JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 39, No. 5, September–October 2002

# Arizona State University Satellite 1 (ASUSat1): Low-Cost, Student-Designed Nanosatellite

Assi Friedman,* Brian Underhill,† Shea Ferring,‡ Christian Lenz,§ Joel Rademacher,¶ and Helen Reed**
*Arizona State University, Tempe, Arizona 85287-6106*

**On 27 January 2000 at 03:03:06 (coordinated Universal time) Arizona State University Satellite 1 (ASUSat1) was launched into space. The launch was the culmination of six years of effort by over 400 students. ASUSat1 is an innovative nanosatellite bringing new concepts for low-power, low-mass, highly constrained designs. Its primary mission was Earth imaging, with several secondary missions including attitude and orbit determination, amateur-radio communications, passive stabilization techniques, and composite-material research. After the successful launch and deployment of ASUSat1, the satellite operated for 14 h. In spite of this, the team collected telemetry from and commanded the satellite and verified many of the design concepts incorporated into the satellite. A majority of components and subsystems performed as designed and built by the students, including the Marmon clamp deployment mechanism, boom deployer, microswitches, tape antennas, gravity-gradient stabilization system, carbon-composite structure, boot-loader software, computer, modem, receivers, transmitter, passive thermal control, thermal sensors, power storage and regulation system, dynamics board, sun/Earth sensors, and ground station. Following the on-orbit failure of ASUSat1, the team conducted an investigation to single out the problem. Even though no specific problem was identified, the team has noted several design and system-level issues to be taken as lessons learned from this project to future student satellite projects.**

## Introduction

ARIZONA State University Satellite Laboratory (ASUSat Lab) is managed entirely by undergraduate and graduate students with oversight by a faculty advisor. Industry engineers and additional faculty are available for consultation and periodic evaluations of student progress. There are over half of a dozen projects currently under way. These range from soda-can-sized systems launched from amateur rockets to as high as 3.6 km before descending under parachute, to a constellation of three nanosatellites demonstrating imaging, formation flying, innovative communications, innovative command and data handling, and micropropulsion to be launched from the NASA space shuttle in 2003 as part of the U.S. Air Force Office of Scientific Research/Defense Advanced Research Projects Agency/U.S. Air Force Research Laboratory/NASA Goddard Space Flight Center/Department of Defense Space Test Program University Nanosat Program. The latter project is a joint effort with the University of Colorado at Boulder and New Mexico State University (for example, see Ref. 1).

Received 19 January 2001; revision received 12 March 2002; accepted for publication 13 March 2002. 

*Project Leader, ASUSat1; currently CHIPSat Integration and Test Manager, Flight Systems Department, SpaceDev, Poway, CA 92064; 4x1kx@iarc.org.

†Program Manager, ASUSat1; currently Engineer, Honeywell Space Systems, Honeywell, Glendale, AZ 85308-9650; brian.underhill@asu.edu.

‡Program Manager, ASUSat1; currently Technical Manager of Vehicle Systems Engineering, NASA Expendable Launch Vechicles Department, Analex Corp., Kennedy Space Center, FL 32899-0001; shea.ferring@analex.com.

§Deputy Program Manager, ASUSat1; currently Space Systems Engineer, Broad Reach Engineering, Tempe, AZ 85260; christian.lenz@broad-reach.net.

¶Program Manager, ASUSat1; currently Mars Exploration Rovers Payload Project Element Manager, Space Experiments Systems and Technology Section 387, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099. Member AIAA.

**Director, Satellite Laboratory; Associate Director, National Space Grant College and Fellowship Program; and Professor, Mechanical and Aerospace Engineering Department; helen.reed@asu.edu. Associate Fellow AIAA.

Arizona State University Satellite 1 (ASUSat1) is the original project. Begun in October 1993, over 400 students (90% undergraduate) participated in the numerous iterations of ASUSat1 from initial concept, through design and development, integration and testing, and flight and ground operations. These students gained valuable hands-on experience in the design and application of nanosatellite technologies, and today many of them are practicing engineers in the space industry.

The purpose of this paper is to describe our approach to student projects and our program's first project, ASUSat1. New concepts for the highly constrained designs characteristic of nanosatellites and how the system performed on orbit are described.

## ASUSat Lab

### Motivation

ASUSat Lab was founded in October of 1993, when a local launch vehicle company agreed to launch a small payload for the students if the satellite would perform meaningful science, weigh under 8 kg (including the release mechanism), and fit within an envelope of 33 cm in diameter and 27 cm in height. Students from high school through the doctoral level, from engineering, liberal arts and sciences, business, communications, and social work have participated in all leadership, management, and teaming aspects of real aerospace projects. Approximately 50 students presently work on the various projects sponsored by ASUSat Lab each semester, 90% are undergraduates. Students either are paid as interns, receive course credit, or volunteer. The students also participate in a significant number of outreach activities to local schools and community and professional functions and are called on frequently for recruiting and awareness by the university. The various projects depend on industry and the National Space Grant College and Fellowship Program for support, including mentoring and assessment, financial support, hardware/software donations, and use of fabrication and testing facilities. Details may be found in Ref. 2.

Student projects such as those sponsored by ASUSat Lab provide a unique opportunity to combine the educational, research, and service missions of a university in a single program. The students are presented with a multidisciplinary work environment, where team effort is a must. This experience, although it represents the real working environment of most engineers today, is still unusual in a university setting. Moreover, the limited resources and rigid constraints typically placed on the projects require the development of innovative technical solutions. These new solutions range from the design of new low-cost components to the development of manufacturing techniques that can be easily performed by students with little manufacturing experience.

In recent years, the space community has been faced with new constraints, lower budgets, shorter design times, etc. (the faster, better, cheaper philosophy). In this new environment, the kind of thinking found in student projects may provide some of the solutions that are required for the success of space exploration in the future. It is our opinion that such projects can make valuable contributions to the aerospace field, not only by training scientists and engineers, but also as a tool for the development and testing of new technologies. A university satellite program with its industry and government partners can provide an inexpensive testbed and innovative solutions to satellite technologies.

Moreover, over the past decade, many issues on university strategy have been the subject of continuous discussion. In particular, industry has submitted inputs about the quality of engineering education.[3] Student projects very successfully address these needs by involving predominantly undergraduate students in isotropically integrated projects. These projects provide the relevance to students' basic classes and help them see what engineering is all about and choose a direction. One feature of such a program that strongly impacts the students' education is interaction with industry and government. This day-to-day contact brings the students closer to the industry environment and helps students learn industry/NASA practices, establish a long-lasting network, and identify future job opportunities. With the large amount of industry interaction associated with such a project, students also gain confidence in their abilities and develop effective public-speaking and human-interaction skills. Students acquiring these skills at the university level become even more valuable to their profession.

