temperatures (represented by the voltage out of a solid state temperature sensor), system currents (represented by the voltage output from a series of solid state current sensors), and digital input (state) and output (control) points.

The H&S system was designed to directly interface to a simple, 16b parallel input port and a simple 8b (control) digital output port, both of which were eventually implemented using a standard interface card commonly used by industrial IO controllers.

The full H&S system was prototyped using conventional digital electronic components and then redesigned using high reliability surface mount components. Both products were fully functional. A picture of both H&S systems is shown.



Original (top) and final H&S data acquisition boards.

Magnetometer Instrumentation

The design of the system magnetometer was not a critical design issue. A Honeywell HMR2300 avionic/mil. certified tri-axial solid state magnetic sensor was purchased for use as the Pansat magnetometer. Other than a simple analog interface to the magnetometer (using the H&S analog data acquisition system) no other electronic design issues were encountered.

Magnetometer Boom System

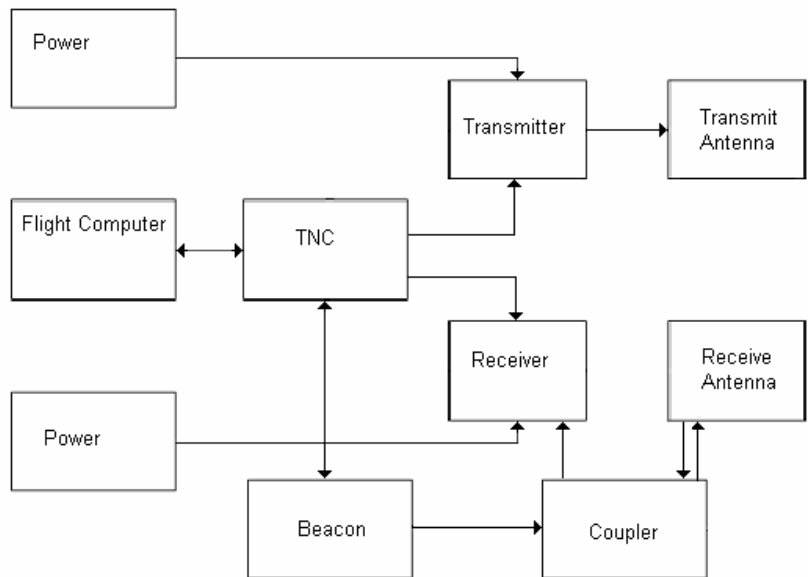
The goal of this project was to design a collapsible/extendable boom system for the magnetometer. As is well know, placing a magnetometer too close to the satellite bus structure or within the bus structure exposes the magnetometer to the magnetic fields generated by the satellite. Therefore a boom was required to place the magnetometer at a safe distance away from the bus structure. Accomplishments included the following.

- researched boom operation, design, safety, extension and structural requirements
- considered numerous methods for boom storage and deployment
- constructed prototype boom deployment system using non-ferrous tape components
- tested prototype boom deployment system

Unfortunately, the mechanical engineering students working on the boom design were not quite up to the task and were not able to demonstrate a fully functional, reliable and well designed boom deployment system.

End to End Satellite Comm. Systems

The goal of this project was to design, implement and test an end-to-end packet radio system that supported up- and down-link of digital data via an interface to the PANSAT flight computer. This was a particularly interesting project since WPI has one of the oldest amateur radio clubs among US colleges, but had no experience what so ever with satellite communications, RF systems and so forth. Regardless, appropriate communication models, receivers, transmitters, coding schemes, communication protocols, antennas, tracking methods and command structure were developed and implemented. The system was based on the use of Amateur Radio frequencies and required cooperation with the AMSAT organization to coordinate appropriate frequency allocations for the PANSAT.



Communications System Block Diagram

The system that was designed will provide end-to-end communications and includes a ground station in addition to the radio communications system to be flown on PANSAT.

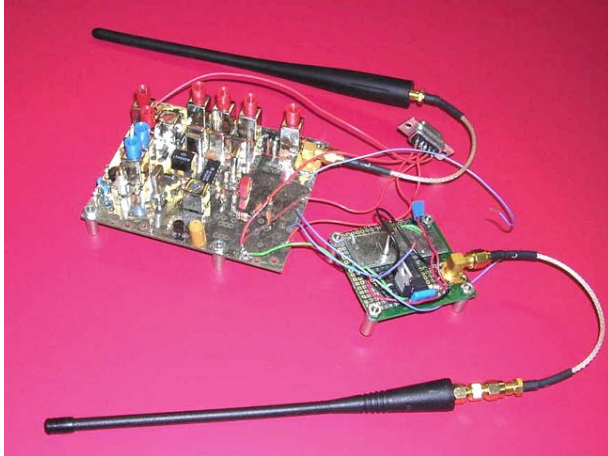
Specific accomplishments included the following.

- researched satellite communications, particularly as they applied to the WPI PANSAT and developed communications requirements document
- designed a complete satellite communications system that would meet the requirements
- selected and purchased system components such as a TNC, transmitters and receivers for the satellite and ground stations
- selected and purchased an amateur radio ground station for satellite communications
- selected and purchased ground antennas, rotors, masts and so forth
- set up a complete end-to-end system for testing components
- demonstrated desired performance levels



Communications system with integrated computer control, tracking system, and antenna pointing control.

