Building "Smaller, Cheaper, Faster" Satellites Within the Constraints of an Academic Environment

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Abstract

Student driven satellite projects are working under the constraints of extremely limited budgets, short development times due to student turnover, limited technical expertise, and other academic time commitment pressures. These are issues prevalent throughout the university system, but many programs do not directly address these realities. So how can educational programs promote a "smaller, cheaper, faster" philosophy and at the same time effectively realize its potential?

This question was asked of the students in Stanford University's Satellite Systems Development Laboratory (SSDL). In response, the Satellite QUIck Research Testbed (SQUIRT) program was developed to give students the opportunity to participate in the entire lifecycle of a satellite development.

This paper will summarize the technical solutions they have achieved, given the environmental constraints the program is under. In particular, the issues addressed are those relevant to the subsystems which the authors manage: Communications, Thermal Control, and Attitude Determination & Control. Each subsystem section will describe its goals, constraints, and technical approaches, as well as the integral role of industry.

It is hoped that this research and approach is transportable to other universities that wish to build their own small satellites. The successful matriculation of such "smaller, cheaper, faster" programs are not only fantastic educational opportunities for young engineers and future program managers, but eventually will prove beneficial to industry as this paradigm becomes the competitive norm.

1. Introduction

Since early 1993 graduate students in Stanford University's Aeronautics and Astronautics Department have been developing a laboratory to enable student design and construction of small satellites. In 1994, the Satellite Systems Development Laboratory (SSDL) was founded. Its focus is to construct microsatellites for under $50,000 and launch them within a year's time [1]. Each year, Master's degree students will initiate the next Satellite QUIck Research Testbed (SQUIRT) class spacecraft. SQUIRT-I is the Stanford AudioPhonic PHotographic InfraRed Experiment (SAPPHIRE) satellite.

The SAPPHIRE design team has been charged not only with the design and construction of the first satellite, but the generation of SSDL's facilities. The team has encountered many difficulties inherent to an academic environment: funds are severely restricted for a new laboratory; often access to proper design and construction facilities is

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*** SAPPHIRE Program Manager and Attitude Determination & Control Subsystem Manager, AIAA Student Member limited or nonexistent; and students often do not possess the technical expertise required for a project of this scope. Moreover, a graduate student's time commitment is limited by other coursework or projects.

In spite of these constraints, the SAPPHIRE satellite is well on its way to completion. This paper will address some of the design and technical obstacles that were encountered during SAPPHIRE's development. Solutions to these challenges were obtained through setting reasonable goals, maximizing the use of commercial "off-the-shelf" parts, and soliciting the help of industry mentors. It is the hopeful intention of the authors that these experiences and insights will help foster academic and industry partnerships towards the advancement of "smaller, cheaper, faster" satellite programs.

2. SAPPHIRE Description

SAPPHIRE will fly four payloads. The primary payload is a pair of micromachined tunneling infrared sensors sponsored by Professor Tom Kenny of Stanford's Mechanical Engineering Design Division in cooperation with NASA's Jet Propulsion Laboratory. These non-cryogenic sensors will see their first flight on SAPPHIRE. The second payload is a student-sponsored black and white digital camera that will take pictures of the Northern Hemisphere that will be digitally downlinked. The third payload is a voice synthesizer that translates uploaded ASCII text into a simulated voice signal that is FM broadcast. It will be principally used as an educational tool for elementary and secondary schools. The fourth payload is another student interest: a modified civilian GPS receiver to study the maximum performance which can be derived from non-optimal operation. This has never been done before.

SAPPHIRE is hexagonal cylinder measuring 8" on a side and 11" from top to bottom, weighing 35 pounds. The structure is primarily 0.5" aluminum honeycomb. The subsystems are arranged in a stack of four modular trays, as shown in Figure 1. The bottom tray contains NiCad batteries and the 5V and 12V DC-DC converters. The second tray contains the transmitter, receiver and terminal node controller of the communications subsystem. The next tray holds the CPU, memory, serial interfaces, and error correction electronics. The top tray is for the aforementioned payload electronics and sensors. SAPPHIRE will be fully assembled by September 1995, with all environmental tests and preparations completed by December 1995.

