ASUSat1: The Development of a Low-Cost Nano-Satellite

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ABSTRACT

In October 1993, the students at Arizona State University (ASU) were challenged by Orbital Sciences Corporation to develop a 4.5-kg (10-lb) satellite (ASUSat1) to be launched as a piggyback payload on a Pegasus rocket. The challenge also included the requirements for the satellite to perform meaningful science and to fit inside the Pegasus avionics section (0.033 m^2 X 0.027 m). Moreover, the students were faced with the cost constraints associated with university projects. This unusual set of requirements resulted in a design and development process, which is fundamentally different from that of traditional space projects. The spacecraft capabilities and scientific mission evolved in an extremely rigid environment where cost, size and weight limits were set before the design process even started. In the ASUSat1 project, severe constraints were determined first, and then a meaningful scientific mission was chosen to fit those constraints. This design philosophy can be applied to future satellite systems. In addition, the ASUSat1 program demonstrates that universities can provide an open-minded source for the innovative nano-spacecraft technologies required for the next generation of low-cost missions, as well as an economical testbed to evaluate those technologies. At the same time, the program provides hands-on training for the space scientists and engineers of the future.

1.0 INTRODUCTION

Giving students the opportunity to apply what they are learning in class and to learn more with hands-on experience is a tremendous asset. Open-ended design projects allow students to design, analyze, build, test and use a final functioning product through a team effort. This type of project mimics how engineering industry operates in many ways, which is rare to see at a university level. In addition, industry is becoming more inclined to sponsor these types of projects because they see the new ideas developed by the students. This type of industry involvement also gives industry a sneak peak at future employees.

Recently, the space community has been faced with new constraints, lower budgets, shorter design times, etc, which has led to the smaller, faster cheaper philosophy. University satellite programs start the students off in the right direction by teaching them how to design as inexpensively as possible and not designing to cost. These programs also teach the students to think smaller and lighter and always question the so-called best ways of doing things. This allows the student to come up with new ideas that tightly fit the requirements of the project at hand.

1.1 Three-Year Journey

In October of 1993, a student/professor team met with Scott Webster from Orbital Sciences Corporation (OSC) to discuss the possibility of OSC launching a student satellite. OSC agreed to launch a small satellite on their Pegasus rocket that would perform meaningful science, weigh under 13 pounds (including the release mechanism), and fit within an envelope of 31 cm in diameter and 26 cm in height. The team, who started the work immediately, willingly accepted this challenge.

With the given constraints from OSC, ASUSat1 would be designed to be one of the lightest satellites ever to do valuable science. The size and

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weight restrictions eliminated many commonly used techniques, adding another dimension of technology demonstration to the project. Due to weight constraints, active control, radiation shielding, large battery packs, aluminum structures, and many complex mechanisms were eliminated from the design. Also with the minimal power that could be generated from the small surface areas, only the lowest power consuming devices could be used onboard the satellite.

The initial design was for a 450-km altitude, 6am-6pm, sun-synchronous orbit. Though a large portion of the satellite was technology demonstration, the science of the mission was to collect particles and measure the flux, temperature, mass and velocity of these particles in this low earth orbit (LEO). The student-designed device to be used for this mission was named the Micro-particle Recognition Experiment (MRE)[1]. This device consisted of a composite parabolic dish that was covered with a pyro-electric polyvinylidine fluoride (PVDF) film to characterize the particles. The satellite was a cylindrical structure made of a carbon-fiber composite. The design also incorporated a gravity-gradient boom and a composite solar-array panel. After about a year into the design, a firm launch emerged, changing the orbit for which this preliminary satellite was designed.

The new launch opportunity was a 325-km altitude, 6am-6pm, sun-synchronous orbit. Though already in the testing stages, the MRE was found to be unusable at the new orbit due to the high levels of atomic oxygen. At this stage of the program, few components had been completed, so redesign around a new science experiment was acceptable. The new science that emerged was a study of the ionospheric plasma environment found in the highest layers of the atmosphere. This new experiment named the Ionospheric Plasma Research Experiment (IPRE)[2] was expected to test Hall accelerators using the atmospheric plasma. This new design also incorporated two CMOS (Complementary Metal-Oxide Semiconductor) cameras, one looking directly at earth and one looking at the horizon. These cameras would work as a secondary source of attitude determination.