- with appropriate path loss insertions, noise corruption and antenna losses
- analyzed the commercial circuit boards for modifications needed to insure proper operation in an LEO environment



Representative communication system components with testing antennas.



PANSAT communications tower with 432 and 140MHz circularly polarized antennas on top of the ECE Building.

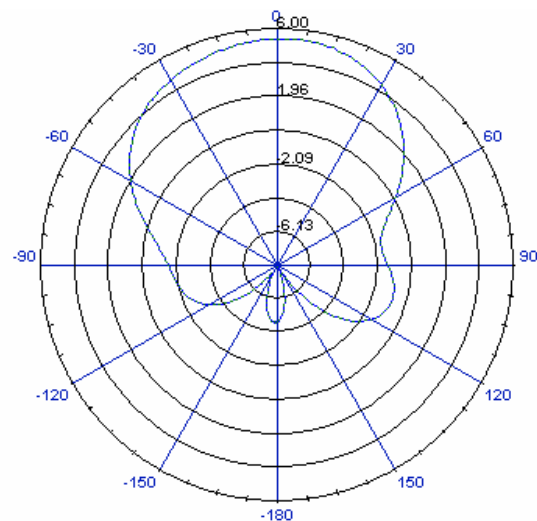
Satellite Patch Antennas

The goal of this project was to design a circularly polarized satellite patch antenna for PANSAT. Because of launch canister restrictions, it was decided early on to design state-of-the-art patch antennas for both receiving, transmitting and if possible the satellite beacon. The two student teams that worked on this project successfully;

- designed and modeled a patch antenna with the desired performance characteristics
- constructed and successfully tested a patch antenna based on the model design

The goal of the specific project design was for a patch antenna with the following characteristics.

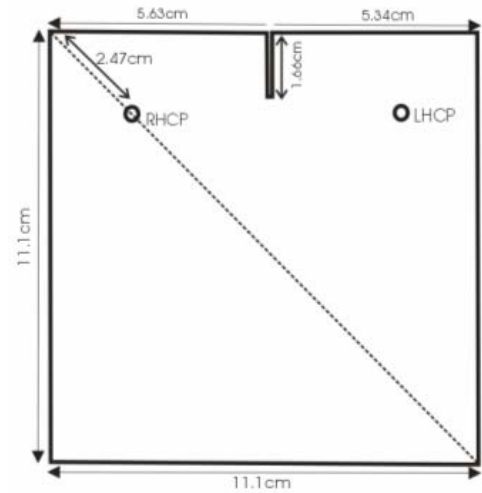
- a gain of 4.0-6.0 dB
- a CP bandwidth of 50 kHz (3 dB axial ratio)
- a return loss of less than -10 dB within the CP bandwidth
- a beamwidth (3 dB) of 90° - 120° .
- a size not exceeding 45cm in any linear dimension (since it had to fit on the top/bottom of the satellite).



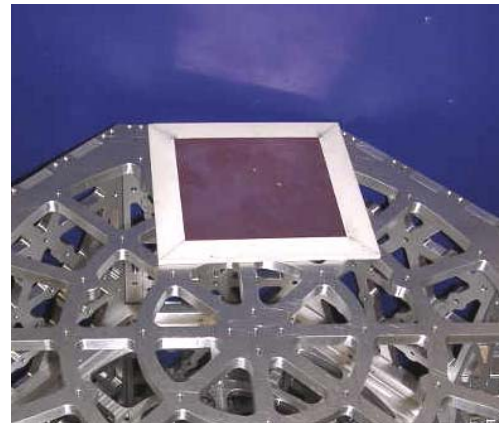
XY Plane Patch Antenna Field Strength Pattern



Professor Robert Labonte' holding two experimental, high performance, wide band patch antennas (140MHz left, 432MHz right).



Patch Antenna Design



Patch antenna mounted on structure for mounting and performance testing.

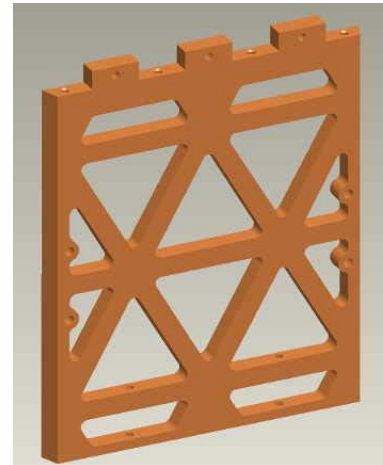
Powder Metals Bus Structure

A primary focus of the PANSAT project has been to determine the feasibility of creating a bus structure using powder metallurgy (P/M) manufacturing. In general, the design of the structure is compatible with the P/M compaction process - for example there are no interlocking tunnels and the wall design is a simple and regular design replicated for both the top and bottom section of each of the satellite walls - therefore making the wall design a perfect candidate for P/M processing.

Subsequent to establishing the practicability of the P/M process, efforts were focused on the choice of powder materials. Data and laboratory testing of P/M dog bones (ASTME standard sized material samples for numerous P/M candidate materials) confirmed the equivalence, and occasionally slightly greater strength of the P/M powders compared to their wrought counterparts, the latter of which are of course acceptable NASA materials for space hardware.

Specific accomplishments of the structure design teams included the following.