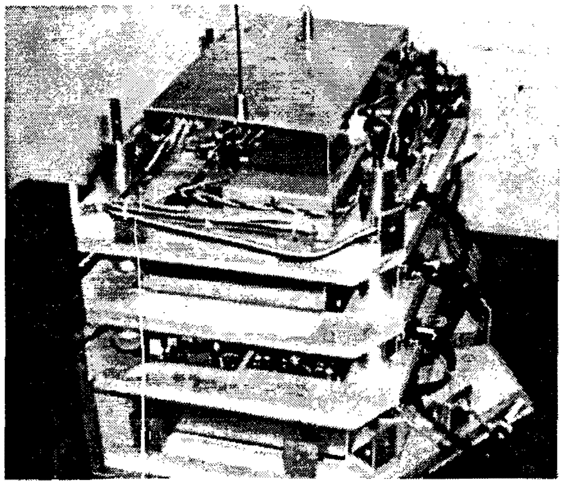

Figure 1: SAPPHIRE Functional Prototype

3. Communications Subsystem

The design of the communications subsystem is constrained by three major issues: it must have modulation schemes and frequencies that are easily accessible to the public, which ensures more community involvement and support; it must adhere to all the constraints laid down by the satellite bus itself, such as low power consumption, good heat dissipation, etc., and it must be accomplished very quickly.

Design Approach

The design, fabrication, and testing of a custom transceiver in one year's time proved to be a monumental task for students. Thus, a fallback plan of taking off-the-shelf components and modifying them to be flight worthy was enacted. The inherent challenge of using off-the-shelf communications products is that there are no vendors that make transmitters or receivers optimized for satellite operation. Thus many modifications had to be performed. In fact, certain sections of the transceiver boards had to be wholly redesigned. Establishing a net of mentors and industry support was also essential. Due to their advice and technical support, the educational experience was greatly enhanced.

Subsystem Overview

The baseline communications subsystem provides two-way data packet transmission as well as downlink analog output. Composed of one modified Hamtronics R144 receiver and one modified Hamtronics TA451 transmitter, the subsystem offers a 145.945 MHz uplink frequency and a downlink frequency of 437.100 MHz. These are amateur radio satellite bands that are allotted for SAPPHIRE. The extensive involvement of the amateur radio community will be discussed in more detail later in this section.

Two different modulation modes will be used. The first is terrestrial Audio Frequency Shift Keying (AFSK) modulation with full handshaking via a commercially available Terminal Node Controller (TNC). The 1200-baud TNC utilizes AX.25 packet protocols. AX.25 has error detection and correction bits, as well as addressable source bits and destination protocols. The second modulation mode is standard frequency modulation (FM) of the carrier for the Digitalker's synthesized voice downlinks. This was done so anyone with a handheld ham radio can listen to it "talk".

The full scale audio output power is 2.3 watts at an efficiency of almost 55 percent! This provides an acceptable energy per bit to noise ratio of 14-15 dB. All downlink signals go to four pseudo-circularly polarized 1/4 wave whip antennas. To account for any polarization losses, the difference will be made up at the ground station with higher gain Yagi antennas.

When the transmitter is not sending pictures or sending down voice messages, it will be put in a low power beacon mode of 200 mW audio output to conserve satellite power.

The receiver is a standard narrow band FM receiver with enhanced sensitivity (-117dBm) and 30 kHz of bandwidth. The output is then routed through the TNC for error detection and passed on to the CPU.

Technical Modifications

To achieve these results, technical modifications for the transmitter and receiver were necessary. These modifications are numerous but highly applicable to almost any small satellite, low earth orbit mission.