The new low-altitude orbit also changed the dynamics of the mission drastically due to aerodynamic drag. The pendulum concept with a gravity-gradient boom could no longer be used, so it was replaced with a weather-vane-type concept, which used an aerodynamic boom to stabilize the satellite. Due to the lack of roll control of the new orbit, body-mounted solar cells were implemented and the structure changed to a 14-sided cylinder.

The IPRE experiment would be abandoned with the emergence of a new Pegasus launch at 550-km altitude, 10:30am-10:30pm, sun-synchronous. The ion content at this new altitude was too sparse to continue with the IPRE and the satellite was far too advanced for major design changes. Thus the mission was refined to one of earth imaging, technology demonstration and a voice repeater for the amateur radio community. With the removal of the IPRE, larger cameras with higher resolutions could replace the previous, low-resolution, CMOS cameras. The new design also incorporated another battery pack, more Gallium Arsenide (GaAs) solar cells, a spherical fluid damper, and a torque coil.

The fall of 1996 brought about another new mission at 778 X 790 km with an inclination of 108 degrees and a launch in Fall of 1997. The orbital environment of this new mission did not change too drastically from the previous mission, but the launch vehicle changed to the more acoustically severe Taurus. With the modular design of the 550-km altitude mission, ASUSat1 needed only minor changes to cope with the new orbit. This newest version of ASUSat1 is the one described in this paper.

2.0 SUBSYSTEMS

2.1 Systems

The ASUSat1 team is made up entirely of students, supervised by Dr. Helen Reed and sponsored by industry and the government. The multi-disciplinary project consists of engineering students from all backgrounds and class levels at Arizona State University. The team is divided into subsystems consisting of Systems, Structures, Dynamics, Power, Thermal, Communications, Commands, Science, Ground Support (GSE), Software, and Deployment. These subsystems each have a leader and each meet separately once a week. All satellite members also attend a general meeting once a week, which is run and organized by the program manager. The Systems team, made up of the program manager and the leaders, is responsible for enforcing weights, costs, volumes, power, and other constraints that must be met by the project. The Systems team is also in charge of integration of subsystems within the satellite and with the launch vehicle. The systems of each of the subsystems teams are described below.

2.2 Science

To fulfill the mission characteristics of earth imaging, the science package consists of two Dycam cameras. The Dycam modular camera system is essentially a camera electronics board that takes one picture at a time and transfers it to the commands board upon request. With each camera having its own processor and memory (1 Megabyte apiece), they are capable of automatically compressing the images and storing them until they are ready to be downloaded to the commands board.

The two cameras are daisy-chained inside a single compact anodized aluminum housing measuring approximately 2in. x 2.5in x 6.5in and weighing close to 14 ounces. This is bolted to the bottom bulkhead and L-bracketed to the top bulkhead and panel 14. Each camera uses only 5 volts and will operate in a sleep mode for most of the time drawing only 3.5mA (See Figure 1). During wake mode, the cameras use 125mA and will spike to roughly 650mA for about 15 milliseconds during the image capture.

Each camera has a resolution of 496 x 365 giving a clarity of approximately 0.7km/pixel at an altitude of 780km. The first camera is color and has the ability to pick up the visible red and near infrared (NIR) spectrum at approximately 600nm - 800nm. The second camera will be a gray scale and will employ the use of a short pass filter in the visible blue spectrum picking up the wavelengths between 420nm and 550nm.

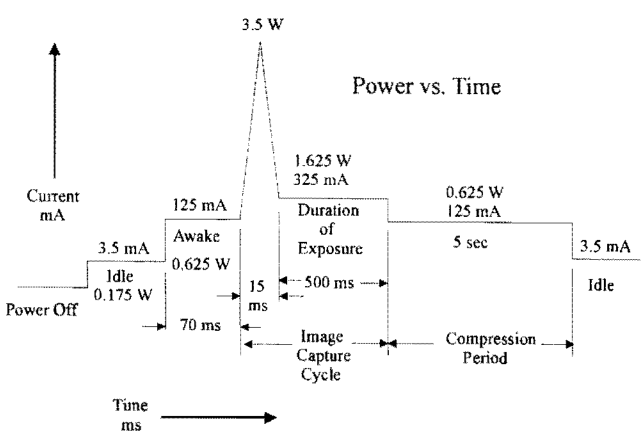

Figure 1: Camera Power Usage

With the aid of various departments at Arizona State University, image applications will vary from the main function of vegetation indexing to coastal mapping and cloud analysis.

