The Design and Construction of the Stanford Audio Phonic Photographic Infrared Experiment (SAPPHIRE) Satellite

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Abstract

The students of Stanford University's Satellite Systems Development Laboratory (SSDL) have commenced detailed design and construction of a new micro satellite. Named the Stanford Audio Phonic Photographic Infrared Experiment (SAPPHIRE), this spacecraft's payloads include a miniature infrared (IR) research package, a digital camera, and a voice synthesizer. The bus consists of a 25 pound, 9 inch tall, 16 inch diameter hexagonal structure with complete processor, communication, power, thermal, and attitude control subsystems.

The SAPPHIRE spacecraft is the first vehicle of the SSDL's new Satellite Quick Research Testbed (SQUIRT) program. The goal of this project is to produce student engineered satellites capable of servicing state-of-the-art research payloads on a yearly basis. Through student participation, voluntary mentoring from the industrial and academic community, and the extensive use of off-the-shelf components, the initial cash outlay target for SQUIRT class vehicles is $50,000. This paper introduces the goals of the SQUIRT program and details the design progress of the current SAPPHIRE vehicle.

1. Introduction

Stanford University's Department of Aeronautics and Astronautics has recently broadened the mission and expanded the scope of its traditional spacecraft design curriculum. This expansion is a direct response to industry demand for graduate level emphasis and hands-on experience in systems engineering and spacecraft technologies.

The new focal point for these activities is the Satellite Systems Development Laboratory. Officially inaugurated in January 1994, the SSDL charter is to provide world class education and research in the field of spacecraft design, technology, and operation. Accordingly, its personnel create and instruct a comprehensive academic program as well as guide and manage a state-of-the-art research agenda. The specific execution of these tasks is accomplished through classroom instruction, research work, and project experience.

As a means of supporting these goals, the SSDL is actively engaged in a number of advanced satellite mission design projects. Scientific and engineering partners in these projects include a variety of academic research programs, government laboratories, and industrial corporations.

2. The Satellite Quick Research Testbed (SQUIRT) Program

The goal of the SQUIRT program is to produce student engineered satellites capable of servicing state-of-the-art research payloads on a yearly basis. Participation in this program prepares graduate degree students for the SSDL's advanced spacecraft programs and offers a comprehensive educational experience.

To limit the scope of the program and to provide direction in the yearly academic setting, the following design guidelines are stressed. SQUIRT vehicle mission and environmental lifetimes are set at approximately one year, and relatively small cash budgets of $50,000 are targeted.

The SQUIRT physical requirement is loosely specified as a highly modular bus weighing 25 pounds and having a 9 inch high by 16 inch diameter hexagonal form as depicted in Figure 1. Continuous development of alternate processor, communications, power, thermal, attitude control, and detailed structural options serves to populate the satellite design toolbox available to future SQUIRT teams. Additionally, guidelines require that all employed design tools, facilities, and technologies are available within the Stanford community and its academic, governmental, and industrial affiliates.

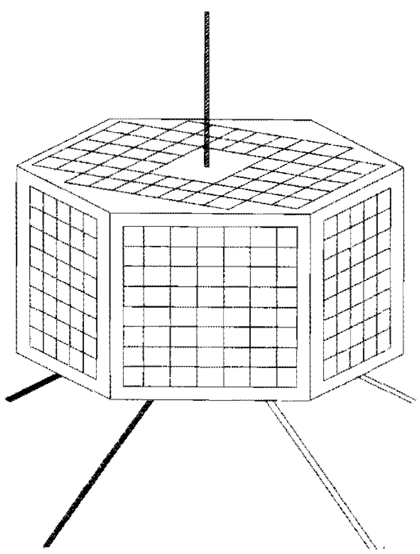

***Figure 1** - SQUIRT Physical Form.*

Design teams are also urged to employ amateur satellite radio standards in order to foster a cooperative and mutually beneficial relationship with that community. Current plans call for flight operations to commence with emphasis placed on payload research and educational activities. During this initial period, moderate access is granted to satellite experimenters and includes command ability for the educational payloads. With research and educational activities finished, complete operational authority of the vehicles is transferred to the amateur satellite community.