To begin with, the overall full power efficiency had to be improved. This was attained by meticulous optimization of the matching networks between the signal power amplifiers. It was found that most of the inefficiency, outside of the frequency multipliers, was due to the impedance matching. The average factory level tolerances are less than ideal. Biasing the amplifiers to nonlinear class C operation also helped. But the tightness of the bandpass filters had to be increased to clean off the harmonics due to this.

The variable power option for the beacon was obtained by switching the voltage bus to the power amplifiers from +12 to +5 volts. At the same time, this section was purposely de-tuned slightly (creating an impedance mismatch) through adjustable capacitive shunting.

The receiver's intermediate frequency (IF) bandwidth was not wide enough to account for Doppler shifts in uplink frequency. So the IF filters were removed and an Automatic Frequency Control circuit (AFC) was put in its place. Three to four kHz of Doppler is expected for our intended orbit, so the AFC circuit will effectively track the uplink carrier to account for this.

Repackaging of the transmitter, receiver, and TNC was necessary. All the electrolytic capacitors were replaced with tantalums. Most of the variable components were replaced by fixed value components. Extensive grounding measures to minimize feedback and increase resilience to switch noise was implemented. Vacuum sealed, cold welded, 15 ppm crystals were used to stabilize the local oscillators to temperature drifts. And the TNC's EEPROM was replaced by a reprogrammed radiation hardened PROM. A bit flip in the TNC software would have been mission ending.

Another circuit board had to be designed and fabricated to handle the CPU commandable multiplexing of the analog signals to the transmitter. Unfortunately, commercially available analog multiplexers (MUX) typically run off dual supplies. To circumvent this problem, the power inputs were hooked up to +5 volts and ground. Then the inputs were biased at +2.5V to keep the input signals from hitting the rails. The MUX chip is a CMOS fabricated chip, so as a precaution the input voltages were clamped with zener diodes to avoid any possible latch-ups.

Also placed on the same board was the circuitry needed to turn on and off the TNC and the transmitter. This ability is needed not only to reset the TNC in case of a loop, but also to comply with FCC regulations.

Industry Involvement

The communications subsystem could not have been successfully completed without the advice and cooperation of industry mentors. Mentors from the Lockheed Missiles and Space Company (LMSC) and various communications consulting companies donated their valuable time to critique the designs and offer leads on components. All the mentors were Amateur Expert Level Ham Radio Operators. They are very experienced at design and quick to offer their advice for a project that will promote educational engineering, which is one of their charters [2].

The use of ham radio frequencies is also paramount. The amateur radio community has been instrumental in framing the technical and operational scope of the SAPPHIRE program. This relationship serves to enhance the educational experience of the project's students, and it reinvests the skills and experiences of the mentors in a new generation of engineering designers.

Essential assistance was provided by industry partners Space Electronics Inc. and Harris Semiconductor Inc. These companies provided access and technical support for radiation hardened chips used by both the Communications and CPU subsystems. Such cooperation benefits the students in acquiring industry contacts and access to expensive parts, and the companies benefit from opportunities for space qualifying their parts.

4. Thermal Control Subsystem

The thermal control subsystem's purpose is to maintain all parts of the satellite within specified temperature ranges. This is to be done using no power and less than 1 lb of mass. These constraints require a passive design using special coatings, conductive strips, and insulation for SAPPHIRE.

Aside from designing the actual thermal control subsystem for SAPPHIRE, the thermal control subsystem was charged with the task of creating the infrastructure for SSDL to perform in-house thermal analyses. Because no capability existed in the Aero/Astro department, the thermal control design team had to determine what kind of software existed to aid in thermal analysis which could account for radiative as well as conductive heat transfer, procure it, and learn how to use it.

Design Approach

To begin the design process, a simple-hand calculation was used to determine the average satellite hot and cold temperatures. For a range of orbits and eclipse scenarios, this calculation yielded average satellite temperatures ranging from 323 K to 556 K. These values give a basic idea of how hot the satellite will be operating, depending on the final orbit selection.