2.2.1 Vegetation Indexing

The reason that plants look so green is not because they are reflecting a lot of green light, but because they are absorbing so much of the rest of the visible light. The cells in plant leaves are very effective for scattering light because of the high contrast between the index of refraction in the water-rich cell contents and the intercellular air spaces. Vegetation is very dark in the visible spectrum (400nm-700nm) because of the high absorption pigments which occur in leaves i.e. chlorophyll, xanthophyll, etc. There is a slight increase in reflectivity around 550nm (visible green) because the pigments are least absorptive there. There is no strong absorption in the spectral range 700nm-1300nm, hence plants appear very bright.

A vegetation index is a number that is generated by some combination of these spectral ranges that have some algebraic relationship to the amount of vegetation in a given image pixel.

For the data to best show vegetation, it is necessary to take the ratio of two different band lengths in order to minimize albedo effects and atmospheric noise. Essentially a band where vegetation is bright on top of the ratio, and a band where vegetation is dark on the bottom, is needed. Thus the first camera contains a red pass filter which picks up the visible red and NIR bands where vegetation appears bright and the second camera has a 550 nm short wave pass filter which makes vegetation seem dark.

Also the spectral sensitivity of the second camera (420nm-600nm) allows for further applications such as coastal mapping, water-body penetration, forest mapping, and deciduous / coniferous differentiation.

An assumption made by the vegetation indices is the idea that all bare soil in an image will form a line in spectral space. The soil line is a hypothetical line that describes the variation of bare soil in the image. The line can be found by locating two or more patches of bare soil in the image having different reflectivity and finding the best fit line in spectral space. Nearly all the commonly used vegetation indices are concerned with red and NIR space, thus a red-NIR line for bare soil is assumed. This line is considered to be the line of zero vegetation. Isovegetation lines, or lines of equal vegetation, converge at a single point for the indices we will be using. These indices measure the slope of the line between the point of convergence and the red-NIR point of the pixel.

RVI is the most widely calculated vegetation index. Essentially it is a ratio of NIR to red.

RVI=NIR/red

- ratio-based index
- isovegetation lines converge at origin
- range goes from 0 to infinity

NDVI is the Normalized Difference Vegetation Index. This index varies between -1 and 1. RVI and NDVI are functionally equivalent and related to each other

NDVI=(RVI-1)/(RVI+1)
NDVI=(NIR-red)/(NIR+red)

- ratio-based index
- isovegetation lines converge at origin
- range goes from -1 to 1

IPVI is the Infrared Percentage Vegetation Index. It is restricted to values between 0 and 1, which eliminates the need for storing a sign for the vegetation-index values, hence improving calculation speed. IPVI and NDVI are also functionally equivalent and related to each other.

IPVI=(NDVI+1)/2
IPVI=NIR/(NIR+red)

- Ratio based index
- Isovegetation lines converge at origin
- Range 0 to +1

2.3 Structures

New ideas are used on ASUSat1 to allow for a structure that is proven strong enough to withstand the Pegasus harsh acceleration loading and acoustics during launch, and still meet the tight 2.25-pound structural-weight budget. The structural design consists of a full monocoque composite structure that holds all components within a 25 X 32 cm diameter envelope (Figure 2). The 14-sided structure is capped off with two composite bulkheads, one being fixed and the other acting as a removable lid. The fixed bulkhead is recessed 4 cm from the lip of the body to allow for components such as the damper to be mounted on the exterior of the structure. The removable bulkhead is mounted flush with the opposite lip of the bus with 12 bolts and locking-nut plates. Located within the structure are two component panels carrying all of the electronics. These panels can slide in and out of the structure with the removal of the top bulkhead. The modular design allows for easy access to all components during assembly and for removal if necessary. All five of these structural parts are made of a 12-layer lay-up of unidirectional carbon-fiber composite material with a non-outgassing cyanate resin. The '0,0,45,-45,90,90,90,90, -45,45,0,0' lay-up gives the structural parts a total thickness of only 0.03 inches and a structural weight of only 1.8 pounds. Small composite brackets are used to hold the parts in place and to stiffen the structure. These small brackets were made of a carbon fiber composite weave material with a low-outgassing epoxy resin. A small amount of aluminum is also used on the structure in the form of brackets and standoffs. Standard stainless-steel socket-head cap screws are used throughout the structure, ranging from sizes 2-8. The total structural assembly comes to only 2.25 pounds.