The benefits of these projects far outweigh the obstacles. The ASUSat Lab team feels strongly about the educational aspects of the program and is always willing to share ideas and suggestions.

**Management Aspects**

From our experiences and many lessons learned over the past eight-plus years, our approach to working with students can be expressed by the following points:

1) Students thrive in an environment created around a real-world program relevant to national needs (such as a space program) in which research results are transformed into hardware and then tested. In the ASUSat Lab, students (principally undergraduate) research, design, build, and launch or test low-cost satellites and other space systems.

2) Set high standards and live by them. Promote ethics.

3) Encourage students to take initiative and make decisions. Give students as much responsibility as is feasible.

4) Encourage students to explore different areas of the project. They should not be confined to work on a problem that directly correlates with their major; they should be able to explore and grow by learning other subsystems.

5) Involve as many students as possible in industry-related activities, such as tours, teleconferences, and technical reviews and exchanges, and other aspects of a research program, such as paper and proposal writing, reviews, and conference presentations.

6) Spend the extra time teaching a student how to do a task properly . It seems faster as a manager to do it yourself, but if you teach students properly, then they can continually perform the task and pass the skill along.

7) Create and continuously improve a friendly and useful documentation system that makes it as easy as possible on the various team members, and document everything. This is a tough one but especially critical because of high student turnover.

8) Provide access to state-of-the-art tools. Over the years, the ASUSat Lab program has attained various resources, along with many dedicated industry partners. ASUSat Lab resources developed include high-end workstations, software packages, class 10,000 clean room, ground station, and a knowledgeable team of engineering students with satellite-design experience. University resources made available for the students include a professionally run machine shop, a student-use machine shop containing four computer numerically controlled machines, and a rapid-prototyping laboratory. Most universities, including Arizona State University, cannot provide the full range of resources needed for project success, and so industry has helped fill the voids in many areas. Industry is one of the main supporters of the ASUSat Lab, not only through its generous monetary and component donations, but also through its provision of advisors, many needed tools, and manufacturing and testing facilities.

9) Interact frequently, patiently, and respectfully with students. Listen to their opinions. Mentors should include faculty, industry, graduate students, and undergraduate peers. Industry engineers provide a very important facet to mentoring. Students view these individuals as coming from the real world and providing a sense of relevance. The experienced students on the team (both graduate and undergraduate) also make very important contributions to mentoring and take this responsibility very seriously. The closeness in age and similarities in life experiences are major reasons for this success.

10) Involve students in outreach to local kindergarten through 12th grade schools and community and professional organizations. The students actually embrace this activity as a very important aspect of the program and readily respond to and seek opportunities to inform the public. This contributes to addressing current national concerns about the availability of a sufficient future workforce, by encouraging precollege students to seek careers in science, engineering, and mathematics.

11) Promote diversity. Efforts are made to attract members of underrepresented groups and students who might not otherwise have the opportunity to participate in research. ASUSat Lab has a history of success in recruiting women and minorities. At present, 42% of the undergraduate interns are women and 29% are minority. Once again, this has been recognized as a key element to future workforce needs. An effective way to generate diversity is to encourage minority/women students presently on the team to serve as role models and to make personal contacts with other minority/women students.

**Organization**

Projects are modeled as much as possible after industry and are completely student managed. Projects are conducted from a systems point of view keeping requirements and constraints in mind; the students are contributing to a multidisciplinary team. The projects are required to actually work to perform valuable research or science, giving students invaluable hands-on teaching in design. Preferably there is an industry- or government-sponsored launch on an expendable launch vehicle, sounding rocket, balloon, or the shuttle, thus providing students with real constraints on testing, safety, deadlines, documentation, and size, power, and mass.

Student projects have added challenges to face. Most have limited funding available. However, minimal resources do encourage innovative technical solutions and interactions with local industry professionals. Also it is critical to promote and to improve continuously team organization. Challenges here include project continuity as students graduate or otherwise leave the team. Information is very easily lost as people leave. To this end, establishing a friendly documentation system (on the computer) is crucial; paperwork is not as much fun as design and building, and different strategies have to be tried for different students. There is no simple solution. Many times, multiple organizations work together, and students have to learn to run programs over long distances, taking into account time zones, cultural differences, and perhaps language. Students often times do not initially have an appreciation for or experience in working with students in other disciplines or other majors. Students also join a team with greatly varying experience levels, usually very little experience; bringing new members up to speed is a challenge. An effective idea is to assign a more experienced student mentor to each new participant. Finally, students have many demands on their time, classes, laboratories, homework, exams, family, etc. It is critical to establish a team structure that is flexible, adaptive, and time efficient: Do not keep students in too many meetings.

ASUSat Lab presently operates in the following way. Students serve in the following capacities. Individual projects, for example, ASUSat1, have project leaders, subsystem leaders (science, structures and materials, attitude and orbit determination and control, power, command and data handling, propulsion, etc.), and identifiable team members. Each project leader reports to the faculty advisor (last author of this paper). The subsystem leaders report to their respective project leaders, and team members report to their respective subsystem leaders. Team members typically contribute to more than one project, that is, cross talk.

An organized meeting structure ensures communication among all team members. All members of a project are required to attend a weekly general meeting, unless there is a class conflict. Weekly general meetings are held to ensure that all team members are aware of the general team progress and any outstanding issues To promote communication skills and confidence, a different student prepares the agenda and runs the meeting each week. The progress and status of the individual projects is reported at this time. The project leader and subsystem leaders make up the systems team and meet weekly to lay out milestones and discuss systems issues. Subsystem leaders are then responsible for assembling their groups to delegate tasks and to prepare the weekly report. Each subsystem has a separate 1-h meeting once a week to discuss tasks within the group and to help each other out. Faculty and industry meet with students at all levels, from regular one-on-one consultations to systems-level interactions.

Team-building activities are necessary and can be made enjoyable. For example, have a team party or hold a car wash for charity or take a group of elementary-school students to a local museum. These types of activities bond the team closer together and encourage the students to enjoy working together more. These management techniques build teams that are comfortable with each other, respect one another, and are less likely to quarrel among themselves. We hold (at least) monthly activities/socials. The faculty and industry are invited to these activities.