Based on this, it is known that without thermal control, the satellite will operate too hot. However, the most important issue with the thermal control subsystem design is that each component of the satellite be maintained within their specific temperature ranges, as shown in Table 1. This can only be done through a nodal-network, transient analysis which requires detailed knowledge of the orbit, internal power generation, and internal structure in order to analyze the potential hot or cold spots of the satellite.

The main obstacles faced have been: a) the actual orbit in which SAPPHIRE will be placed is still unknown; b) the subsystems' designs are still evolving; c) the final power use as well as shape, size, and placement of many of the electronic components will be unknown until the actual flight hardware is built; and d) many components are off-the-shelf, not space-rated, and therefore the manufacturers are not concerned with detailing the thermal parameters required for space operation analysis. Thus it is difficult for students to find out the necessary information about the components.

Component	Standby T.	Operate T.
Fotoman	-40 to 50 C	0 to 40 C
Digitalker	-65 to 150 C	0 to 70 C
IR A and B	-20 to 50 C	-10 to 50 C
CC&DH	-20 to 50 C	0 to 40 C
Transmitter	-20 to 30 C	-20 to 30 C
TNC	-20 to 30 C	-20 to 30 C
Receiver	-20 to 30 C	-20 to 30 C
Regulator	-20 to 100 C	-20 to 100 C
Batteries		
Drawing	-20 to 50 C	-20 to 50 C
Charging	0 to 50 C	0 to 50 C
Solar Panels	Cold as Poss.	Cold as Poss.
Launch Interface	N/A	0 to 100 C

Table 1: Component Temperature Constraints

The NEVADA and G/SINDA software packages were used to perform the transient nodal analysis. SAPPHIRE was broken into 201 nodes. The RENO sub-program of the NEVADA package calculates radiation interchange factors between the nodes of SAPPHIRE. These factors are geometry- as well as surface-property dependent which make them extremely difficult to calculate by hand, even for as simple a structure as SAPPHIRE. The RENO output is then processed by another sub-program called GRID which creates actual radiative conductance values between the nodes. Next, the VEGAS sub-program is used to calculate on-orbit heating rates. These rates depend on the satellite geometry, as well as the orbit and satellite rotation.

To complete the analysis, a G/SINDA input file is created which defines the initial temperature and thermal capacitance of each node, the power generated at each node, and also the conductance (through both conductive heat transfer and radiative heat transfer) between nodes. Output from both GRID and VEGAS is already in compatible G/SINDA format for ready inclusion into the G/SINDA input file. This file is then pre-processed, turning into actual FORTRAN code which is compiled and linked. A preliminary analysis of SAPPHIRE yielded the typical results shown in Table 2.

Node #	Description	Temperature Range (K)
11	Fotoman	301 to 351
12	Digitalker	301 to 391
14	IR A and B	300 to 339
22	CC&DH	302 to 339
32	Transmitter	301 to 332
33	TNC	302 to 350
31	Receiver	302 to 333
43	Regulator	303 to 390
41	Batteries	301 to 345
8103	Launch Interface	301 to 381
105	Solar Panel 1	441 to 629
303	Solar Panel 3	435 to 629
508	Solar Panel 5	437 to 728
701	Solar Panel 7	406 to 680
804	Solar Panel 8	522 to 695

Table 2: Preliminary Results, No Thermal Control

These results were then analyzed to determine the problem areas in the satellite. As can be seen, SAPPHIRE, in general, runs too hot. Based on this analysis, special coatings, conductive strips, and multi-layer insulation (MLI) will be placed as described in the next section.

Subsystem Overview

Not surprisingly, the biggest problems are getting the heat away from the batteries and then out of the satellite itself. As SAPPHIRE is structurally designed, there are no good heat paths between panels. Also, aluminum honeycomb (k = 1.97 W/m/K) does not conduct as well as aluminum (k = 237 W/m/K) which makes it even more difficult to get the heat spread about the satellite and to the outer structure.