Because of the program's time and monetary considerations, much of the design process involves the modification of off-the-shelf non-space-rated consumer products. Once a particular component model has been selected, engineering studies are executed in order to determine the hardware, electronic, and software modifications and redesigns required for space environment operation at reasonable confidence levels. These steps are documented in modification plans that are then submitted for review to the SSDL's academic and industrial mentors as well as the component's vendor. Once approved, the modifications are implemented and the components are interfaced and assessed through hardware, software, and electrical diagnostic checks. Through cooperation with local industrial affiliates, these checks include structural vibration, acoustic, and thermal vacuum tests.

Educationally, the SQUIRT program exposes graduate engineering students to satellite design by providing hands-on technical and managerial experience in the conceptual design, requirements formulation, subsystem analysis, detailed design, fabrication, integration, test, launch, and operation of a flight quality micro satellite. With respect to research, SQUIRT vehicles serve as a generic space based platform for the variety of low power, volume, and mass experiments currently under development within the SSDL, Stanford, and affiliated academic, industrial, and governmental centers. Already, conceptual designs for future SQUIRT missions are being formulated for the following payloads: a miniature arc jet thruster, an analog television transmitter, a radiation sensor, various flight qualification packages, and an autonomously coordinated constellation experiment involving multiple SQUIRT vehicles.

Philosophically, SQUIRT satellites are intended to be excellent examples of simple, fast, cheap, flexible, and smart micro satellite design. Simplicity permits success in the allotted time and allows students to gain technical insight into the entire design and operation of the satellite. Speed allows the student to witness the entire life cycle of the satellite design process. It also provides rapid access to space and focuses efforts towards incremental and iterative technical upgrades. Low cost design satisfies the practical monetary constraints of the SSDL and provides an attractive platform alternative to potential researchers. Flexibility in the design allows the satellite to interface with a variety of potential payloads, to be launched on an assortment of launch vehicles, and to operate in a wide range of orbits. It also permits the design to withstand the uncertainties and technical evolution inherent in a student activity. On board intelligence allows the vehicle to overcome the natural inefficiencies of the low precision spacecraft that typically result from the aforementioned programmatic considerations.

Given this philosophical direction, the SQUIRT program accepts a number of characteristics typically denounced in commercial spacecraft development. These include acceptance of high risk, little component redundancy, low precision control, non-optimal designs, and inefficient spacecraft operations.

3. The Stanford Audio Phonic Photographic Infrared Experiment (SAPPHIRE)

Based on student interest and the capabilities of the SSDL's affiliated researchers, the selected missions for the SAPPHIRE spacecraft include 1) assessing the performance of experimental IR sensors, 2) performing digital space photography, and 3) broadcasting voice synthesized messages. The IR sensor package is the result of micro machinery research based in Stanford University's Department of Mechanical Engineering. Digital black and white photography is achieved through the modification of a Fotoman camera in cooperation with engineering staff at Logitech. Digital voice synthesis is obtained through the modification of a commercially available synthesizer board. Broadcasts are transmitted so that they may be received on a hand held radio.

Given these objectives, as well as the SQUIRT program goals previously outlined, students commenced the formal design of the SAPPHIRE satellite by formulating the applicable system requirements and flowing them down to the respective subsystems. Design alternatives were then generated and analyzed through software simulation and hardware modeling. Finally, a series of formal trade-off studies and industry design reviews led to the selection of a baseline spacecraft and component configuration.

With respect to functionality, the selected bus baseline consists of a microprocessor board that monitors and controls component activity, processes command inputs, and formats telemetry outputs. Data and voice communications are achieved through the use of Amateur Satellite frequency bands. Power system solar arrays produce more than 8 watts of average power and are augmented with battery storage. A Global Positioning System (GPS) receiver, Earth sensors, and virtual sun sensors provide orbit and attitude information crucial to payload and downlink operation. Passive magnetic and spin control is utilized to properly orient the camera and smooth the solar load on the passive thermal regulation system. Figure 2 displays the functional electrical interfacing of the active components.