## ASUSat1

Miniature satellites are considered to be those under 200 kg (Ref. 4, p. 853), microsatellites as between 10 and 50 kg, and nanosatellites as between 1 and 10 kg. Figure 1 shows nanosatellite ASUSat1 of mass 5.9 kg, easily being held by one person.

The original goal of the ASUSat1 project was to show capability in a very low-mass, low-power, low-volume, and low-cost package and to provide technology demonstration in flight to enable other nanosatellite missions. The strict mass, volume, and power constraints associated with nanosatellites eliminate the use of many common off-the-shelf components and require innovative rethinking of many commonly used techniques such as active attitude control, radiation shielding, large battery packs, structures, thermal control, and many complex mechanisms. Also with the minimal power that can be generated from the small surface areas, only the lowest power consuming devices could be used. Moreover, when considering the design of nanosatellites, system considerations are particularly important. No longer are size, power, and mass unlimited as with larger satellites. The entire system must be carefully integrated together. No longer is this just a bus with systems added inside; every part must be justified, minimized, optimized, and ideally multifunctional. Performance is not the only issue from a systems standpoint.

**Fig. 1 ASUSat1; 5.9-kg mass.**

Students went through a series of invaluable lessons in search of feasible solutions. These lessons ranged from problem definition, exploring design space, conducting trade studies, determining the feasibility of manufacturing, and quality control. Note that these lessons are not taught in the classroom but were learned hands on by participating in a real design project. In retrospect, the core objective of the project has been to explore the frontier of the smaller, faster, cheaper product space, which is the fundamental challenge to all nanosatellites and all of the subsystems that support the mission. The next sections outline the solutions developed by the students.

### Mission Objectives

The mission objectives chosen for ASUSat1 and representative of likely, typical nanosatellite objectives include the following:

The first is spectral imaging. The cameras onboard had relatively coarse resolution. These cameras could be used to identify potential targets and suggest where one should point for finer resolution. Also, this capability could be used in the future for detecting other spacecraft.

The second was a global positioning system. A terrestrial system was flown to demonstrate the ability to determine position. This unit had been conditioned for space by the use of epoxies and shielding and was expected to give position accuracy within 150 m and similar accuracy for velocity measurements.

The third was to achieve three-axis passive stabilization. Stabilizing a nanosatellite is not a trivial task. Because of the strict power, cost, and weight constraints, the dynamics team could not use standard devices such as off-the-shelf torque rods, magnetometers, thrusters, and sensors. However, for Earth imaging and for communications optimization, a stable Earth-pointing orientation is needed. The ASUSat1 team developed an innovative passive stabilization and damping collaboration incorporating many student-designed components. The students developed an innovative, passive, gravity-gradient fluid damper. This coupled with the gravity-gradient boom was to provide three-axis stabilization.

The fourth was to achieve $\pm 10$-deg attitude determination at low cost ($1000 per satellite). This was a low-power, low-weight, student-designed system utilizing 23 inexpensive sun/Earth sensors.

The fifth was autonomous operations. An onboard computer and power and dynamics boards together were to monitor and regulate power, control all of the satellite subsystems, gather all of the data from the various subsystems and experiments, and store and make available all of these data for download by the satellite operators.

The last objective was communications. ASUSat1 was to demonstrate that it could carry onboard a low-power transmitter, modem, and two receivers, along with a transmit and a receive antenna, and have useful contact with the ground. The ASUSat1 team was to demonstrate the ability to send up new commands and receive new data. Amateur radio operators around the world were also to be able to use the satellite as an analog voice repeater as well as to download telemetry.

## Mission Implementation/Satellite Overview

### Earth Imaging

To demonstrate imaging capability in a 6-kg package, Earth imaging with an emphasis on vegetation indexing was chosen as the primary scientific mission. The science package consisted of two cameras. The modular camera system was essentially a camera electronics board that takes one picture at a time and transfers it to the command board on request. Both cameras were to work as independent units with each having 1 MB of random access memory for image storage and a microcontroller unit for image capture and compression. Both cameras also had different modes of operation including a low-power standby mode, which made them attractive for the mission. When the extensive features of the camera were used, all that was required to interface it to the satellite was one standard serial port.

The two cameras were daisy-chained inside a single compact anodized aluminum housing measuring approximately $5.08 \times 6.35 \times 16.51$ cm$^3$ and of mass close to 0.4 kg. Each camera required only 5 V and would operate in a sleep mode for most of the time drawing only 3.5 mA. During wake mode, the cameras used 125 mA and would spike to roughly 650 mA for about 15 m during the image capture.

Each camera had a resolution of $496 \times 365$, which gave a clarity of approximately 0.5 km/pixel at an altitude of 700 km with a viewing angle of 18 deg. The first camera was color with 24-bit resolution and had the ability to pick up the visible red and near infrared (NIR) spectrum at approximately 600–800 nm. The second camera was a gray scale with 8-bit resolution and would use a short-pass filter in the visible blue spectrum to capture wavelengths between 420 and 550 nm.

When vegetation indexing is considered, 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 (400–700 nm) because of the high-absorption pigments that occur in leaves, that is, chlorophyll, xanthophyll, etc. There is a slight increase in reflectivity around 550 nm (visible green) because the pigments are least absorptive there. There is no strong absorption in the spectral range 700–1300 nm; 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 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 contained a red-pass filter that would pick up the visible red and NIR bands where vegetation appears bright, and the second camera had a 550-nm short-wave-pass filter that would make vegetation appear dark. Also the spectral sensitivity of the second camera (420–600 nm) would allow for further applications such as coastal mapping, water-body penetration, forest mapping, and deciduous/coniferous differentiation.

### Structure

New ideas were used on ASUSat1 to allow for a structure strong enough to withstand the acceleration loading and acoustics environment during launch and still meet the tight 1-kg structural-weight budget. The structural design consisted of a full monocoque composite structure that held all components within a $25 \times 32$ cm diameter envelope. The 14-sided structure was capped off with two composite bulkheads, one being fixed and the other acting as a removable lid. The fixed bulkhead was 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 was mounted flush with the opposite lip of the bus with 12 bolts and locking-nut plates. Located within the structure were two component panels carrying all of the electronics. These panels could slide in and out of the structure with the removal of the top bulkhead. The modular design allowed for easy access to all components during assembly and for removal if necessary. All five of these structural parts were made of a 12-layer unidirectional carbon-fiber composite material with a nonoutgassing cyanate resin. A 0/0/45/−45/90/90/90/90/−45/45/0/0 layup gave the structural parts a total thickness of only 0.08 cm and a structural weight of only 0.82 kg. Small composite brackets were 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 was also used on the structure in the form of brackets and standoffs. Standard stainless-steel socket-head cap screws were used throughout the structure, ranging from sizes 2 to 8. The total structural assembly came to only 1 kg.