To compensate for these problems, conductive strips will be used to seal the edges of the honeycomb panels and to create paths between the panels. The batteries will be mounted to the baseplate with special epoxies to allow the most conduction possible between them and the structure. Where it will not interfere with the solar cells, the exterior structure will be painted with a coating such has white paint which has low absorptivity and high emissivity. A radiator block will be placed in both the top and bottom solar panels with copper strips leading to these from the hottest areas of the satellite.

This design has yet to be analyzed. Currently, the thermal model is being refined to adequately model existing conduction paths between structural pieces as well as components. This type of modification should allow all components to be maintained within their operational temperature ranges.

To monitor potential problems, temperature sensors will be placed in the following locations: the center of every other side panel, the center of the top and bottom panels, the voice synthesizer, the microprocessor, the transmitter, and each battery pack.

To verify the design, SAPPHIRE will be cycled through thermal vacuum tests later this year.

Industry Involvement

Industry involvement has been vital to the development of this subystem. The thermal control subsystem design problem is mostly one of analysis, but it can be extremely complicated and involved. In normal academic heat transfer courses, only very simple, uncoupled problems are posed involving radiation due to the nonlinear and geometry-dependent behavior of the transfer mode. These problems have closed-form, analytic solutions which is not the case for most satellite applications. In industry, software packages have been developed to aid in this type of analysis through numerical solution. However, this software can cost tens of thousands of dollars or not even be available to the general public, let alone students.

Industry partners have been invaluable in providing access and training for a number of analysis tools. LMSC has allowed student use of its Thermal Systems Synthesizer (TSS) software on site in Sunnyvale, CA. Turner Associates has donated the NEVADA software package to the laboratory . Network Analysis Associates Inc. has donated G/SINDA, a personal computer version of the government developed SINDA/FLUINT general thermal analysis mainframe software. Additionally, employees of LMSC and Space Systems/Loral have provided analysis and design tips and suggested materials for use in the final design.

5. Attitude Determination & Control Subsystem

The mission goals for the Attitude Determination & Control Subsystem (ADCS) are divided between sensing and pointing requirements. The pointing requirements are to orient SAPPHIRE for picturetaking of North America and to provide a predictable spin to improve IR sensor performance. There are no hard sensing requirements; the ADCS team was asked to try to provide attitude and position information which is useful to predict good picturetaking times and that could help in IR sensor data analysis.

The program goals involve the practical consideration of serving student interests. The ADCS team members are interested in the issues of satellite autonomy and attitude sensing, thus SAPPHIRE design goals reflect their research plans. In addition, SSDL has set a long-term goal to provide three-axis stabilization of a microsatellite and the ADCS team was asked to plan a course to achieve that goal.

The constraints are similar to those affecting the other subsystems: to meet all requirements using minimal mass, power, volume and price, all in one year's time. ADCS design is further affected by the difficult test conditions: attitude control methods cannot be adequately tested with the equipment available to SSDL. The students' limited background in hardware or sensing at the outset of the project also impacted the design. The final constraint is that the primary ADCS team members are also the project managers, limiting the time available for subsystem development.

Design Approach

The critical development in the design of the ADCS has been a humble acceptance of reality: this subsystem does not try to do more than is asked of it. The other subsystems placed minimal performance requirements on the ADCS, meaning that a simple design is possible. Although active control is a program goal, it was recognized early that such an effort should be considered a payload in itself, and therefore deferred for future studies.

In addition, students were given time to follow their specific interests, leading to serendipitous developments. What was originally a few lines of code to guess at the expected available solar power has become an orbit, attitude and electrical power simulation used heavily by the ADCS and Power Subsystem design teams.

Critical support and guidance was provided by faculty and industry mentors for direction in the design of the subsystem.