This section describes the current state of design of the various SAPPHIRE subsystems. In addition, an in-depth description of the trade-off analysis undertaken for the structural configuration has been included in order to present the systems engineering methodologies employed throughout the SAPPHIRE project.

3.1 - Payloads

The purpose of the infrared experiment is to space qualify a new IR sensing technique and packaging scheme. This work is based on low power micro machined sensor research being performed in conjunction with Stanford Professor Tom Kenny and the Jet Propulsion Laboratory. The camera and voice synthesizer are included to serve as interesting and educational student payloads with distinct benefits to the Amateur Satellite and educational communities. As a student project, these payloads will attract attention and foster involvement in the SSDL's satellite operations. They will intrigue the Amateur Satellite community by permitting the commanding of individualized pictures and messages. And several secondary schools are studying the idea of classroom based satellite contacts in order to generate interest in science and math education.

Infrared Sensor Experiment: The IR sensor is a fixed, narrow field-of-view horizon crossing instrument based on tunneling sensor transducer technology. The new measuring technique consists of sensing pressure differences between gases separated by a thin membrane. Physically, each sensor has a 2 square millimeter active surface mounted within a 28 pin IC socket. A DC-to-DC converter is employed to accept a 12 volt regulated bus voltage and output a low current 100 volt supply to the instrument. Sensor output consists of a 0-5 volt analog signal to be sampled at 1000 Hertz.

Current plans call for the sensors to be acquired from the Jet Propulsion Laboratory or possibly fabricated at Stanford University. The

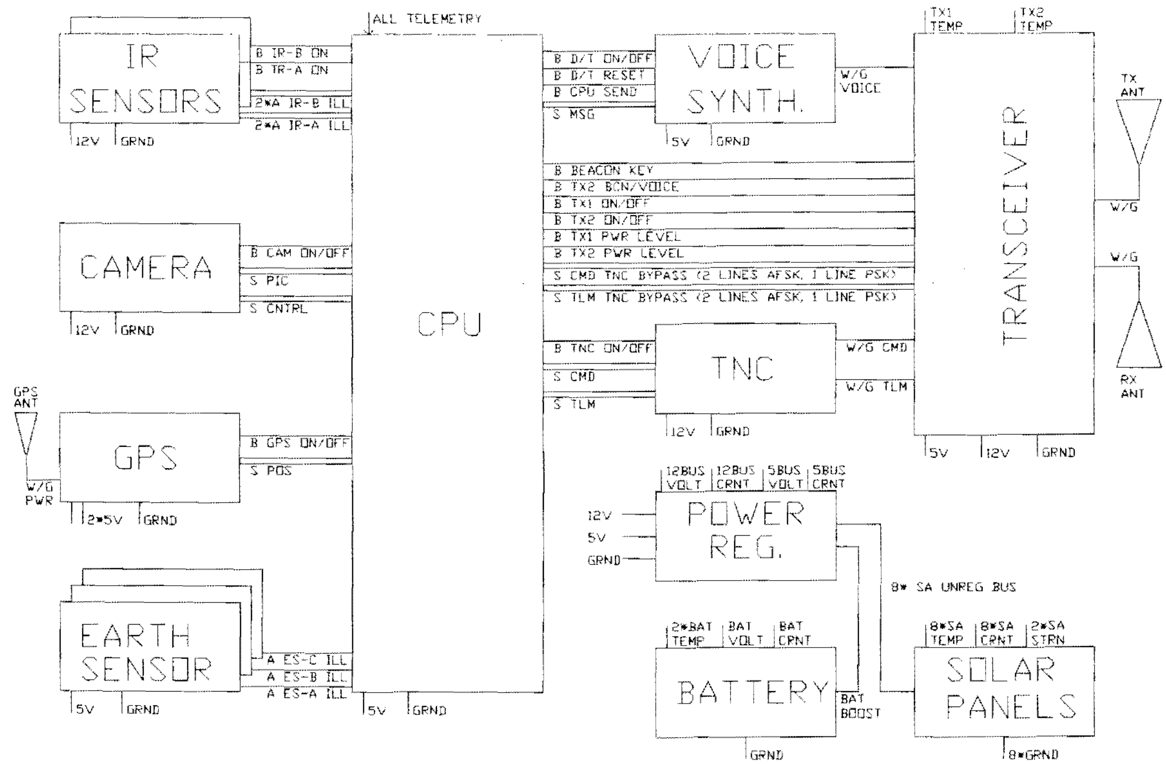

Figure 2 - SAPPHIRE Functional Interfaces

power converter and other support circuitry will be designed, built, and tested by students.