The temperatures in the cold and hot areas start becoming a problem once in orbit. Limiting temperatures (as determined from the operating temperatures of internal components) ranged from 0 to +50°C. To prevent component failures due to high temperatures, thermal modeling was constantly performed for ASUSat1. The satellite was 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 lightweight, low-cost, no-power methods such as the use of black paint, silverized Teflon®, thermally conductive epoxy, and anodized aluminum would help keep components at acceptable temperature levels. 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, 25 thermal transducers were located around the satellite.

### Dynamics and Control

Stabilizing a nanosatellite is not a trivial task. Because of the strict power, cost, and weight constraints, the dynamics team could not use standard devices such as off-the-shelf torque rods, magnetometers, thrusters, and sensors. However, for Earth imaging and for communications optimization, a stable Earth-pointing orientation was needed. The ASUSat1 team developed an innovative passive stabilization and damping collaboration incorporating many student-designed components. One of these components was a passive gravity-gradient fluid damper. This damper coupled with the gravity-gradient boom was to provide three-axis stabilization.

The main stabilization system was the gravity-gradient boom, a cylindrical 2-m beryllium copper element with a 135-g tip mass. The boom was to be deployed from a student-designed release mechanism that is $3.8 \times 3.8 \times 6.6$ cm and of mass less than 130 g. The release mechanism was an offshoot of current industry designs, but was much smaller and lighter. One electrical signal was required from the launch vehicle at the beginning of the mission to release the element, stabilizing the satellite for the duration of the mission.

Figure 2 shows the spacecraft in its deployed configuration, showing the extended gravity-gradient boom and transmit and receive antennas. The extended tip mass provided the relative difference in principal moments of inertia that enabled a gravity-gradient stabilization scheme.

When the pitch and roll/yaw decoupled equations of motion of a gravity-gradient stabilized spacecraft in low Earth orbit are utilized, the stability of the craft can be easily determined from the two parameters $k_1$ and $k_3$, functions of the principal moments of inertia. ASUSat1's principal moments of inertia are 9.616, 9.438, 0.671 $\mathrm{N \cdot m}$ (Ref. 5). These values give $k_1$ and $k_3$ parameters of 0.9 and 0.3, respectively. According to Ref. 5, ASUSat1 was clearly stable.

One advantage of the extremely lightweight spacecraft is that, to obtain the 0.9 parameter value, the required mass for the boom tip (an otherwise unutilized cost to the mass budget) is only 135 g. In spacecraft design, and especially in nanosatellite design, mass, begets additional mass, and the inverse is also true. That is, as component mass increases/decreases, so does structural mass to support it and attitude control hardware to control it.

A gravity-gradient boom [about ±5 deg (Ref. 4, p. 359)] cannot provide fine stabilization because the satellite is expected to wobble around its equilibrium point. This wobble could cause the images to miss the targeted areas of interest, and so a finer stabilizing system was added.

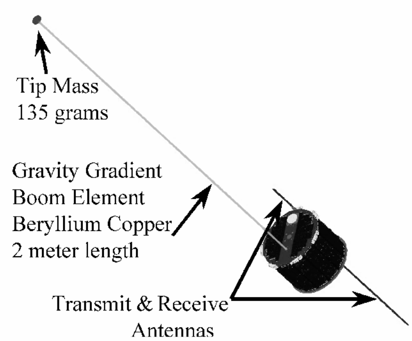



**Fig. 2 ASUSat1 deployed.**

**Fig. 3 Gravity-gradient fluid damper.**

The fine attitude control was also a passive system, called the gravity-gradient fluid damper. The system can be described as follows. A ball with four different mass concentrations that floated in a viscous silicone liquid inside a larger shell was attached to and moving with the satellite body. The physical principle behind it was that the inner ball should tend to remain aligned with both the Earth's gravity vector and with the velocity vector of the satellite's orbital motion. Because the satellite would wobble around its equilibrium point, the wobble energy should be dissipated with time in the viscous liquid between the inner ball and the outer shell. This method was based on a new concept and had not been space proven. The system was designed by analysis, solving the equations of motion including the damping torque provided by the two spheres separated by a thin layer of fluid and rotating relative to each other. The model was derived after the work of Kumar.[6] Manufacturing advice was provided by a local aerospace company. If successful, it was expected that the satellite would reach a steady state in about 600 orbits. Both of the methods (gravity-gradient boom and gravity-gradient fluid damper) were completely passive, thus being an ideal solution for a satellite with a low power budget. Figure 3 is an image of the damper housing and the interior ball. The holes in the ball accommodated tungsten caps to provide the different moments of inertia.

Because it was only a 6-kg-class satellite, not much room was available for redundancy. One of the few areas in which a redundant system was used was control. Gravity-gradient stabilization schemes have two stable orientations: one pointing nadir and one pointing zenith. If an uncontrollable event caused the satellite to flip or if the satellite was deployed in the wrong direction from the launch vehicle, many of the satellite's functions would cease to work. The only active means of attitude control added on the satellite was one small, lightweight, student-designed $Z$-axis magnetorquer. This $z$ coil was to be used to flip the satellite over in case of an upside-down orientation. Because of the large current draw of the coil, it was limited to emergency situations only.

For attitude determination, various commercial sun/Earth horizon sensors were evaluated, but due to the large cost of these units, the students reverted to designing their own sun/Earth sensors. The emphasis in the design was to build a low-weight, low-cost sensor array for determining the satellite's orientation to within $\pm 10$ deg. The sensor array was built using 23 photosensors mounted on the circumference of the satellite and sampling at three different angles. Such an array reduced costs to under \$1000 and minimized required internal volume. The data from the sensors coupled with the camera images were to provide the information to refine the attitude determination algorithm. Figure 4 is a closeup of the sensor blocks; the long blocks were mounted on the side of the spacecraft, with the short blocks mounted on the top and bottom bulkheads.