Subsystem Overview

The subsystem uses completely passive control. The ADCS borrows from its AMSAT Microsat heritage in the design of its pointing control, assuring reliability. Four Alnico V bar magnets are mounted along the satellite's vertical axis, orienting it with the Earth's magnetic field. The camera looks out of the top (North-seeking face), so it will be viewing the Earth as the satellite flies over the Northern Hemisphere. The four transmitting antennae are painted white on one side and black on the other, and are arranged to provide a very small but very steady torque about the vertical axis. This "radiometer effect" is due to solar pressure. Ferrous bars with strong hysterisis properties are oriented perpendicular to the spin axis to damp nutations as well as create a maximum spin rate. All these elements were present aboard WEBERSAT , launched in 1990. While no precise data is available from its predecessors, SAPPHIRE is expected to align itself within 20° of the magnetic field and spin at about 1/2 rpm.

With the pointing control established, design emphasis has been on sensing. Sensor development furthers program goals without risking the project because no component relies on these sensors for information, and failure does not affect satellite operations. For SAPPHIRE, infrared phototransistors are mounted with the same field of view as the digital camera, indicating when it has a full view of the Earth. The presence of the IR sensor and GPS receiver payloads provide more information to determine attitude and position. Students are evaluating the effectiveness of measuring attitude relative to the Sun using only telemetry from solar panel currents and battery voltage and charge [3]. This attitude determination method is a standard troubleshooting tool in the event of satellite failures; the SSDL contribution is a formal study to understand the effects the power subsystem and the space environment have on accurate analysis, in order to use this method as a "regular" sensor. It is expected that ground processing will determine the orientation of SAPPHIRE with respect to the Sun to within 7°, and be able to determine if the camera can see the Earth.

All project goals were met with the above design. Because it relied on proven methods, the baseline was chosen early in the design process and has allowed other subsystems flexibility in choosing their options. All requirements were met using 0.7 lbs, 50 μW, and approximately $400 for materials.

Industry Involvement

The inexperience of students is overcome through active support of faculty and local industry. Experienced engineers have donated time and insight in developing a thorough design approach. It is hoped that the resource base that has been gathered for SAPPHIRE will be expanded upon by future SQUIRT teams.

The attitude simulation has been the primary program contribution from the ADCS team. It is a modular, expandable tool that will be refined and upgraded as the SSDL knowledge base increases. The ADCS team for SAPPHIRE has laid the foundation for future SQUIRT missions; the steps necessary to develop active control are more clearly identified.

The SAPPHIRE accomplishments do not merely impact student satellite projects at Stanford and other universities. The innovative re-examination of an old Sun sensing method is of potential use to all small satellites. More importantly, experience with SAPPHIRE is leading to basic research in satellite autonomy with the support of NASA Ames Research Center.

6. Conclusion

In an academic environment, the challenges of successfully building a student-run, student-made satellite program are enormous. At the Stanford Satellite Systems Development Laboratory, students have overcome the inherent academic barriers of little or no funding, limited technical expertise, time commitment pressures, and fast student turnover to successfully develop the SQUIRT program. The program is founded on the "smaller, cheaper, faster" philosophy that is essential in today's political, academic, and business climates. The technical solutions outlined in this paper are a manifestation of that very philosophy.

The SSDL team has developed an effective style to achieve success. The subsystems summarized in this paper illustrate the different approaches necessary for each subsystem to individually succeed and ensure a viable satellite. The Communications Subsystem capitalizes on modifications to off-the-shelf technology. It also has relied on strong industry partnerships for hardware experience and mentoring. The Thermal Control Subsystem has built an infrastructure for subsequent satellite design, analysis, and testing. The Attitude Determination & Control Subsystem has set attainable goals and pursued long-term program objectives. All have benefitted from active industry and community involvement.

In essence, to advance the state-of-the-art of small satellites requires more than individual technical accomplishments, it requires an infrastructure that nurtures such programs with similar goals to flourish at the university level on up. SSDL's SQUIRT program is not the final answer, but it can be used as an effective model by which other universities can implement their own scientific and technical space research programs. Only then will the academic environment provide an atmosphere that is less cumbersome and restrictive towards programs of this magnitude. The effective cooperation of academia, the community, and industry will make small satellite technology smaller, cheaper, and faster than ever before.

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