Camera: Due to the attitude precision and memory issues prevalent in the SQUIRT program, a digital camera based upon CCD technology was chosen to perform the SAPPHIRE's photographic mission. The Logitech Fotoman was chosen to provide this service due to its data handling ability, its convenient computer based operation, and the outstanding level of educational and technical support provided by Logitech engineers. The Fotoman can take and simultaneously store 32 different 496x360 pixel images using 256 gray levels. JPEG compression is used to reduce each photo to about 23 Kb.

Current modification plans require potting, coating, and repackaging the electronics, disabling the flash assembly, and adding a power switch. Software modifications will permit the reloading of the Fotoman RAM code in case of radiation upset. This code permits the taking and downloading of a particular picture as well as the quick transmission of low resolution 'thumbnail' sketches of all photos.

Voice Synthesizer: Voice synthesizers accept ASCII text strings, phonetically translate the strings, and generate an analog audio output equivalent to human speech. The RC Systems v8600 model was selected to provide this function over two other contending units due to its ease of use and interfacing, quality of voice output, and cost. Development plans consist of structurally mounting the board in a shielding box and replacing and coating low confidence electronic components. In addition, student designed reset circuitry will be implemented in order to simplify the board's interface with the bus computer.

3.2 - Structural Subsystem

Particular attention has been focused on the SAPPHIRE structural design due to the desire to employ its basic configuration for all future SQUIRT vehicles. This intention is rooted in the requirement to provide a solid foundation on which to base the yearly projects. Also, a characteristic look for the satellite will foster the growth and popularity of the SQUIRT program.

As previously stated, the SQUIRT structural configuration consists of a right hexagonal prism that is approximately nine inches tall and sixteen inches in diameter. The hexagonal shape was chosen as a compromise between octagonal and rectangular geometries since it allows for adequate solar panel exposure and internal volume while reducing the number of side panels. An octagonal geometry has a high usable surface area per volume ratio but is relatively difficult to manufacture. A rectangular geometry has a lower usable surface area per volume ratio but is relatively easy to manufacture. The external dimensions and vehicle mass were selected in an attempt to meet eighty-five percent of all secondary launch vehicle opportunities.

Requirements: Given the SQUIRT program's design objectives and constraints, a set of structural configuration requirements was generated. The structure must survive launch loads and environments, be easily analyzed and verified, provide mounting points for components, provide shielding for components, provide adequate thermal pathways, be lightweight, and be inexpensive. In addition to the above requirements, the quality of the structural configuration was evaluated on its manufacturability, component accessibility, and versatility.

The manufacturability of the configuration was based on its fabrication methods (machining, sheet metal forming, computer numerical control (CNC) machining, hand tools), material selection (metal sheet/bar/plate, graphite/epoxy composite, aluminum honeycomb sandwich), fabrication location (in the classroom, on-campus machine shop, off-campus machine shop), joint types (bonded, fastened, welded), part count (unique parts, modular parts), and part complexity (number of operations to manufacture each part).

The accessibility of the configuration was based on the time required to expose one component in laboratory and launch pad environments, the time required to expose all components in laboratory and launch pad environments, the amount of hand clearance around components, and the complexity of the wire harness layout.

The versatility of the configuration was based on the ability of the configuration to allow for re-sized components, to accommodate additional components, to minimize unusable volume, to allow payload access to multiple external faces, and to provide separation between the vehicle bus and payload.

Design Alternatives: After generating more than a dozen structural configurations which could satisfy the requirements, two were selected for further investigation: the spaceframe, and the stacked tray design.

