SAPPHIRE – Stanford's First Amateur Satellite

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Abstract

Stanford's first student built microsatellite SAPPHIRE was be completed on July 10, 1998. The launch date is still undetermined, but now is the time to inform the amateur community of the capability of this satellite and how the amateur community can use it. SAPPHIRE operates in mode J and has the capability of operating with multiple users. Users can control its two main payloads. The primary payloads are a B/W digital camera and a voice synthesizer, similar to the Dove microsatellite.

The operating system is very user friendly in that it operates much like a bulletin board interface which allows the user easy access to commands with command listing and diagnostics on improper commands. The details of the satellite development is reviewed and followed by some details on the user communications interface.

Introduction and Motivation

The pioneering efforts of AMSAT-NA with Jan King –W3GEY, Tom Clark – W3IWI and many other satellite amateur radio enthusiasts have set a standard for a "non-traditional way" of designing, building and launching novel, inexpensive communications satellites.

Through association with AMSAT-NA, local hams and industry, Weber State University in Ogden, Utah set a course in 1982 to enhance education of engineering students with a project to build a microsatellite using the AMSAT-NA "non-traditional way". The first satellite from this program, NUSAT, was launched from the Get-Away-Special (GAS) canister on the NASA Space Shuttle Challenger in April 1985. NUSAT operated for twenty months, then reentered and burned up in December 1986. NUSAT did not even use the quality and engineering practices developed by AMSAT-NA for the "non-traditional way", yet the satellite performed in space for a significant period of time.

The development and operation of NUSAT turned out to be an excellent project for training undergraduate students. In 1988 AMSAT-NA started a project with Weber State University assisting in the development of the four microsatellites that were launched in 1990.

This "non-traditional way" used by AMSAT-NA engineering is to build microsatellites with the current commercial technology. Due to limited budgets, the "latest" space rated components were not used because they were extremely expensive and "old" technology. Good engineering practices were used with "commercial-off-the-shelf" (COTS) components to minimize the impact of operation in the space environment.

The accomplishments of AMSAT-NA and its success of using this "non-traditional way" of building microsatellites has, in some cases, been a real embarrassment to the aerospace industry and the government satellite builders. With smaller budgets the trend now seen at the annual AIAA/Utah State University Small Satellite Conference at Logan, Utah held in August and September of each year is to use this "non-traditional way" to build "small, cheaper, faster" satellites for commercial, military and science applications.

In 1993 the industry affiliates board established for the Department of Aeronautics and Astronautics at Stanford University to recommend improvements in the graduate program, directed the department to create a program that would give the graduate students systems engineering experience. In 1994 the department then selected the author, who was working on the Weber State University satellite program, to develop a similar program at Stanford. Since the author had been "schooled" in the AMSAT "non-traditional way" of building satellites at Weber State University, this same approach is being used for the Stanford program. The work on the microsatellites is directed through the Space Systems Development Laboratory at Stanford.

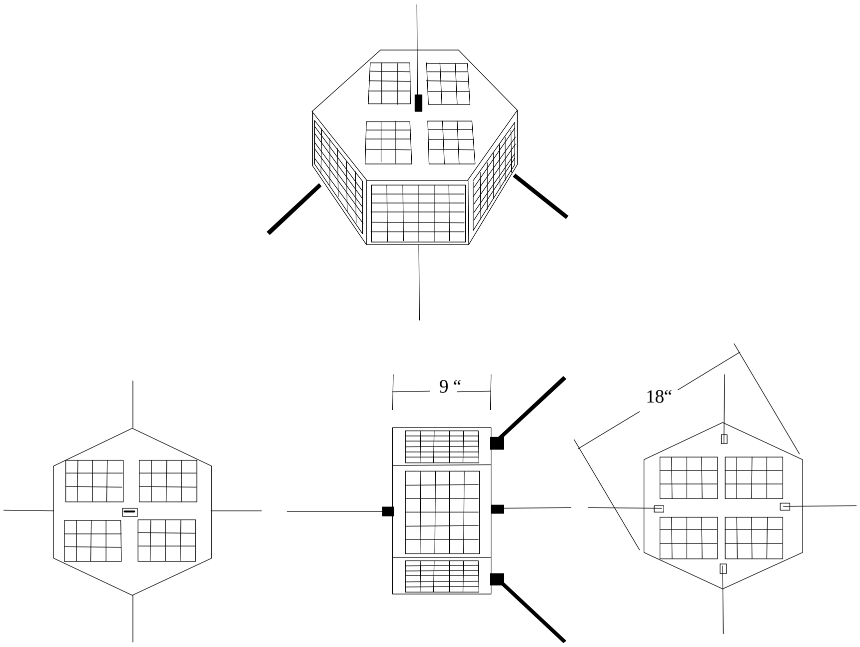
The first satellite developed in the Stanford program is SAPPHIRE; it will be described in detail in this paper.