- worked extensively with local PM suppliers to obtain aluminum and titanium dog-bones for structural testing
- developed ProE models of the dog-bones for static and dynamic testing
- researched and implemented standard testing procedures for the PM dog-bones
- tested the dog-bones to ASTM standards
- demonstrated acceptable structural stability in the PM dog-bones through laboratory testing
- developed a full frame model of the desired structure
- developed plans for manufacturing a prototype aluminum structure for fit, form and test of PANSAT components
- obtained PM plates for the sides and top/bottom of the structure
- machined from aluminum a full Pansat structure
- machined from PM multiple components of the Pansat structure
- integrated the PM and aluminum components to demonstrate creating a PM bus structure



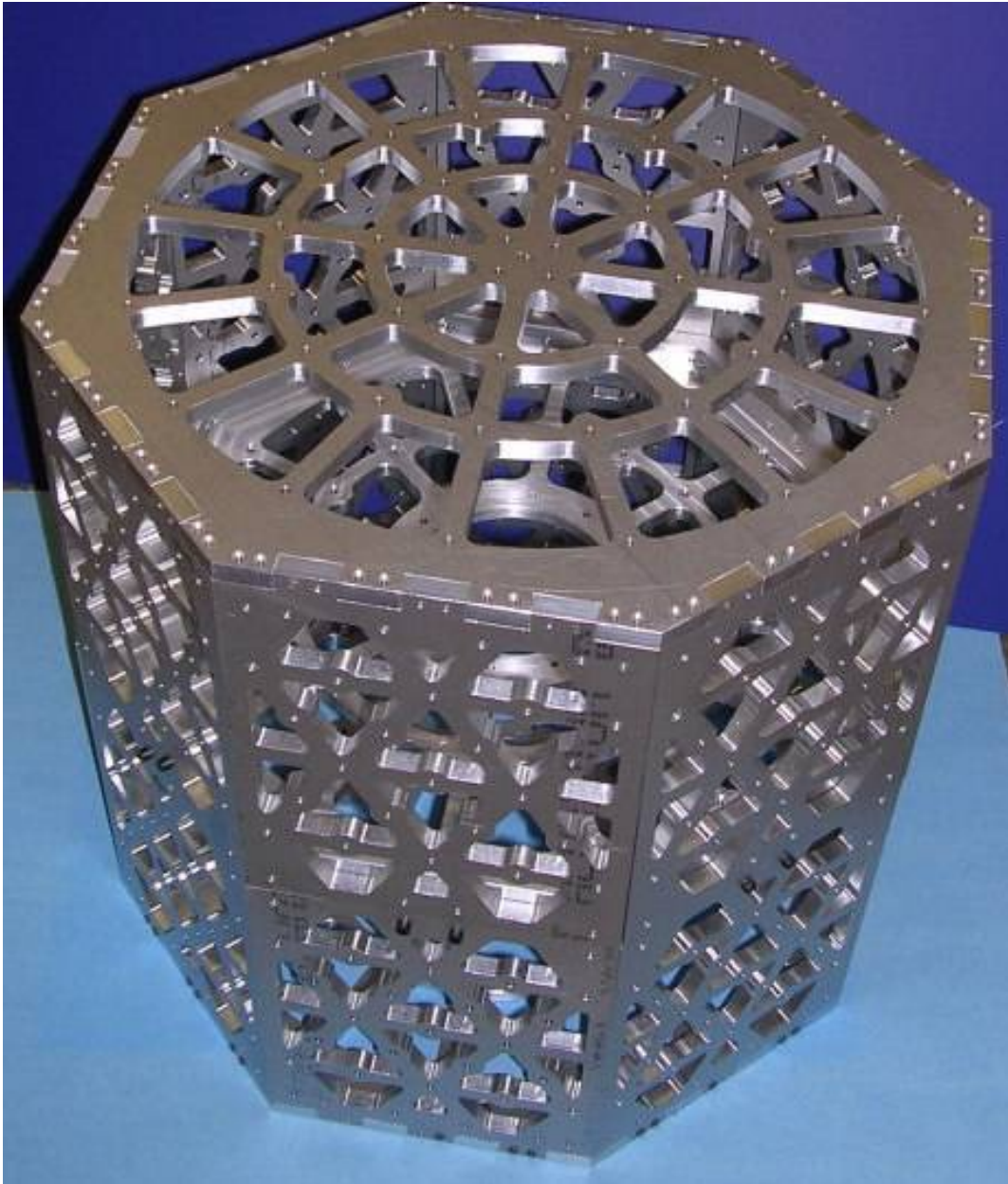
Model structure wall design.

The development of the PM structure, a key technological success of our NS3 project, was supported by the WPI Powder Metallurgy Research Consortium (PMRC). Briefly, the WPI PMRC was formed in 1992 by Prof. Diran Apelian to address the scientific, engineering and management problems of the powder metallurgy (P/M) industry. The center promotes the manufacturing excellence and competitiveness of the P/M industry, by undertaking research programs that are consistent with the priorities of the industry. Research projects are initiated and/or approved by members and are carried out by students and faculty members from a variety of academic disciplines, and are guided by the insights of P/M industrialists.



Structure team with prototype top and bottom plates.

PMRC acts as an independent catalyst for industrial innovation and the exchange of information and ideas in powder metallurgy technology and management. It also serves as an educational center by disseminating research results to consortium members (and, eventually, to the P/M industry at large), and by developing courses and continuing education programs that address the educational needs of the industry. It is important to note that the P/M Center at WPI has ties with over 20 industrial corporations in the P/M industry. The latter enables WPI researchers access to industrial resources, as well as materials.