To ensure that the structure and all of its components survive the launch environment, testing and finite-element analysis were performed on the current design. Static, shock and vibrational simulations were applied to the developmental structure to ensure the integrity of the satellite. These initial tests proved the structure to be sturdy enough for a ride on the Pegasus. These tests will be followed by qualification testing, which will once again prove the quality of the design, this time for the Taurus environment. Finite element analysis was also performed, using Pro Engineer on the structural model and has proven the structure to be worthy.

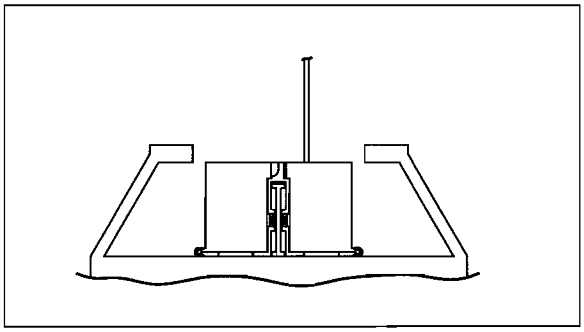

Figure 2 : Mounted Satellite

2.4 Dynamics and Control

Stabilizing the nano-satellite is not a trivial task, which is why the dynamics subsystem is one of the most experimental subsystems. Due to small power, cost and weight constraints, the dynamics team could not use standard devices such as torque rods, magnetometers and off the shelf sensors. Instead, ASUSat1 uses a passive stabilization and damping collaboration incorporating many student-designed components.

For stabilization, the satellite uses a cylindrical 2-meter beryllium copper boom with a

136-gram tip mass. The boom is deployed from a student-designed release mechanism that is 3.8 x 3.8 x 6.6-cm and weighs less than 130 grams. The release mechanism is an offshoot of current designs, but is much smaller and lighter. Only one electrical signal is required from Taurus at the beginning of the mission to release the element, stabilizing the satellite for the duration of the mission.

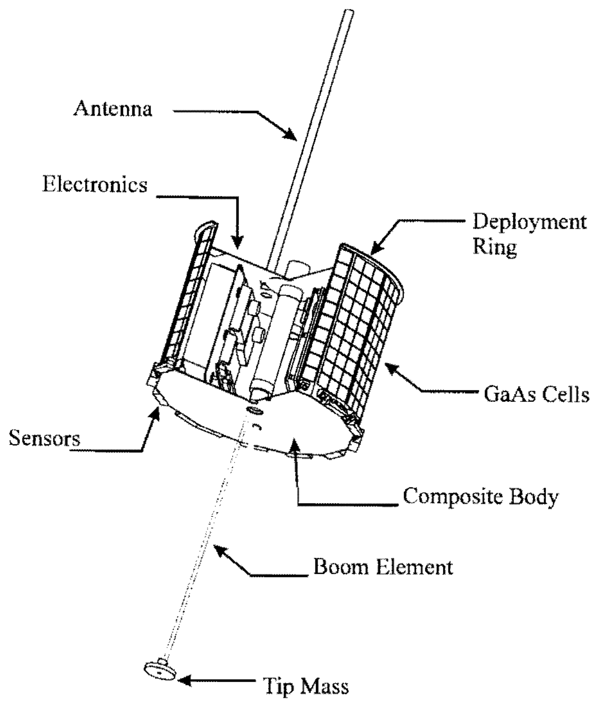

Figure 3: Satellite Cut-View

Once stabilized by the deployed boom element, the satellite must not stray from its current orientation. Solar, magnetic, and misalignment disturbances can cause libration problems, which if not counteracted could potentially flip the satellite. This counteractive restoring force is accomplished by using a fluid-damper design. The ball-within-a-ball design is a promising idea which will give the satellite three-axis stabilization. It is based on a mathematical model and has never been used in space. The inner ball of the damper has three substantially different inertias, causing it to align itself with the gravity and velocity vectors. The movement of this ball within the fluid will dissipate enough energy to damp out the oscillations within a reasonable amount of time.