The spaceframe design, displayed in Figure 3, consists of a top and bottom CNC machined, hexagonal aluminum plate. The two plates are attached by six aluminum beams. Components are attached on each of the six sides of the structure with aluminum brackets, and the batteries are mounted in the center of the structure. Six rectangular graphite/epoxy composite solar panels are fastened to the sides of the structure, and two hexagonal graphite/epoxy composite solar panels are fastened to the top and bottom of the structure. The electrical interface is located in the interior of the structure.

The core of the stacked tray design is made up of four aluminum honeycomb rectangular trays with two rectangular solar panels fastened to the front and back of the structure. Two angled solar panels are fastened to the sides of the structure forming the right hexagonal prism. Hexagonal solar panels are fastened to the top and bottom of the structure as well. All solar panels are constructed of aluminum honeycomb. Each tray is fastened to the tray above and below it with aluminum brackets. Components are then fastened to the trays. The components are arranged such that each tray or shelf contains one subsystem. The electrical interface is located along the outside of the stacked tray in the volume between the stack and the angled solar panels. This configuration is pictured in Figure 4.

Trade Study: Students and engineers with a wide variety of experience rated the quality of these two configurations based upon manufacturability, component accessibility, and versatility. Students determined that either design could be engineered to meet the other seven requirements. For the three traded

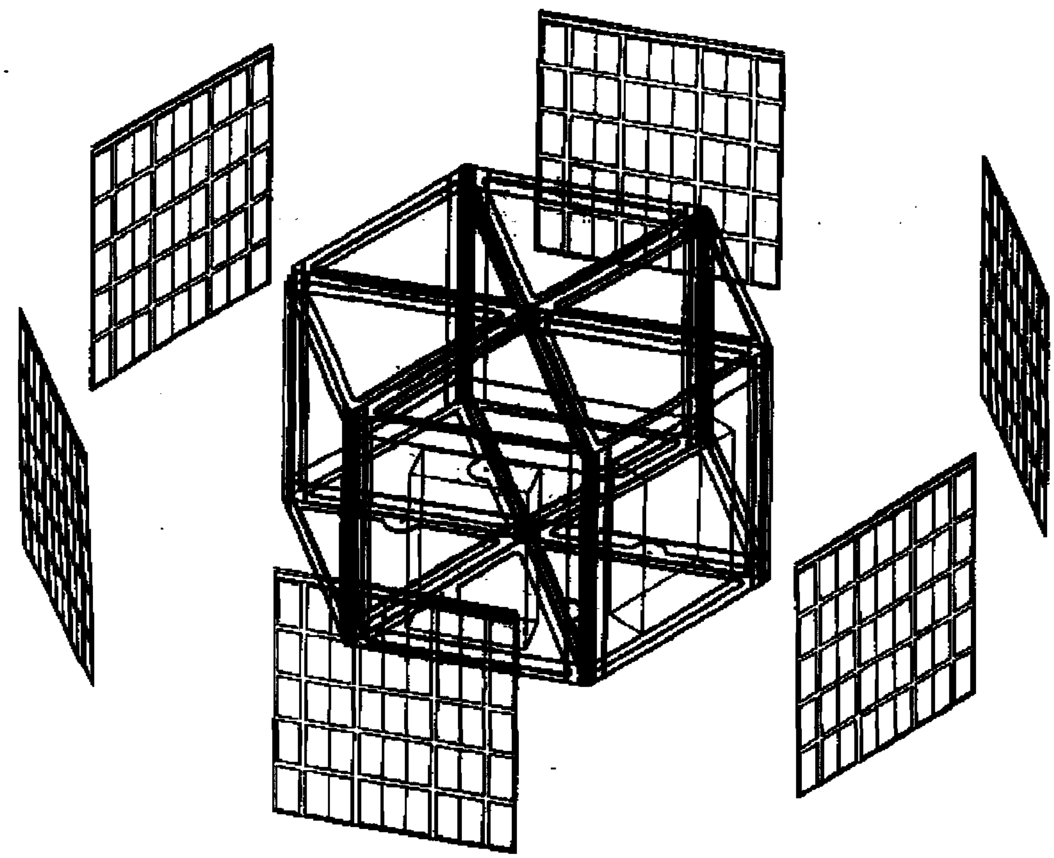

Figure 3 - Spaceframe Configuration.

requirements, numerical values were assigned to both configurations for each criterion. After normalizing and weighting the results, a total numerical value was assigned to each configuration by each evaluator.