Fully assembled, ~25% PM Pansat structure.

Satellite Processor System

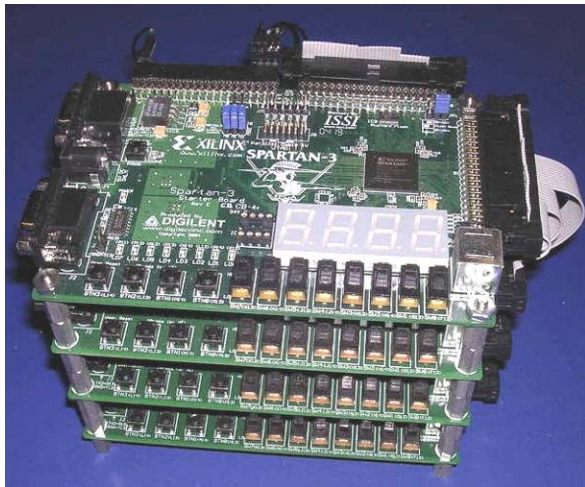
Early on the WPI team decided to research and develop a reliable, low cost, open source processor system for space flight applications. As a result, the goal of this project was to research, design, develop, build and test a triple-modular-redundant (TMR) flight computer that exhibits high reliability in LEO. As a back up, a standard bus computer was also purchased and developed since it was expected that the TMR would take a significant amount of time and effort to get to a fully functional state.

To date, the accomplishments of the student TMR teams have been as follows.

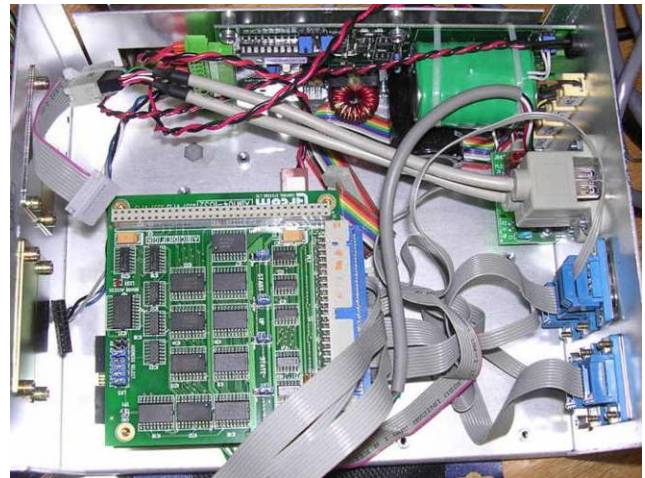
- researched TMR designs and existing LEO small-sat flight computer systems
- selected a processor architecture (XScale)

- developed a detailed system design
- developed a detailed circuit design and a high reliability voter design
- designed and tested voter circuit operation
- developed a PIC processor TMR demonstration system as a proof-of-concept prototype
- developed a portion of the PCB that would be used to implement the TMR design
- redesigned the TMR to be based on a multiple processor, VHDL FPGA implementation with each processor module and memory controller implemented in a Xilinx FPGA.

The design of the TMR is still on-going because of the system complexity. However, the project has been a worth while investment in time and effort, has led to several student team projects, and is not being recast as a MS thesis for one student who is continuing the TMR design as his MS thesis work next year.



Original TMR prototype implemented on Xilinx FPGA development boards.



Mono-processor satellite test and backup system.

GPS Navigation and Orientation System Design

The goal of the GPS Navigation and Orientation System project was to develop a GPS based navigation and orientation determination system for PANSAT. The idea was to use a set of three GPS receivers and three GPS antennas on a very short baseline to determine the orientation of the satellite. Determining orientation using multiple GPS receivers is not unknown, and in fact is relatively easy to do provided one has a long baseline between the individual GPS antennas. What made this project difficult was that the baseline of the three GPS antennas was very short, in fact significantly shorter than any baseline length used in any previous GPS based orientation determination system.

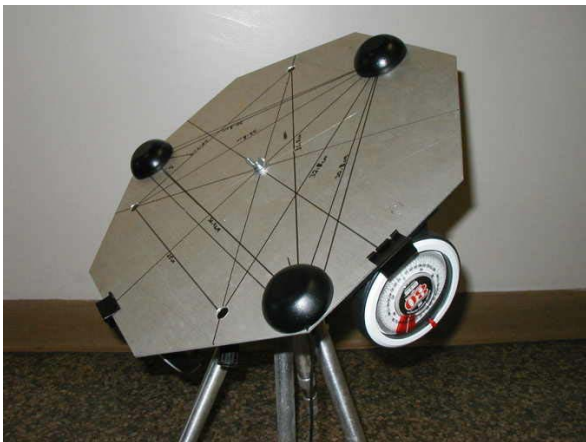
Regardless, the specific accomplishments of the students who worked on this project were as follows.