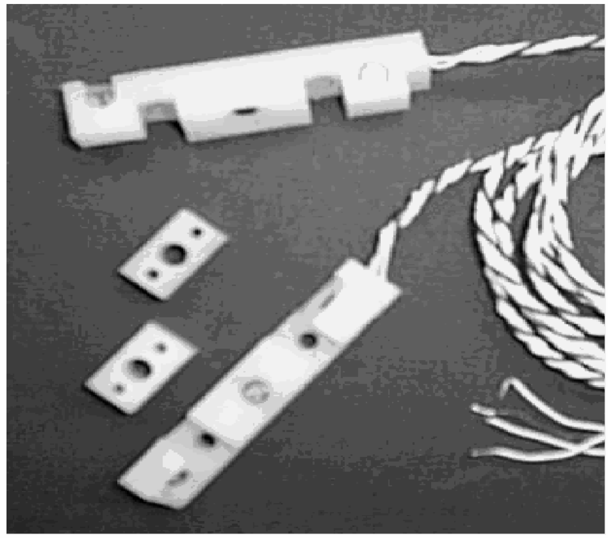


**Fig. 4 Attitude-determination sensors.**

Ephemeris determination was by the global positioning system. The global positioning system has been introduced to satellites only during the past several years but is rapidly becoming a standard in spacecraft design. The global positioning system unit consumed only 1.5 W and was to be used to collect orbital data points periodically that would be stored in the satellite's computer and transmitted to the ground station for analysis. Onboard ephemeris determination was not expected at this point because the spacecraft computer did not have floating-point capability. The global positioning unit selected was a terrestrial (nonspace rated) unit that was conditioned for space by the use of epoxies and shielding and was expected to give position accuracy within 0.15 km and similar accuracy for velocity measurements.

When the described techniques were used, it was expected that the entire attitude and orbit determination and control system would have a mean power consumption of less than 0.75 W. This system was predicted to provide 0.15-km position accuracy and $\pm 10$ deg knowledge in support of all of the mission objectives.

### Command and Data Handling/Command Board

The command board was to control all of the satellite subsystems, gather all of the data from the various subsystems and experiments, and store and make available all of the data for download by the satellite operators. The system was based on a microcontroller unit, incorporating direct memory access, interrupt control unit, chip select unit, watchdog timer, power control, and serial ports all in one chip. The central processing unit had a 1-MB random access memory bank, which was the microcontroller unit's full capacity. The random access memory was interfaced to the microcontroller unit through an error detection and correction state machine. The error detection and correction was completely transparent to the central processing unit, thus simplifying software writing for the system. The error detection and correction system could detect and correct up to one error per byte without any fatal consequences to the system. In the case of more than one error per byte, the system might crash (assuming a code byte was damaged). The probability for this based on the experience gained with other amateur satellites is very low, thus making error detection and correction a reliable solution. In the case of an unfortunate system crash, the command board had a watchdog timer and a reset state machine. The watchdog timer was a microcontroller unit integrated safety feature that would reset the system if it did not activate within a specified interval. The reset state machine was an independent state machine that would monitor the uplink channel for a special sequence. In case the ground controller wanted to reset the satellite, that sequence would be transmitted and the reset state machine would initiate a system reset.

The satellite was to be operating-system agile. On power-up, only a bootloader would operate. The bootloader would set the satellite to a power-safe mode and enable the operators to upload an operating system to the satellite. This feature would give the ASUSat1 team the ability to tailor its mission characteristics to any new ideas or requirements that might occur after launch. At launch, the bootloader and initial operating system were to be stored on a 128-kB erasable programmable read-only memory.

The interface to the communications system was a dual channel serial communications controller. This chip was a full-featured communications controller that simplified the communication task on the microcontroller unit.

The global positioning system and cameras were interfaced to the microcontroller unit using its onboard serial ports. The last two main units on the command board were two parallel ports that were interfaced to the dynamics and power board.

In the design of the command board, emphasis was put on reliability, low part count, and low-power consumption. The total power consumption was rated at about 1.2 W. Components selected were mostly from the commercial line with a temperature range from $-25$ to $+125^{\circ}$C. The technology selected was mainly from older line series due to the better radiation handling that those components offer.

**Dynamics Board**

ASUSat1 had about 100 data sources, most of which were analog inputs by the sun/Earth sensors, thermal transducers, power readings, and system status units. Handling such a large variety of sensors posed an interesting challenge. The resulting system was a software-controlled dynamics data acquisition board.

The system was designed with three main sections. The first unit was the front end, composed of a matrix-type multiplexer that enabled the command board to select the required input. From there the signal was passed through a dynamic bias/gain amplifier, which was set by the command board to fit the characteristics of the specific sensor. The last unit was an 8-bit analog to digital converter.

With this design, the process of sensor selection and preflight calibration was greatly simplified. The dynamics board could accommodate a large variety of sensor types because the bias and gain for each sensor was controlled by the command board. Another advantage of the design was that calibration of the different sensors could be done by the command board after integration and small differences between similar sensors could be compensated by software.

**Electrical Power System/Power Board**

Power availability was the primary factor in determining the mission profile. Because of the small size of the satellite, the available power from the solar array was limited. Size restriction and that deployable solar panels could not be implemented due to weight and complexity limitations meant that power could be generated solely using body-mounted panels. Because every watt counted, the team decided to use gallium-arsenide cells, which have an 18% efficiency. Gallium–arsenide solar panels were mounted on all 14 sides and the top bulkhead of the satellite. The solar cells were divided into eight groups, each connected to a peak power tracker. A peak power tracker is a device whose function is to follow the current–voltage curve characteristic of the solar panel and to find the peak power point. Because the lighting and thermal conditions on the panels were expected to change continuously, the peak power trackers were to search constantly and detect the peak power point to ensure maximum power transfer.

Power from the solar array was transferred directly to the battery pack. The battery pack was a six-cell nickel–cadmium pack with a capacity of 5 A $\cdot$ h and a nominal voltage of 7.2 V. From the battery, power was transferred to a high-efficiency direct current/direct current 5 V voltage regulator (developed for the commercial cellular industry). The last part of the power system was the switching network, which fed all of the subsystems. Because power management was so important, all payloads had power switches, except the onboard computer. Calculations estimated that the system should have 6 W average available for mission operations. Overall, the total efficiency of the power system was expected to be over 85%.

**Communications**

ASUSat1 was to demonstrate that it could carry onboard a low-power transmitter, modem, and two receivers along with transmit and receive antenna, and have useful contact with the ground. The ASUSat1 team wished to demonstrate the ability to send up new commands and receive new data. Amateur radio operators around world would also be able to use the satellite as an analog voice repeater as well as to download telemetry. Antennas were simple tape measure segments. The ground station was set up at Arizona State University.