The manufacturability of the two configurations was deemed nearly equivalent (most raters numerically judged the designs as being within 3% of each other). The spaceframe requires significant CNC machining and some sheet metal forming. The stacked trays require working with honeycomb panels and some machining. The spaceframe, while requiring some graphite/epoxy composite materials, is made up of mostly aluminum beams which are easier to work with than the aluminum honeycomb sandwich material used for the stacked trays. Both designs can be manufactured on-campus but probably can not be made in the classroom. Both designs also rely heavily on mechanical fasteners and have modular parts, but the spaceframe joints are less complex and have fewer parts. The stacked trays require a complex bracket to be built, but the spaceframe requires an even more difficult beam to be machined

The component accessibility of the two designs was also judged to be nearly the same (again, most calculated the designs to be within 3% of each other). The time required to expose one or all of the components in the spaceframe is less than or equal to the time required for the stacked trays since, in many cases, only one solar panel needs to be removed. More hand clearance around components is available in the stacked trays, and its linear wire harness layout is simpler than the layout required for the spaceframe.
The versatility of the stacked trays was judged as being considerably better than the versatility of the spaceframe (the stacked configuration numerically scored at least 15% higher in all

cases). The large tray area allows for component and payload size changes and additional components. The spaceframe has a much smaller area on each of the six sides of the structure and has limited opportunity for additional components. Both designs contain some unused volume. Both designs allow for access to many vehicle external faces, but the stacked trays can access the faces from one location due to the placement of the payloads in a single tray. The spaceframe cannot access external faces as well. The stacked trays provide for distinct bus and payload separation since subsystems are arranged on separate trays. The spaceframe does not isolate the payload from the vehicle's bus components.

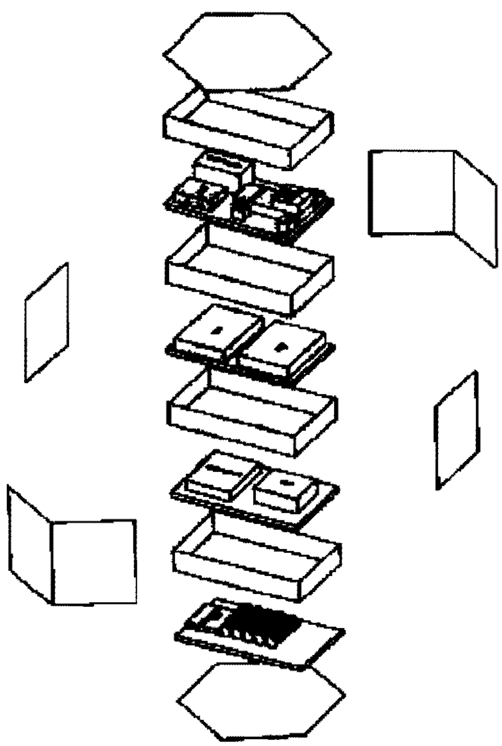

Figure 4 *- Stacked Tray Configuration.*

Weighting: The versatility criterion received a higher weighting than the manufacturability and component accessibility criteria. While not a trivial undertaking, the fabrication and integration of either vehicle can be done. Versatility, on the other hand, is a quality that should set the chosen SQUIRT structural configuration apart from other alternatives. A highly versatile configuration allows the design to evolve and endure.

Selected Baseline: Both alternatives received nearly equivalent scores for manufacturability and accessibility. The stacked tray design, however, received much higher scores in the more important category of versatility. This resulted in a higher total score for the stacked trays. This weighted objectives methodology validated the instincts of the majority of the design team. For these reasons, the stacked tray configuration was selected as the baseline structural design. An example of the numerical analysis used for this study is shown in Figure 5.