- researched and developed a system design document that addressed desired navigation and orientation accuracy requirements
- developed a complete navigation system design
- selected, purchased and tested GPS receivers

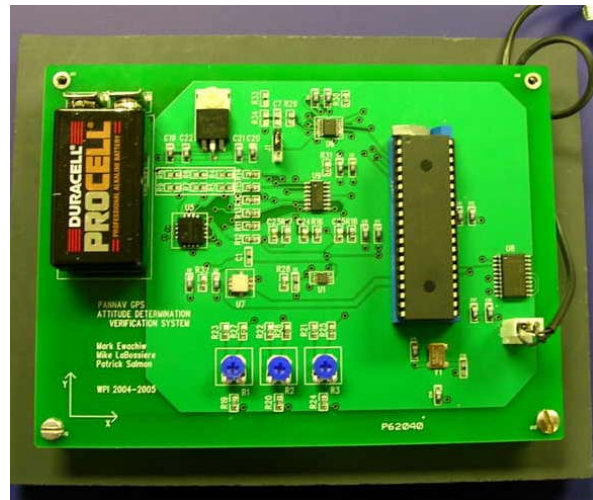
- researched and developed a MATLAB-based Kalman filtering algorithm to improve the accuracy of the navigation system data
- successfully demonstrated Kalman filter ability to improve navigation accuracy
- developed prototype PCB for navigation system GPS receivers
- flew a successful demonstration prototype of GPS components of the navigation system during the SHOT II high altitude balloon payload flight workshop in June 2004.



Flight prototype x3 GPS receiver and integration board.



GPS antenna test fixture.



GPS attitude determination test board.

Picosat

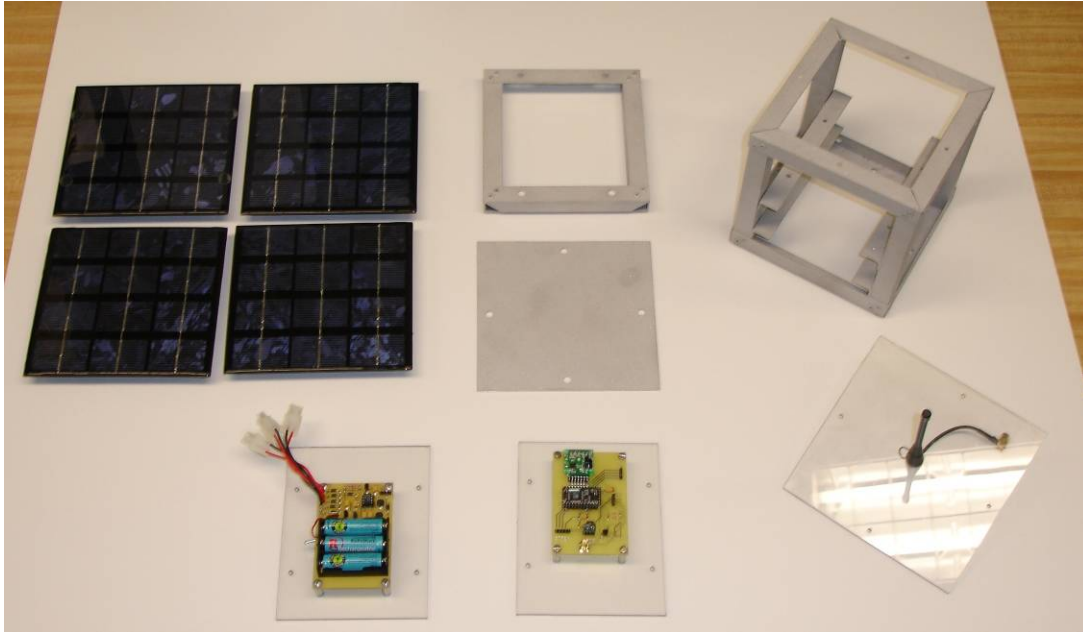
The objective of the Picosat project is the construction of a low cost proof of concept satellite with instrumentation for magnetic field readings and wireless transmission capability. The design of this demonstration (non-flying) satellite was undertaken as part of continuing projects under the PANSAT umbrella, but not supported by the NS3 program. The idea was to use some of the technology developed for PANSAT in the design of a pico-satellite as a technology demonstration project.

Overview

The first step in the project was component research and selection. The main purpose of the satellite is magnetic field readings, so a three-axis magnetometer was sourced from PNI Corporation because of its small size and low cost. The magnetometer requires a processor with an SPI bus for communication. This led the group to select a BasicX-24 processor to handle magnetometer communication as well as voltage and temperature monitoring tasks onboard the satellite. Finally, a simple 433 MHz AM transmitter/receiver pair was selected for one way communication between the satellite and the base station. Since this project is only a proof of concept, longer range communication is not necessary. The base station needed a display for output, so a combination LCD screen/BasicX-35 processor module was chosen. A 16 key keypad was chosen for use on the base station so that a user interface could be programmed.

After the desired components were selected, design work began on a power system. The satellite has exterior solar panels, so the power system design must properly adjust the voltage from the panels to operate the 5V instrumentation. The power system also features a battery system to allow the satellite to operate in low or no-light situation. From the components listed above, it was calculated that the power requirements for the satellite, ignoring any converter efficiencies, would be around 30 mA at 5V. A power system was designed that utilized a trickle charge system for three AA size NiCad batteries. A boost converter was implemented to step up the battery voltage to the desired 5V. This power system operates with an experimentally determined efficiency of 79%. The base station can operate either from an AC wall adapter, or from six AA size batteries.