SAPPHIRE Development

The initial assignment to the graduate students in the spacecraft design program at Stanford University was to design a microsatellite. They were given some basic physical parameters shown as the initial concept in Figure 1. This spacecraft would then be a student managed program for a student-designed, student-built spacecraft that is fully functional. Total costs for the spacecraft parts were to be less than $50,000.

The student selected the name SAPPHIRE that is the acronym for Stanford AudioPhonic PHotographic InfraRed Experiment. Those letters describe the three instrument-based missions of this project. The infrared detectors are a new-generation micromachined horizon detector, operating at room temperature and consuming about one watt. A voice synthesizer broadcasts an FM "computerized" voice. A commercial digital camera takes pictures of the Earth. In addition, several other missions advance basic research in spacecraft automation and operations. ***But the primary mission of this project is to train students in all aspects of spacecraft design, fabrication, testing and operations***.

This spacecraft emphasizes simple designs, reasonable objectives, short mission timelines and use of commercial parts and processes. The initial spacecraft structure was made out of plywood Figure 2. The final design would use honeycomb, but for prototyping purposes the plywood was a good simulation of the honeycomb and much easier to work with. This wooden structure was later covered with aluminum to simulate the final honeycomb flight structure.



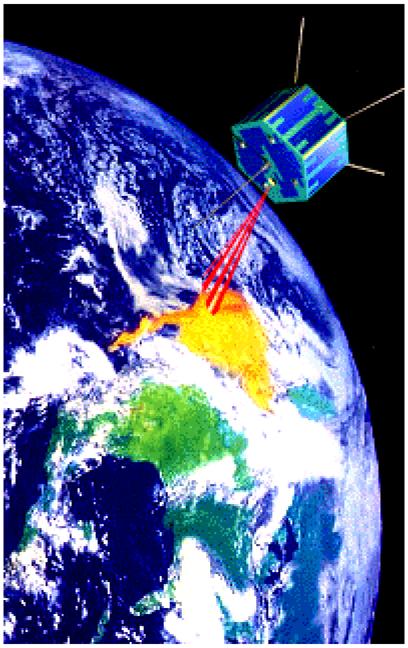


Figure 1 Initial SAPPHIE Concept

Thus with the combination of aluminum and wood the student now affectionately refer to the prototype as Al Wood shown in Figure 2.