The precise component layout of the stacked tray design is as follows. Numbered from bottom to top, power subsystem components are in tray one, communications equipment is in tray two, processor and data handling boards are in tray three, and the payloads and GPS receiver are in tray 4. Benign attitude control components and the wiring bus are located in the lateral spaces between the rectangular core and the solar panels. Solar cells, communication and GPS antennae, and attitude sensors are located on the vehicle's exterior.

Detailed Design, Analysis, and Verification: With the stacked tray configuration selected, detailed design work and simulation has commenced. This includes the fabrication of several configuration mockups, the generation of a detailed structural analysis model, and the fabrication, integration, and test of the final structure.

3.3 - Computer, Command, and Data Handling Subsystem

This subsystem serves as the primary component interface and flight manager for the entire spacecraft. It consists of a computer board, an I/O board, and a modular software architecture.

An initial trade study narrowed the choice of computer boards to 4 alternatives. Although a more complete study continues at this time, a Motorola 68332 processor was purchased in order to begin component interfacing and programming. The final design choice will be based upon capability, cost, ease of interfacing and support, space environment performance, and schedule considerations.

0.3	Manufacturability	Score	SPACEFRAME Comments	Pts.	Score	STACKED TRAYS Comments	Pts.
20	Material Selection	7	Graphite epoxy	140	6	Aluminum honeycomb	120
30	Fabrication Methods	5	Significant CNC, some bending	150	5	Honeycomb tools, small CNC	150
10	Joint Types	8	Many bolts, but simple	80	7	Many bolts, complex interface	70
10	Part Count (unique parts)	8	High repeatability	80	7	Very simple or repeatable	70
20	Fabrication Location	6	All on-campus, not all in rm. 174	120	6	All on-campus, not all in rm. 174	120
10	Part Complexity	5	Difficult cuts	60	6	Brackets are difficult	60
			Total	620		Total	590
			Weighted Performance	186		Weighted Performance	177

0.3	Accessibility	Score	SPACEFRAME Comments	Pts.	Score	STACKED TRAYS Comments	Pts.
5	Exposed electronics, from fully assembled	7	Solar panels/multiple boxes	35	7	Solar panels and opening whole stack	35
25	Single box exposed, from fully assembled	8	Single panel and single box	200	6	All panels, much of the stack	150
10	Exposed electronics, from lab setup	8	Almost already done	80	8	Just open the stack	80
30	Exposed box, from lab setup	8	Box is automatically accessible	240	7	Same time as whole system	210
20	Component clearance (hand room)	7	Tight in spots	140	8	Wires right where you want them	160
10	Difficulty in initial wire layup	5	Rat's nest waiting to happen	50	8	"Linear" and plenty of room	80
				745		Total	715
			Weighted Performance	223.5		Weighted Performance	214.5

0.4	Versatility	Score	SPACEFRAME Comments	Pts.	Score	STACKED TRAYS Comments	Pts.
10	Bus and payload separation (distinct)	5	Payloads are integrated as any other	60	7	Payloads have own shell/shelves	70
30	Allow for resized components and payloads	5	Limited size/shape availability	150	7	Expandable size/shape	210
15	Payload fields-of-view	7	Many available - but not all at once	105	8	Many view, and all at once	120
25	Accommodate additional components	5	Fundamental "wall" limitation	125	7	Limited by shelf height	175
20	Minimize unusable volume	6	Corners and other places	120	6	Much unusable volume	120
			Total	550		Total	695
			Weighted Performance	220		Weighted Performance	278
			Total Score for Spaceframe	629.5		Total Score for Stacked Trays	669.5

Figure 5 - Example Weighted Objectives Worksheet

Due to baseline choices in other subsystems, a mature design for a student engineered I/O board has been developed. This board multiplexes telemetry inputs and handles all binary component control lines.

Implementation of required software has been initiated through a formal requirements review process that has specified all software functions and interface criteria. A high level flight manager module regulates component operation and determines the appropriate processor computational support required at all times. Low level code controls all component interfacing.