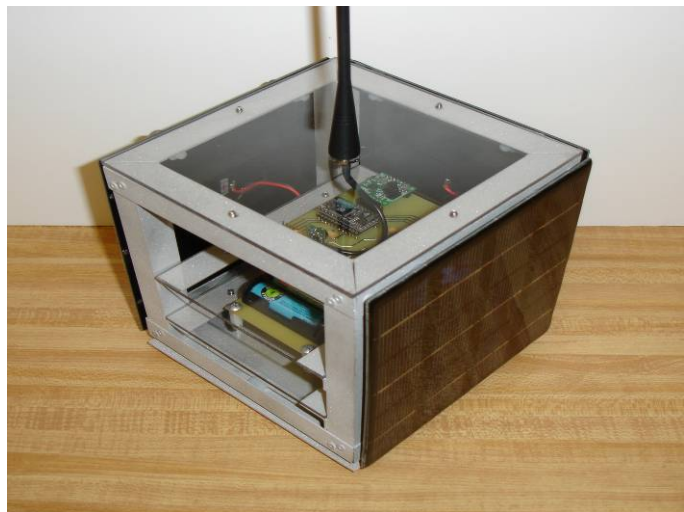
The physical construction of the satellite frame was ongoing through the whole design process. A simple box design was chosen, with aluminum square and angle stock being utilized to outline the frame. The frame is comprised of square aluminum uprights with angle aluminum top and bottom caps. Solar panels are affixed to three sides with nylon bolts that pass through holes drilled through the angle aluminum top and bottom frame rails. An aluminum bottom plate was machined to allow attachment of a hanging point for balloon testing, and a clear polycarbonate top plate was also machined for mounting of an antenna and visual appeal. Internally, two sets of rails were mounted. Each set of rails is tapped to accept a sheet of polycarbonate attached with machine screws. These sheets serve as mounting boards for two PCBs. One PCB holds the entire power system, including batteries, while the other holds the magnetometer, processor, transmitter, and a temperature sensor. The PCBs are mounted on standoffs, which screw into the polycarbonate cards. The entire satellite, with three solar panels affixed, weighs 3 pounds, 4.4 ounces. The final project parts are shown below in disassembled form.



Picosat Components

The solar panels used can be seen in the top left corner. The satellite frame is at the top right. The square component at the top center was used as a guide for attaching bolts to the solar panels. Directly below the guide is the aluminum bottom plate. The polycarbonate top plate can be seen in the bottom right corner, with antenna attached. The circuit board on the left hand side is the power supply, with pigtails for each solar cell. The circuit board on the right is the system board, with the magnetometer, processor, and transmitter.

Construction of the base station box was also an ongoing project. The group began with a project enclosure with an angled top. An aluminum faceplate was originally provided, but that was scrapped in favor of a custom machined polycarbonate plate. Mounting holes were made in the faceplate for a power switch, the keypad, and the LCD display. Mounting holes were also tapped in the bottom of the box for a polycarbonate sheet used to hold the batteries. A small circuit board is also mounted on the bottom of the box on standoffs. The board allows a place for power distribution to take place, and it also provides a mount for the receiver module and the SMA jack for the antenna. A serial port is also provided on the back panel for reprogramming the processor without removing it from the system. The completed unit is shown below.



Fully assembled Picosat.

The final design step was software design. Due to restrictions on the built-in SPI bus on the BasicX-24 processor, the group was forced to code in our own SPI protocol. This enabled the processor to receive raw magnetic field data from the magnetometer. The processor then performs trigonometric operations on the field data to produce a compass heading in degrees, as well as a general reference direction: north, south, east, or west. The processor monitors the battery and solar panel voltage of the power supply, and also monitors a temperature sensor mounted on the system board. All of this data is processed into packets, and sent to the transmitter. The data is transmitted using a group-designed protocol that transmits a known pattern for receiver to lock on to. When the BasicX-35 processor in the base station receives the header packet, it uses a set timing schedule to read bits of data into memory. Once a packet is received, the processor displays the received information



on the LCD screen. Multiple screen modes have been programmed, so that the display can show heading data, power supply data, packet rate data, and other useful indicators.

The satellite construction is currently finished. The project team is working on testing to assess the effectiveness of our design choices. We are also changing processor code to add features and gather data for testing. All of this information will be used to write the final report, which will cover all of the design choices made and the results in much greater detail.

4. Personnel Supported

No faculty, post-docs or graduate students were supported on this grant. Only undergraduate students were supported during summer program and project development work.

5. Publications

All student teams were required, by standard WPI capstone project rules, to make formal presentations and to write detailed project reports addressing their project designs, methods and so forth. A list of completed projects is provided below. **All publications are available from the WPI Library.**

1. Matt Benvenuti, Nate Cambray, Anand Jagannath, Matt Romano “PANSAT Attitude Control and Deployment Systems” R. Labonte’ (ECE)
2. Chuan Huan Hu Michael Swartz, Stephen Aaron “Pansat ACS Boom Design” F. Looft (ECE)