The transmitter was modified to work in the amateur-radio band. The transmission frequencies were in the 70-cm band. The receivers were modified transceivers, with the transmitter disabled. The two receivers operated at separate frequencies in the 2-m band for voice and for commands (undisclosed frequency). The modem and switching portion of the communications subsystem was contained in a student-designed board. The student-designed modem was a two-layer board consisting of a modem and a switching system. The modem was adapted to 9600-baud frequency shift keying, which was used by several amateur radio digital satellites. The switching unit was responsible for routing the digital and analog signals from and to the uplink receivers, downlink transmitter, and modem. The design concept put an emphasis on simplicity and flexibility in modes of operation. Because of this, the satellite would be able to provide the amateur radio community with both voice and digital capabilities.

**Software**

The software of ASUSat1 was composed of two main phases. The bootloader was the phase in which the satellite was to wake up after power-on or system reset. The bootloader's objective was to keep the satellite in a power-safe mode and to enable basic hardware diagnostics and code upload. Once the satellite was determined to be healthy, the operating system was uploaded to the satellite. The operating system used on the satellite was one used by various amateur satellites and proven reliable and easy to use. The system provided multitasking, intertask communications, and low-level hardware handling.

The system had a main module that handled the scheduling of all of the activities on the satellite while maintaining a proper power budget. Each of the subsystems (camera, global positioning system, communications, and telemetry) had a task associated with it and was to be activated based on a predetermined schedule developed by the operations team.

**Satellite Deployment**

Figure 5 shows a flight version of the student-designed and student-built deployment system, which consisted of the guide rod running through the center guide tube on the satellite, the separation spring mounted to the guide rod, the Marmon clamp band for holding the satellite in place during launch, the pyrotechnic bolt cutter, and the base plate for mounting the system into the launch vehicle. This hardware supported the payload during ascent, and then deployed it safely away from the launch vehicle. The plate was 0.95-cm

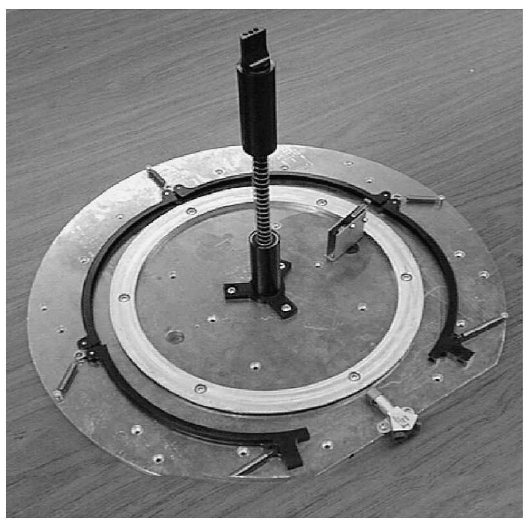
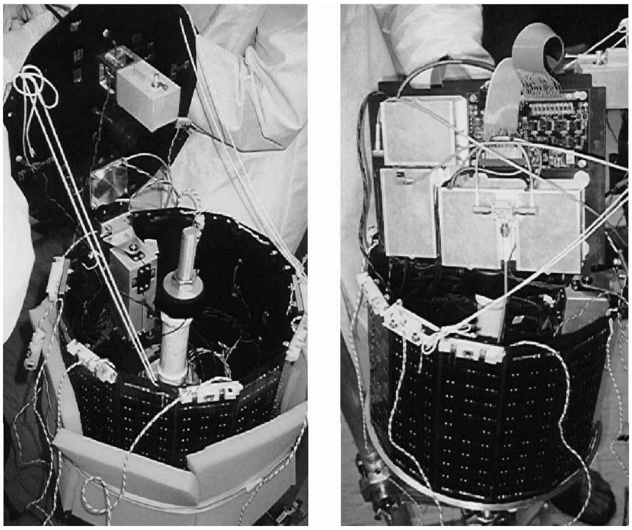


**Fig. 5 Marmon-clamp deployment system.**



a) b)

**Fig. 6 ASUSat1 during final assembly.**

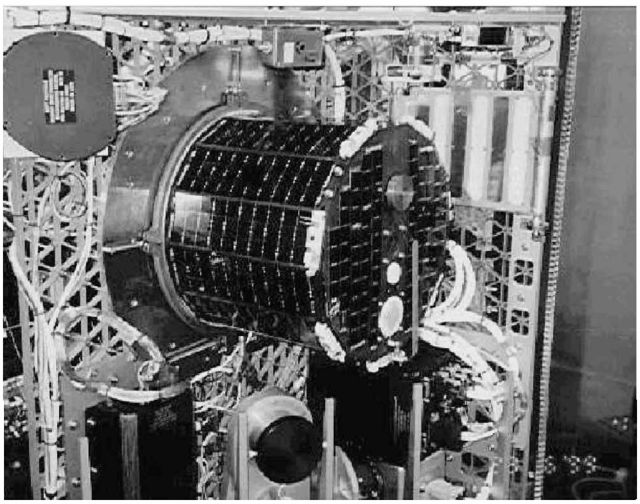


**Fig. 7 Integration of fully functional ASUSat1 to multiple-payload adapter.**

aluminum that was pocketed out from the backside to reduce weight. The deployment system, including cabling and ordnance, had a mass of only 2.3 kg.

#### Integration

Figure 6 shows the final assembly of the ASUSat1 spacecraft. In Fig. 6a, can be seen the boom-deployer housing, the camera housing, the shrink-wrapped $z$ coil, and the attitude-sensor blocks. Figure 6b shows the insertion of the command and communication panel; the visible side is the communication system (receivers, modem, transmitter, and global positioning system). The command and dynamics data acquisition boards are on the other side.

Figure 7 is a photograph of ASUSat1 taken on 23 June 1999, after the satellite passed acceptance and functionality tests and was integrated to the multiple-payload adapter.

## Mission Sequence of Events

After the successful liftoff of the launch vehicle on 27 January 2000 at 03:03:06 coordinated Universal time, the 6-kg nanosatellite ASUSat1 was the first of five payloads to be deployed. The U.S. Air Force requested that each of the payloads immediately inform them of initial signal acquisition, to confirm successful deployment from the fourth stage.

Because ASUSat1 was an amateur-radio satellite, several stations worldwide volunteered to monitor for signs of life. The station that played the most important role in this was that of the South African SunSat team. The launch profile out of Vandenberg sent the payloads south, over Antarctica, and then north directly over South Africa. About 45 mins after liftoff, ASUSat1 was heard by radio amateurs in South Africa. Over the next several hours, telemetry was collected from several stations worldwide. At first, telemetry indicated that all systems were nominal except battery charging. After an evaluation by the operations team, it was decided that the problem could be either a real charging problem or a sensor malfunction. As a precaution, the team decided to command the satellite to reduce power consumption. Nine hours into the mission, the team had the first opportunity to command the satellite, and commissioning began. In later passes, it was confirmed that in fact a critical failure in the power system was preventing the solar arrays from supplying power to the batteries. The last contact with ASUSat1 was made 14 h into the flight. Power budget calculations suggested that the satellite had about 15 h of operational time on battery power alone.