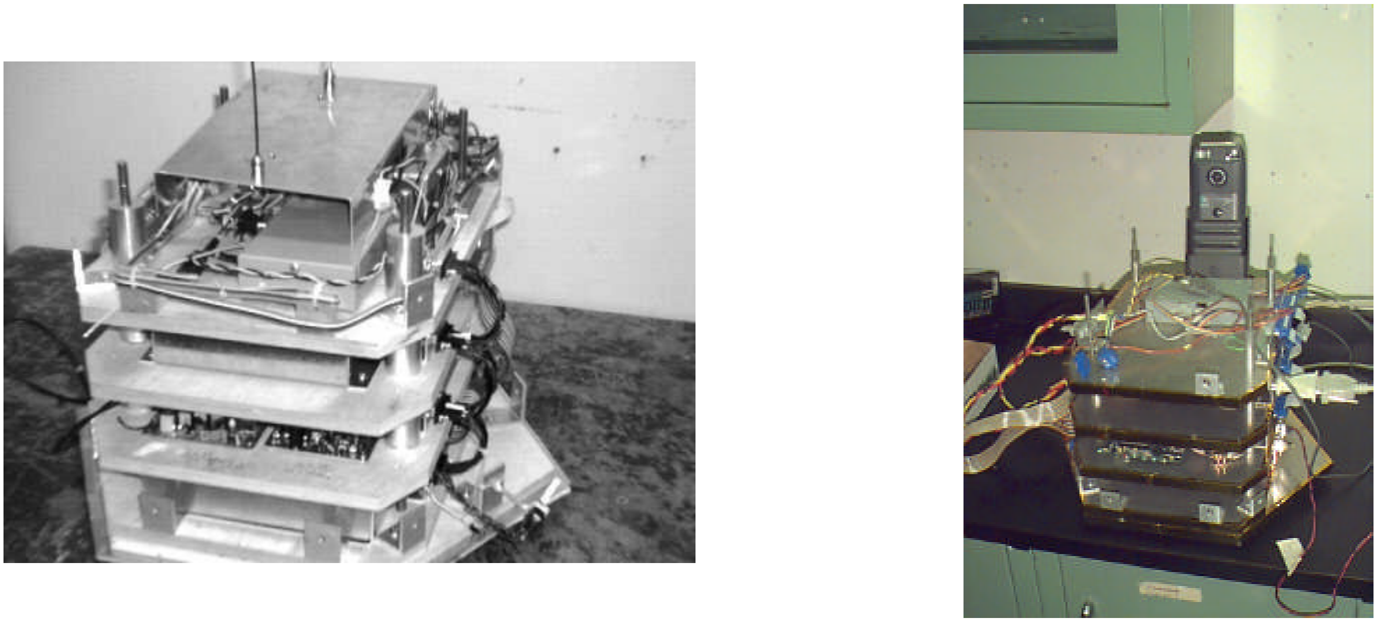


Figure 2 SAPPHIRE Plywood and Al Wood Prototype

The final design is a hexagonal cylinder made from aluminum honeycomb, 17" from tip to tip and 13" tall (including launch interface). It has a total launched mass of 20kg (44 pounds) as shown in Figure 3.