3.4 - Communications Subsystem

The communications system provides uplink and downlink data packet transmission and downlink voice and beacon output. Data transmission operates at 1200 baud and is baselined to use AFSK encoding, AX.25 packet protocol, and standard Mode J Amateur Satellite frequencies. The voice downlink utilizes frequency modulation and operates at variable speeds. The transmitters and receiver are designed, built, and tested by the student design team under the strong mentoring of amateur satellite volunteers.

The reception link captures uplink radio frequencies through a single antenna on the top of the spacecraft. The receiver demodulates command tones from the main carrier. A hardware terminal node controller (TNC) converts these tones to logic signals, extracts command information from the packet protocol, and sends command data to the spacecraft processor. Additionally, receiver output is demodulated and processed by a software TNC module implemented in the spacecraft processor.

The data downlink channel transmits photographic data and spacecraft telemetry. The previously mentioned hardware TNC packetizes this information and converts the result to telemetry modem tones. This output is then modulated by a transmitter with variable power output. The result is combined with the voice downlink and is broadcast through four antennae mounted to the bottom of the satellite.

The voice downlink transmitter modulates, filters, and variably amplifies voice synthesizer output. It is then combined with the data transmitter output for transmission. When the voice synthesizer is idle, a Morse code keyed audio signal is broadcast by this transmitter in order to serve as a satellite beacon. This code will transmit spacecraft telemetry as well as any of the stored messages intended for the voice synthesizer.

3.5 Orbit and Attitude Subsystem

The primary technical attitude control drivers are the general orientation of the camera to permit photos of Earth's northern hemisphere and the smoothing of the solar thermal load. After considering four alternate configurations, a combination of passive magnetic and spin stabilization was chosen. Magnetic control is achieved through the use of permanent magnets mounted to point the camera towards the Earth in the vicinity of the North pole. Hysteresis rods are included to damp oscillations in this motion.

Orbit and attitude determination requirements specify the ability to take fairly accurate photos of the areas of interest on the Earth. A GPS receiver provides primary position data; an open loop timer and an orbital propagation software module augment this function. Attitude sensors include student built Earth sensors and a virtual sun sensing system. This sun sensing will occur through the processor's interpretation of solar panel current data. Due to the hexagonal geometry of the panels, a wide arrangement of panel currents may be differentially biased in order to calculate sun position. Initial simulation of this concept suggests that accuracy to a few degrees may be achieved.

3.6 - Power Subsystem

More than eight watts of average power is generated by covering the satellite's exterior with 14% efficiency Gallium Arsenide solar cells. A single battery augments the power system during eclipse and high power demand situations. Power conditioning circuitry provides regulated 12V and 5V buses to the satellite components.

The power supply and demand balance is monitored by the spacecraft processor through real-time analysis of power conditioning telemetry. A flight manager software module automatically manages component switching based upon user demand and available power. Fine control of bus shunting is achieved through variable power output capability on both communication transmitters.

3.7 - Thermal Subsystem

Due to an even solar radiation load caused by the slow spin, the SAPPHIRE spacecraft is able to satisfy all thermal requirements through a completely passive design. With the dedicated assistance of Lockheed engineers, a detailed thermal model of the spacecraft has been composed and verifies the ability to regulate bus and component temperatures through a judicious choice of thermal coatings and insulation. This model is updated continuously as additional design information is made available.

3.8 - Ground Station

An OSCAR class amateur satellite ground station is being installed on the top floor of Stanford's Durand Building, the home of the SSDL. The configuration of this station will permit the operation of the SAPPHIRE spacecraft, future SQUIRT vehicles, and other SSDL and amateur satellites. The center will be operated and managed by Stanford students and interested local high school pupils. Formal command generation and telemetry analysis will occur in the control center as well as in other SSDL laboratory facilities. Basic mission data formatting and analysis will also be offered by the SSDL.

3.9 - Management and Systems Engineering

Managerial and systems level control is established through weekly student organized design reviews and subsystem manager meetings. System and subsystem specifications are maintained in a formal requirements document, and all component hardware, electrical, and software interfaces are published and reviewed on a weekly basis. Additionally, students regularly