## Results

Even though the mission lifetime was much shorter than the team expected, the telemetry data obtained provided a lot of insight into the operation of the satellite.

#### Deployment

The deployment of ASUSat1 was controlled entirely by the launcher. The deployment occurred in three steps. In the first step, the rocket maneuvered to bring ASUSat1 to a nadir-pointing orientation. Once this maneuver was completed, a signal was sent to initiate the deployment of the satellite's gravity-gradient boom and downlink antenna. Shortly after that, the main bolt cutter was fired, and the Marmon clamp holding the satellite securely in place pulled away, and the satellite was deployed. The satellite was turned on by two microswitches, which activated on physical separation from the deployment mechanism.

Proper deployment of the boom cannot be verified by means of telemetry, yet the downlink signal played an important role in confirming that the satellite was stable. The downlink signal was strong and stable with low cyclic fading. This suggested that the satellite was not tumbling, but gravity-gradient locked, with a very low wobble around the stable point. In addition, a strong downlink could not have been possible if the downlink antenna would not have been deployed. Therefore, it is a safe assumption that all of the elements of deployment took place successfully as expected.

#### Telemetry

The operation of ASUSat1 after power-up was in safe mode and controlled by the bootloader. In safe mode, the satellite turned off all noncritical subsystems of the satellite and awaited command from the ground station. Periodically, it transmitted telemetry and status beacons to help with tracking and analysis. This mode proved to be of extreme importance in this mission. The ability to have multiple ground stations collect data in a nonintrusive mode was a great mode of operation.

#### System Mode Switches

The system mode switches gave the operators a quick summary of the power settings of all payloads and the communications system. The power settings were all set to safe mode. Later, this was verified by actual voltage and current readings. The two receivers were constantly switched into one modem. Again, the switching pattern indicated that the computer was behaving as expected.

#### Thermal

One of the challenges on ASUSat1 was thermal management with the carbon composite structure. To verify the thermal models, 25 thermal sensors were mounted in various locations. The telemetry suggested that the initial temperatures were within the design limits. The maximum external temperature was 30°C, and the internal temperature was a minimum of 10°C. Even though the team did not get to monitor the steady-state conditions, the temperatures actually measured suggested a nominal environment for satellite operation.

**Sun/Earth Sensors**

The sun/Earth sensors required extensive offline analysis, and a special operations mode was required to sample them properly. To enable operators to do a simple test of the sensors, the telemetry data set was designed to include samples well below the ideal sampling rate. The data received from the sensors were not sufficient to make any firm conclusions as to the exact orientation of the satellite. With that, the top and bottom sensors appeared to give values that were consistent with proper satellite orientation (nadir pointing).

**Power Consumption**

Five monitoring points gave a picture of current consumption by the various subsystems. The first four indicated current consumption, which was verified during integration. All of the subsystems were operating nominally. The last telemetry channel was the battery-charging indicator. The indicator read zero charging in all of the telemetry frames. This is the channel that initially got the operators' attention and signaled that something was wrong. Later this would be verified with the battery voltage.

In addition to the current monitors, the system had 11 voltage monitors. The voltages were verified with the system mode switches and were found to match.

The operation of the dc/dc converters that power the regulated 5-V bus met the tight design tolerance. The battery voltage was used to monitor and verify the charging problem. Between the first and last telemetry frames, the battery voltage dropped from 7.36 to 7.02 V. The nominal battery voltage of the pack was 7.2 V.

**Communications**

The digital communications system was the key to communications with the satellite. The downlink signal was reported to be strong and clear during the lifetime of the satellite. Several stations worldwide reported hearing the periodic beacon of the satellite. The ASUSat ground-station established command and control over the satellite. An anomaly occurred in the downlink, yet it was quickly resolved by the team. Subsequently, a more in-depth investigation would have been conducted to determine the cause of the anomaly. With that, the problem resolution would have indicated that it was not a critical issue.

**Flight Computer**

The flight computer was the heart of ASUSat1. The computer controlled all of the functions of the satellite. Throughout the mission lifetime, the data suggested that all of the components of the computer operated flawlessly.

**Dynamics Board**

All of the sensor sampling was accomplished by the dynamics board. The board included a sophisticated software-controlled variable gain, variable bias 128-channel analog to digital conversion system. The system performed as expected, with no apparent problems.

**Global Positioning System, Cameras, Fluid Damper, and Ham Radio Repeater**

Unfortunately, not all of the experiments on the satellite got a chance to be tested. All of the experiments required a multitasking operating system to be uploaded to the satellite. The commissioning of the experiments was expected to take place in the second and third phase of satellite operation, in the month after launch.

## Failure Analysis

After the on-orbit failure of ASUSat1, a formal investigation was done. The possible failure modes were recognized, and plausible causes were considered.

**Launch Environment**

The first big question concerned the launch environment and whether it was within the specifications provided by the launch provider. ASUSat1 was designed and tested to withstand the launch to acceptable industry standards. When data provided postlaunch were used, the launch environment was determined to be within the envelope specified by the launch provider. This ruled out any damage to the satellite by the launcher.

**Fault Analysis Tree**

The fault analysis tree is shown in Fig. 8. The starting point for the analysis was that the satellite failed about 14 h after launch. Supporting evidence included that the charge indication was reading zero current and battery voltage was dropping. Payload failure was