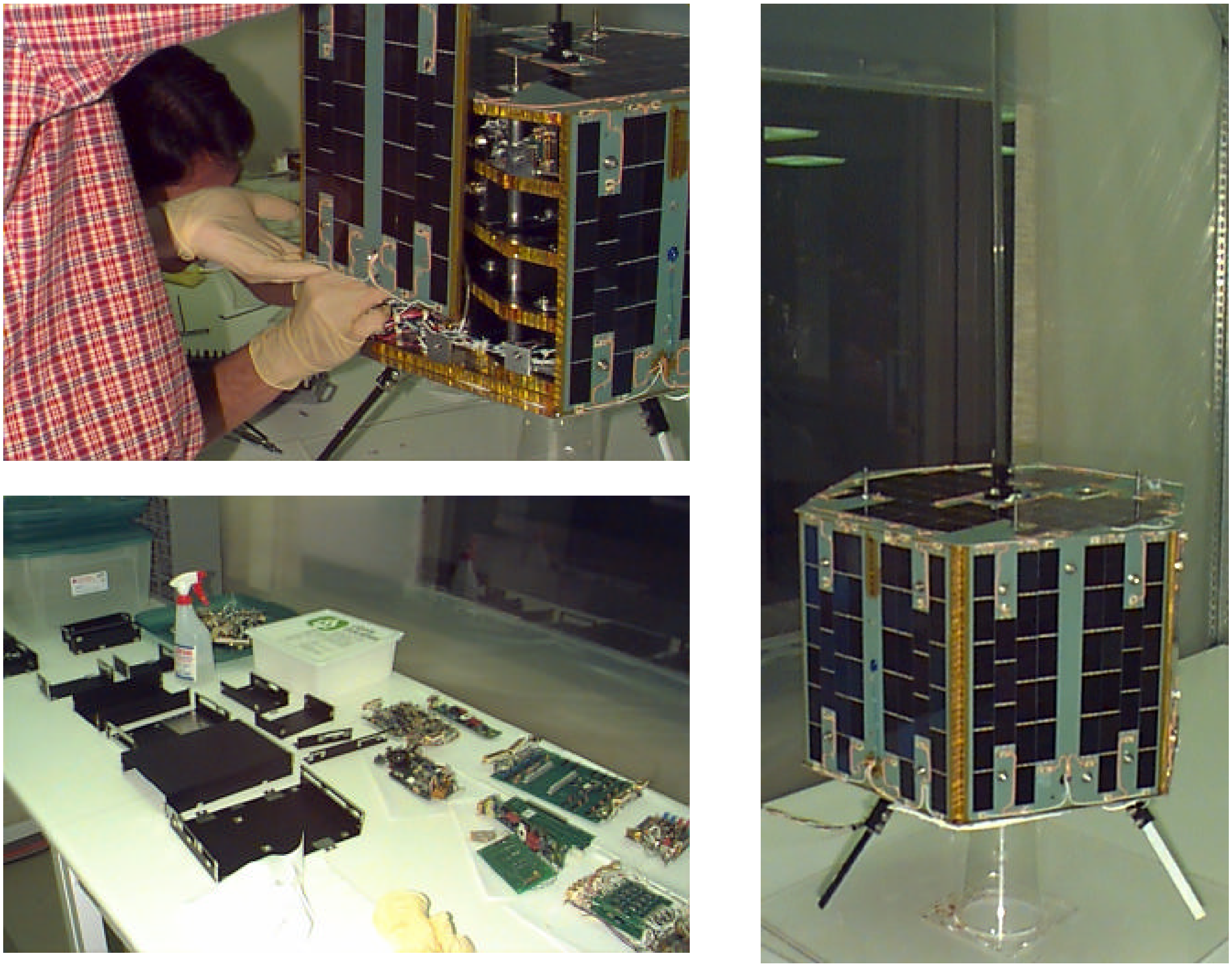


Figure 3 SAPPHIRE in Clean Room During Assembly and Final Operations Testing

Mission Statement & Design Drivers

The mission statement and design drivers for this satellite are shown in Table 1 & 2.

Laboratory Development	Identify, acquire, and maintain design, fabrication and testing equipment Develop contacts and recruit mentors from industry Identify sources for parts and facilities for long-term SQUIRT usage Develop the satellite-concept-to-orbit-operations process for the SQUIRT program
Education	Train students in the practices and importance of systems engineering. Train students in every aspect of a satellite project: Design, Modeling, Fabrication, Testing, Launch, and Operations. Encourage student research
Amateur Payloads	Take a picture of Northern Hemisphere and display it on the SSDL Web page Broadcast a digitalked message to a designated audience
Experiment Payloads	Operate the SAPPHIRE beacon notification system through the ASSET operations system Schedule data requests and deliver the data through the ASSET operations system

Table 1 SAPPHIRE Mission Goals

Driver	Motivation	Effect
Education	Novice students are to become systems engineers	Allow students to make big mistakes
Schedule	The project must be completed within the "lifetime" of the students involved, or risk losing key personnel	Simplify goals
		Emphasize base mission requirements
Lab Development	The project is to assist future SQUIRTs in development, speeding up the life cycle	Modular design
		All elements must be developed within laboratory when at all possible
Cost	The laboratory has very limited resources ($50,000)	Simple designs
		Commercial, off-the-shelf parts

Table 2 SAPPHIRE Design Drivers

Launch and Orbit Requirements

SAPPHIRE is intended to fly as a secondary payload on a wide range of expendable launch vehicles. It was designed to accommodate a wide range of orbits as well. The nominal design orbit was polar, with 500km altitude. Table 3 describes the general orbit requirements.

Requirement	Notes
Less than 1000km altitude	Signal strength for communications, magnetic field strength for attitude control, and radiation hardness all require low altitudes
Greater than 200km altitude	The payloads require about 30 days of operations, thus SAPPHIRE cannot reenter sooner than that
Two ground station passes/day	Originally, this meant that the orbit inclination had to be at least 37°- Stanford's latitude - but that requirement is loosening as other universities join the ASSET network. Granted, any orbit of less than 45° is going to significantly hamper picturetaking abilities, but picturetaking is a secondary mission requirement.

Table 3 SAPPHIRE Orbit Requirements

Project Timeline

Table 4 details the project milestones that have been accomplished. SAPPHIRE has been through operational verification and re-test of the solar panels. Operational verification consists of a one-month "locked operations" test; the spacecraft will be locked into the clean room and operated as if it were on-orbit. It was contacted during constrained time windows to simulate low-Earth orbits, and taken through the complete checkout, nominal operations, and contingency operations testing.

SAPPHIRE AND THE INTEGRATED OPERATIONS SYSTEM

As part of the graduate student research at SSDL, a program to experiment with new ways of spacecraft operations has been established. This new program is called ASSET for Automated Space Systems Experimental Testbed. Using the OSCAR type ground stations, ASSET is establishing a master control center, MMC, and a worldwide-interconnected ground network of satellite control and monitoring stations. A representation distribution of these stations is shown in Figure 4.

The main emphasis of the ASSET research is to reduce human intervention in the spacecraft operations, and reducing command and turn-around time to providing products such as photos, activation of a voice synthesizer, etc. The process is to automate the user interface for the customer needs as well as spacecraft health monitoring and maintenance. This architecture shown in Figure 5 allows the user to interact with the spacecraft through an internet, web browser interface and received returned products such as photos by the same means.