3. Patrick Gaw, Michaels Martin, Nathan Bradley, Prity Patel “Remote Computer Data Acquisition for Satellite” F. Looft (ECE)
4. Dale Ames “Pansat: A Powder Metal Nanosatellite” F. Looft (ECE)
5. Ryan Angilly, Dan DeBiasio, Mitch Lauer “PANSAT TRiple Modular Redundant Flight Computer” F. Looft (ECE)
6. Himanshu Agrawal, Andrew John Coonradt, Joshua Holwell “GPS Navigation Subsystem for PANSAT” F. Looft, W. Michalson (ECE)
7. Gunnari Auvinen, Tiffany Tam, Bandar Turkmani “Control Loop for the PANSAT Power Subsystem” R. Labonte’ (ECE)
8. Jonathan Mulla, Robert Trotte “PANSAT Communications: Link Budget Verification”, R. Labonte’ (ECE)
9. Jared Lindros, Brian O’Donnell “PANSAT Communications System for a Satellite” R. Labonte’ (ECE)
10. Matt Kwiatkowski, Maulin Patel “Developing a TMR Satellite Flight Computer” F. Looft (ECE)
11. Chris Moller “PANSAT: Power Metal Structure Design for Nanosat” F. Looft (ECE)
12. Craig Gendron “Circularly Polarized Dual-Feed Patch Antenna” S. Makarov (ECE)
13. Matt Benvenute “PANSAT Attitude Control and Deployment Systems” F. Looft (ECE)
14. Brandon Gillet, Paul Messier, Christian Shetler “Pansat Power Subsystem”, F. Looft (ECE)
15. Mark Ewachiw, Mike LaBossiere, Patrick Salmon “GPS Navigation Subsystem for PANSAT” W. Michalson (ECE)
16. Andrew Marut “MATLAB Interface to a Patch Antenna Simulator” S. Makarov (ECE)
17. Andrew Hermann, David LaVenture-George “Remote Data Acquisition for a Small Satellite” F. Looft (ECE)
18. Kate Farb-Johnson “PANSAT Power Subsystem” A. Emanuel (ECE)
19. Nobel Mathew, Nobel, Mahima Sethi “Circularly Polarized Single-Feed Patch Antenna” S. Makarov (ECE)
20. Nate Chenarak “Pansat Simulation” F. Looft (ECE)
21. Muhammad Assad, Isaac Waldron “Communications Systems for a LEO Satellite” F. Looft (ECE)
22. Omar Moussa “TREMOR - Triple Modular Redundant Computer Rev2” W. Michalson (ECE)
23. Kyle Fuller, Sidhart Rupani “Thermal Analysis and Design of the WPI PANSAT” F. Looft (ME)
24. David Belliveau, Catherine Price “Powder Metallurgy Structural Design” D. Apelian (ME), F. Looft (ECE, ME)

6. Interactions/Transitions:

Presentations at meetings, conferences and seminars is described, indirectly, in section 2. Since this was not a research project, the students did not present at conferences or seminars. We did, however, present at the SDR, PDR and so forth.

WPI did not providing consulting services to any other laboratory or agency as part of this grant.

Other than some internal technology transitions where certain designs and information have been used internally on student projects, there have been no technology transitions involving work completed within the context of this grant.

7. New Discoveries

A patent was applied for concerning the new voter architecture for our TMR processor.

8. Honors and Awards

Ryan Angilly, a May 2004 graduate from WPI was the winner of the 12th Annual Frank J. Redd Student Scholarship Competition. Angilly presented a paper that described an FPGA multiple processor architecture that uses hardware redundancy to guard against processor faults due to the radiation environment found in Low Earth Orbit (LEO). Angilly's paper was entitled: TREMOR: A TRIPLE MODULAR REDUNDANT FLIGHT COMPUTER AND FAULT-TOLERANCE TESTBED FOR THE WPI PANSAT NANOSATELLITE. TREMOR uses an architecture known as Triple Modular Redundancy to achieve radiation and high energy particle logic upset tolerance. Angilly discussed the TREMOR FPGA system and how it will be used to synchronize the processors and ensure that no erroneous data propagates to the system bus. Angilly also discussed how the flexibility of this design will allow TREMOR to become a new test bed for various implementations of the TMR architecture.

WPI Provost's Senior Project Awards

- First Place - Isaac Waldron '04 and Muhammad Assad '05 "COMMUNICATIONS SYSTEM FOR A LOW-EARTH-ORBIT SATELLITE" Advisors: Professors Robert C. Labonte' and Fred J. Looft
- Second Place - Andrew Coonradt '04, Joshua Holwell '04, and Himanshu Agrawal '05 "GPS-BASED ORBIT AND ATTITUDE DETERMINATION SYSTEM FOR PANSAT" Advisor: Professor William R. Michalson

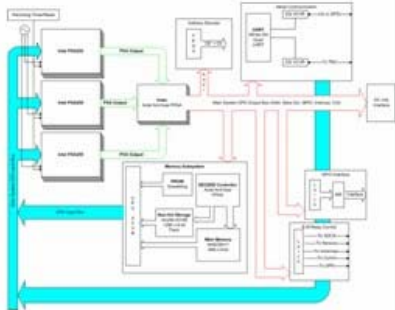
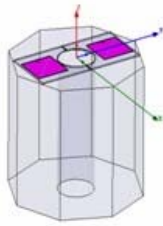
Other Awards

- The PANSAT Attitude Control project team, advised by ECE Professors R. Labonte' and F. Looft, took 1st place for the ME department Senior Project awards.
- The GPS team won the first prize and the TMR team won the third prize at the NE-ASEE 2004 Student Paper Contest Capstone Design Experience Session at Northeastern University.
 - GPS Navigation MQP (Advisor: Prof. Michalson) - Josh Holwell, Andrew Coonradt, Himanshu Agrawal
 - TMR and UniProcessor MQP (Advisor: Prof. Michalson) - Ryan Angilly, Mitch Lauer, Dan Debiasio