Being only a twelve-pound-class satellite, not much room is available for redundancy. One of the only areas that a redundant system is used is in control. If an uncontrollable event causes the satellite to flip, many of the satellite's functions would cease to work. To avoid this dilemma, a small, lightweight, student-designed torque coil is being added. Because of the large current draw of the coil, it is limited to emergency situations only.

A low-cost array of student-designed sun-and-earth sensor blocks are being used to obtain attitude information of the satellite. Sixty lightweight sensors surround the satellite to read different light waves given off by the sun and earth. The sensors are contained in UHMW (Ultra High Molecular Weight) plastic blocks, where each block houses three visible light sensors for the sun and one infrared sensor for the earth. Periodic readings from these sensors will give an orientation accuracy of the satellite of +/- 10 degrees around each axis. Images from the cameras along with GPS readings may help to calibrate the sensors to a better accuracy.

The GPS unit used on ASUSat1 is a terrestrial (non-space-rated) unit that has been conditioned for space by the use of epoxies and shielding. The Trimble Navigation unit is expected to give position accuracy within 10 km and similar accuracy for velocity measurements. GPS readings will be taken on command by the ground station to locate pictures and give updated Keplerian elements.

2.5 Communications

Once ASUSat1 is up and flying, amateur radio operators around the world will be able to use the satellite as an analog voice repeater as well as to download telemetry. The ASUSat1 team will also be talking to the satellite constantly, sending up new commands and receiving new data. To allow all of this communication with the satellite, the satellite must have a reliable transmitter, modem, and receiver along with a transmit and a receive antenna.

The RM735 transmitter is a Maxon unit modified to work in the amateur-radio band. The transmission frequencies are in the 70-cm band at 436.7 MHz. The receivers are modified Motorola P-50 Radius Radio transceivers, which have the transmitter disabled. The two receivers operate at separate frequencies in the 2-meter band at 145.99 MHz for voice and an undisclosed frequency for commands. The modem and switching portion of the communications subsystem is contained in a student-designed board. The student-designed modem is a two-layer board consisting of a modem and a switching system. The modem is based on the Mx-Comm Mx589 high-speed modem adapted to 9600 baud frequency shift keying (FSK), which is used by several Ham radio digital satellites. The switching unit is responsible for routing the digital and analog signals from and to the uplink receivers, downlink transmitter, and modem. The design concept puts an emphasis on simplicity and flexibility in modes of operation. Due to this, the satellite will be able to provide the Amateur radio community with both voice and digital capabilities.

2.6 Commands

The commands team is responsible for the main CPU board and the interface board for the dynamic and thermal sensors. The CPU board is a student-designed board, built around the Intel 80C188EC embedded processor. The board contains a 2-KB PROM for boot-loader software, a 256 KB EPROM for the operating system, and 1 MB of RAM with Error Correction and Detection (EDAC) for telemetry and software modules. The computer will control power switching on command from software. Digital communications are controlled using the Zilog Z85230 HDLC controller. The computer is connected to the GPS and cameras through separate serial links on the board. The CPU board is also hooked up to the dynamics interface board by one of the two parallel ports. The layout of the system is shown in figure 4.

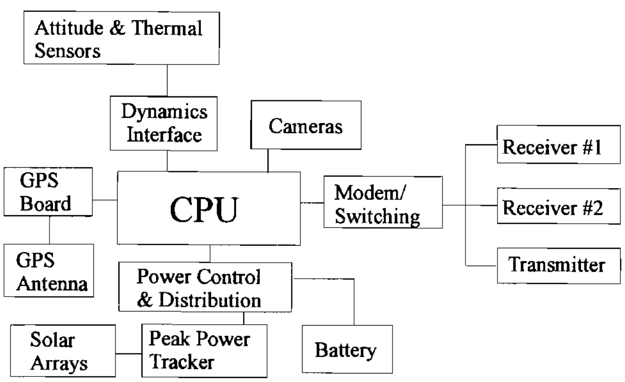

Figure 4: Commands Layout

The dynamics interface board is used for collecting all of the data from the dynamics sensors and the thermal sensors around the satellite. This board, like the main computer, is a 6 X 9 inch student-designed board. The location of both boards can be seen in figure 5.