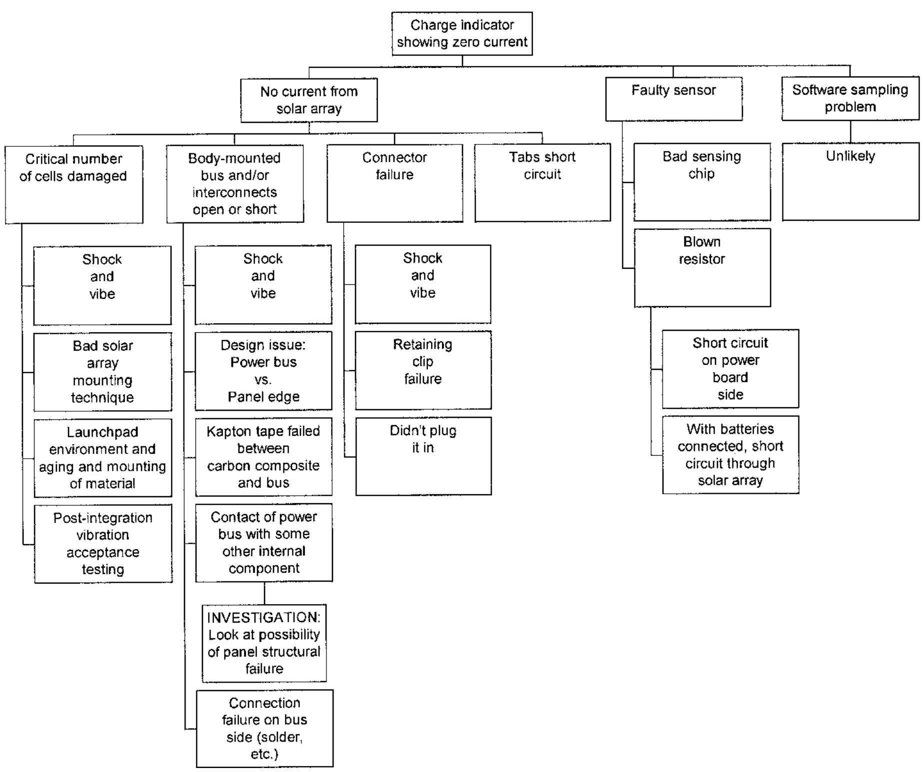



**Fig. 8 Fault tree analysis.**

ruled out because the telemetry indicated that all of the payloads were operating within the design envelope. Two main faults were identified. The first was that the current sensor failed and essentially cut off power to the system. This is not likely because the sensor read zero. In the case of sensor failure, it is most likely that the reading would have been saturated.

The more likely answer is in the tree branch from the "no-charge from array" box. All of the possible scenarios that could have led to no charge from the array are indicated. Because of the small amount of telemetry available, none of the failure modes can be identified as a "smoking gun," and the real reason will never be known.

During the fault analysis process, the team did stumble on a systems failure in the integration process. Throughout the integration and qualification process, the satellite was run through tests that verified all of the critical components of the satellite. Because of the lack of a mobile test fixture, the team was not able to do a full illumination test on the solar array after it was integrated onto the satellite. Even though the arrays were tested before final integration, and just before final closeout, after the array was plugged in, a functional test was not performed. The team recognizes that on the system level this possibly could have mitigated the satellite's on-orbit failure.

## Conclusions

ASUSat1 was all about engineering challenges. The initial design requirements were considered by many to be next to impossible. In 1993, nanosatellites were not considered to be viable spacecraft for any serious mission. ASUSat1 proved that even nanosatellites can be prospective candidates for science and communications missions.

ASUSat1 integrated a never-seen-before number of experiments into a 6-kg package. The team is not aware of any satellite that was designed to achieve so much per unit mass. The short on-orbit lifetime was a great disappointment to the team, but by no means is this project a failure. The experience gained from the design, construction, integration, operation, and failure is enormous. This experience is the baseline of the ASUSat program's ongoing and future projects.

## Acknowledgments

Support for Arizona State University Satellite 1 (ASUSat1) has been provided by the Orbital Sciences Corp.; National Space Grant College and Fellowship Program (NASA Space Grant); AMSAT Organization (Radio Amateur Satellite Corp.); Honeywell Space Systems Group; Lockheed Martin Management and Data Systems, Reconnaissance Systems; National Science Foundation Faculty Awards for Women in Science and Engineering; Cogitec; SpaceQuest; Colorado Satellite Services; Hughes Missile Systems; Orcad, Solid Works Corp.; Zilog; Microchip; Dycam; Motorola (Satcom and University Support); SunCat Solar; PhotoComm, Inc.; Eagle Picher Industries; Intel (University Support); Maxon; Universal Propulsion Co., Inc.; ICI Fiberite Composites; DynAir Tech of Arizona (SabreTech); National Technical Systems; SpectrumAstro; Trimble Navigation; Bell Atlantic Cable; Lee Spring Co.; Astro Aerospace; BekTek; Jet Propulsion Laboratory; Rockwell; Sinclabs, Inc.; Applied Solar Energy Corp.; Gordon Minns and Associates; Communication Specialist; Advanced Foam and Packaging; XL Specialty Percussion, Inc.; Simula, Inc.; KinetX; Equipment Reliability Group; and Arizona State University Center for Solid State Electronics Research.

The authors thank all of the students involved with the ASUSat1 project since its inception in October 1993. Many thanks also go to S. Webster [Orbital Sciences (OSC)], R. Van Riper (Honeywell Space Systems Group), S. Schoneman (OSC), S. Buckley, and all other faculty and industrial sponsors. Without their help, this project would not have been possible.

ASUSat1 has been granted the designation AO-37 (ASUSat OSCAR-37) by AMSAT-NA. OSCAR (Orbiting Satellite Carrying Amateur Radio) numbers are issued by AMSAT-NA, and is a long-lasting tradition recognizing the achievement of various amateur-satellite groups since the first Amateur Radio Satellite beginning with OSCAR-1 in 1961. To qualify for an OSCAR designation, certain specified criteria must be met, including the provision of communication resources for the general amateur radio community and/or the conduct of technical investigations in all respects consistent with the Radio Regulations.

## References

[1]Wong, J., Reed, H. L., and Ketsdever, A., "Temperature and Power Predictions for Flight-testing the Free Molecule Micro-Resistojet," International Electric Propulsion Conf., Paper IEPC-01-232, Oct. 2001.

[2]Reed, H. L., "ASUSat Lab: Student Projects in Aerospace," AIAA Paper 2001-0583, Jan. 2001.

[3]Bowman, D., Lang, J., and McMasters, J., "The Roundtable for Enhancing Engineering Education: An Update," AIAA Paper 97-0844, Jan. 1997.

[4]Wertz, J. R., and Larsen, W. J., *Space Mission Analysis and Design*, 3rd ed., Microcosm, Torrance, CA, 1999, pp. 359, 853.

[5]Wie, B., *Space Vehicle Dynamics and Control*, AIAA Education Series, AIAA, Reston, VA, 1998, pp. 365–371.

[6]Kumar, R. R., "Gravity Anchoring for Passive Spacecraft Damping," *Journal of Spacecraft and Rockets*, Vol. 32, No. 5, 1995, pp. 925–927.

J. A. Martin
*Associate Editor*