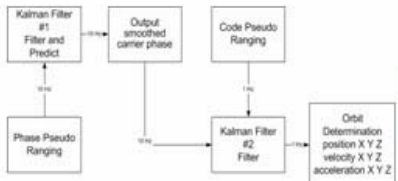
9. Summary

WPI did not "win" the Nanosat 3 competition. However, we are more than pleased with our efforts to develop a very state-of-the-art satellite with advanced features such as a TMR, patch antennas, totally passive magnetic stability system and other technology developments. What are also proud of the fact that we trained about a large number of students in various aspects of space flight systems and spacecraft development. We are more than satisfied with our program performance and look forward to competing in the future.

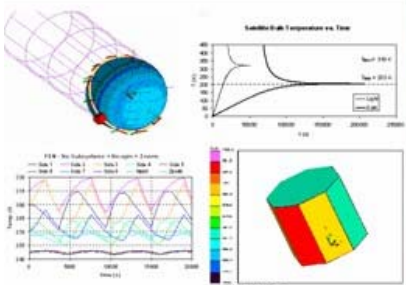
Dual patch antenna placement for modeling and testing.



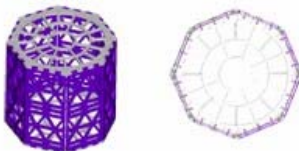
Triple Modular Redundant (TMR) computer block diagram.



Kalman filter processing for GPS navigation data analysis.



Thermal modeling and analysis results for a block octagon PANSAT model.

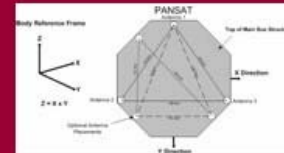


Octagonal isogrid bus structure design based on powder metallurgy isogrid side-wall building blocks.



2003 WPI / GSFC Program Participants

The Goddard Space Flight Center Projects Program is a sequential project center where students satisfy their senior design requirements in one team of intensive project work. Several projects completed at the Center support the work of the WPI PANSAT program. Recent and ongoing projects have included the analysis, selection and identification of orbits for specific mission profiles; the use of STE for on-orbit satellite behavior analysis and systems modeling; the development of a balloon payload data acquisition system for SIMulated SATellite (SIMSAT, similar to SHOT workshop) flights; and using MATLAB/SIMULINK to model the dynamic and static behavior of a satellite.



GPS Antenna Placement Test Configuration



2003 PANSAT Team Members

PANSAT Mission Statement

The WPI Nanosat Projects Program is focused on designing and building a fully functional and innovative nanosat that includes significant educational and scientific objectives. This project program is supported by a grant from the Air Force Office of Scientific Research through the AIAA Nanosat-3 Program and involves students in the departments of Electrical and Computer Engineering and Mechanical and Aerospace Engineering. For further information, contact Fred F. J. Leoh (fleoh@ece.wpi.edu) or R. C. Labonte (rc@ece.wpi.edu).

Specific Mission Objectives

- Use GPS to determine satellite orientation, position and velocity
- Prove that powder metallurgy is an acceptable technique for fabricating low-cost satellite bus structures

Technology Demonstration

- Develop a TMR flight computer from COTS parts for nanosat use.



Team Meetings



SHOT workshop participants...

... and SHOT balloon picture.



WPI PANSAT Laboratory Door Poster

Appendix A - Faculty

Further details on any specific project can be requested from the following PANSAT program managers.

Professor Fred Looft

PI, sensors, structures, magnetometer, thermal, orbital model, summer advising

Professor Diran Apelian

structures

Professor William Michalson

TMR, communications systems

Professor Sergey Makarov

patch antennas, ground antenna

Professor Alex Emanuel

power system, power distribution, solar voltaics

Prof. Robert Labonte

communications, magnetometer, antennas



2004 Pansat Project Team members.

Appendix B - Students

Electrical and Computer Engineering Students

Agrawal, Himanshu
Assad, Muhammad
Benvenuti, Matt
Coonradt, Andrew
Ewachiw, Mark
Gaw, Patrick
Herman, Andrew
Jagannath, Anand
LaBossier, Michael
LaVenture-George, David
Mathew, Nobel
Michaels, Nathan
Mulla, Jonathan
Patel, Maulin
Patel, Prity
Sethi, Mahima
Tam, Tiffany
Turkmani, Bandar

Angilly, Ryan
Auvinen, Gunnair
Chenarak, Nathan V.
DeBiasio, Daniel E
Farb-Johnson, Kate
Gillet, Brandon
Holwell, Joshua
Kwiatkowski, Matthew
Lauer, Mitchell
Lindros, Jared
Messier, Paul
Moussa, Omar
O'Donnell, Brian
Paquette, Joshua
Salmon, J. Patrick
Shetler, Christan
Trotte, Robert
Waldron, Issac

Mechanical and Aero Engineering Students

Belliveau, David
Christopher Moller
Fuller, Kyle
Price, Catherine M.
Rupani, Sid

Cambray, Nathaniel
Ames, Dale
Michael Hu
Romano, Matthew
Stephen Swartz