2.7 Power

The power subsystem is broken down into three systems; the solar arrays, the batteries and the power control board. These three systems are tightly integrated to provide ASUSat1 with ample power at all times. The solar array is a body-mounted array which uses Gallium Arsenide (GaAs) solar cells. These 2-centimeter square black cells cover all fourteen sides of the satellite body, along with seventy percent of the top bulkhead. The cells have an efficiency of 18.5% and are expected to provide 8 to 14 watts of power depending on the temperature and attitude of the array. The leads of the cells that pass through the structure are connected together with a copper-tape design, which eliminates 60 wires and ensures structural integrity. The tape is then connected at six locations, with three pairs of wire each going to one of three peak-power trackers. These peak-power trackers are mounted on the student-designed power-control board, which disperses the power for the various demands.

One of the power needs comes from the drained Nickel-Cadmium (NiCd) batteries, which need to be recharged constantly to be used at eclipse times. The maximum eclipse time at a 780 km altitude is 35.1 minutes. These NiCd batteries are separated into two packs of 6 to allow for a greater operational lifetime. The two packs are packaged in an echofoam mold and mounted to the composite panel, which stiffens the panel and allows for proper thermal dissipation for the batteries. The batteries are not powerful enough to fully support the satellite and all of its components, so a low-power mode is entered when the satellite enters the eclipse. This low-power mode consists of leaving some components warm and taking only some thermal readings.

2.8 Software

The software subsystem of ASUSat1 is responsible for creating integrated software modules that will function with the Bektek Spacecraft Operating System. The Bektek operating system offers a real-time multi-tasking kernel, AX.25 protocol drivers, a message passing facility, and a set of DMA/Interrupt-based I/O drivers designed for the Intel 80C188 microprocessor.

The software modules must control all aspects of the satellite including Communications, Power, Dynamics, Thermal, Camera and GPS all tied together by Exec. These separate modules each control their various systems based on commands sent to the satellite from the ground station. After every pass over the ground station, the software will have a new list of instructions and variables to execute until the next pass. Some of the expected tasks of the satellite include taking pictures at specified times. GPS readings will also be taken constantly during some orbits to update the position versus time calculations, allowing for accurate positioning of pictures. Dynamics sensor measurements will be read and also sent back to earth to be analyzed. Times will be specified for amateur-radio use at certain locations. To add more design flexibility, the option of uploading new software to the satellite is also available.

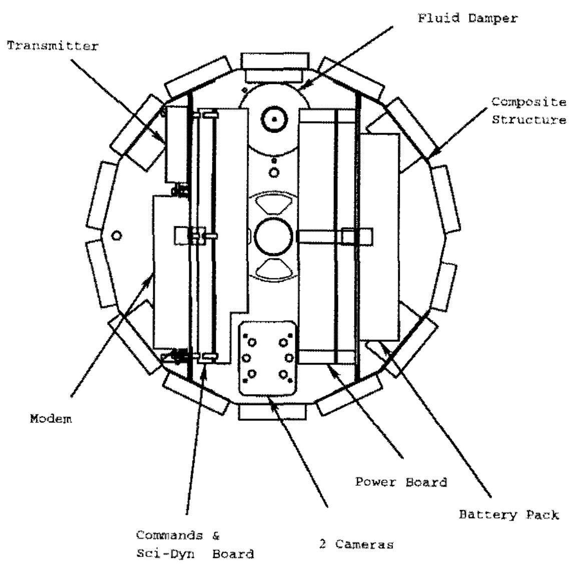

Figure 5: Satellite interior

2.8 Deployment

The two main purposes of the deployment team are to hold the satellite in place during launch and then safely eject the satellite from the launch vehicle when the proper signal is received. The design of the deployment system was limited by tight weight, volume and signal constraints. The design being used for ASUSat1 stiffens the satellite while holding it in place during launch, then gracefully deploys the satellite with only one signal from the launch vehicle.

The deployment consists of two main student-designed structural components. The first of these components is the marmon clamp. This multi-hinge device is held together at one point by a 4-40 threaded rod. This clamp is used to hold the satellite tightly against the launch vehicle until deployment. A bolt cutter that contains two initiators, one for redundancy, encapsulates the rod and cuts it on command. The other main structural component is the extending guide tube. This guide mechanism is used to stiffen the main satellite structure during launch, and then to gently push the satellite away from the launch vehicle during deployment. The gentle push is due to the fact that the 2-meter boom will be deployed prior to deployment of the satellite, and any harsh forces could buckle the boom.

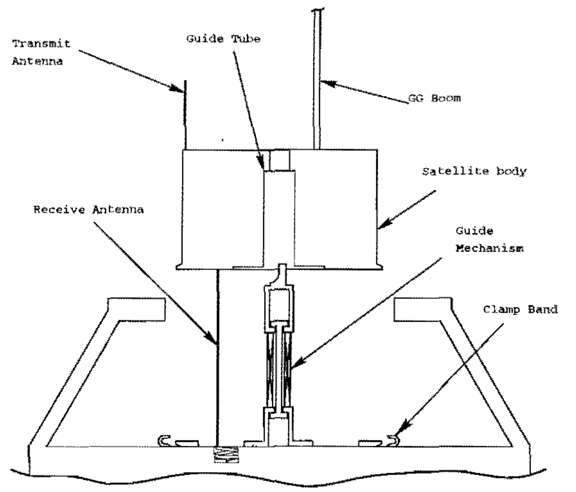

Figure 6: Deploying Satellite

2.9 Thermal

Extreme temperatures in cold and hot areas start becoming a problem once in orbit. To prevent component failures due to high temperatures, thermal modeling is constantly being performed for ASUSat1. The satellite is passively thermally controlled, without the use of heaters, coolers, or thermal insulators. These components would improve the thermal conditions from livable to desirable, but they also add excess weight, cost, and power consumption. Various light-weight, low-cost, no-power methods such as the use of black paint, silverized Teflon, thermally conductive epoxy, and anodized aluminum help keep components at acceptable temperature levels. Twenty five thermal transducers are located around the satellite to track temperatures of components during the lifetime of the satellite and to test the accuracy of the thermal model done for the composite structure.

3.0 MISSION OVERVIEW

3.1 Ground Operations

Once in the air, the work of the ASUSat1 team is not finished. The ASUSat1 ground station located in the Engineering Research Building at ASU will be monitored by students with their technician license. The ground station must be made autonomous so the received telemetry can be analyzed quickly to determine the next set of instructions to be sent. Seven good passes a day will keep the ground station busy. The web page for the satellite will be updated daily with new pictures and information from the orbiting satellite. Also, information such as amateur-radio times and locations will be posted so the Hams will know when they can communicate through the satellite.

3.2 In Orbit

Once in orbit, ASUSat1 will provide proof of concept for the student-designed dynamics sensors, gravity-gradient boom, fluid damper, composite bus, modem, commands board, dynamics board, release mechanism, and power board. ASUSat1 will also prove the functionality of the following non-space-rated components in a harsh space environment: a Trimble GPS unit, six Sanyo batteries, two Dycam cameras, and a Maxon transmitter.

4.0 CONCLUSION

Projects such as ASUSat1 are an important addition to the engineering curriculum of today's student. This project has given over 270 students hands-on experience designing, analyzing, building, and testing flight hardware. This type of teamwork and design experience is invaluable to the students and will help them in their careers upon graduation.

Providing new ideas and inventing new technologies for the growing nano-satellite field, this project is also a valuable research tool for university-industry endeavors. ASUSat1 has provided new ideas for sun and earth sensors, satellite structures, stability and control, and deployment. These ideas help the development of the small satellite market making it more affordable and practical.

5.0 ACKNOWLEDGMENTS

We would like to thank all of the students who have participated in the ASUSat1 project for their long hours of hard work and dedication. Special thanks go to Rich Van Riper and the rest of the team at Honeywell Space Systems Group and Mark Kanawati from Space Quest Inc. and to all of our other industry partners. This project was only possible because of their support.

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