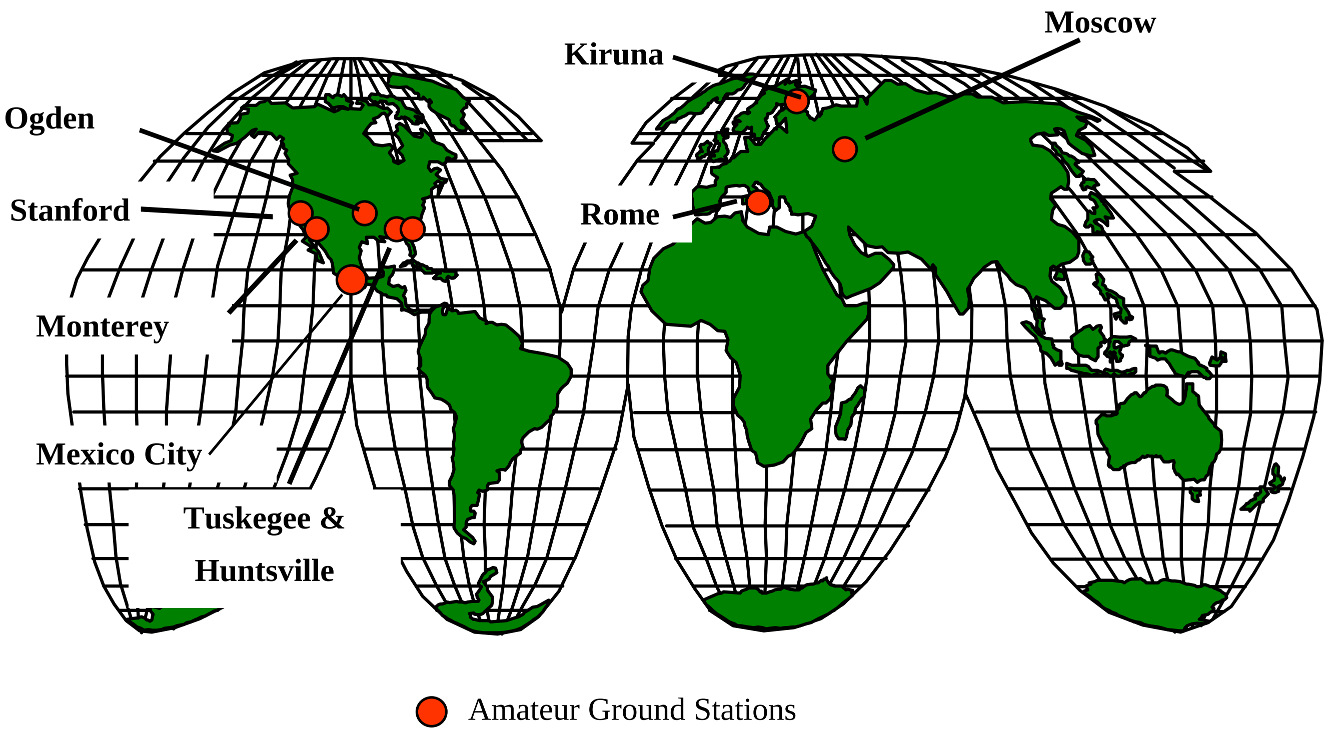


Figure 4 ASSET Control and Monitoring Station

The use of ASSET in the amateur radio community serves several important functions. 1) It provides training for a new group of well-educated, sophisticated users that will be a part of the amateur community and OSCAR operations --- a major goal of Ham radio. 2) It is greatly expanding the use and activity of the amateur frequency bands to assure these are reserved for future amateur use. 3) It provides experimentation and development of new communications technology. 4) It provides new ways for educational outreach to K-12 grades. 5) It promotes international cooperation through collaborative efforts using ground stations around the world. 6) It provides a testing that will have minimal negative impact to develop new operational paradigms. 7) This paradigm shift can reduce commercial and government space costs, improve new spacecraft utilization and generate new means of space use.

The use of SAPPHIRE in a closed room operational mode at Stanford University is already being used as a functional demonstration of ASSET

MISSION

Beyond the ongoing task of educating students, SAPPHIRE has two instrument-based amateur experiments (digital camera, and voice synthesizer). It also has student experiments for one telemetry experiment (virtual sun sensor), and two operations missions (beacon-based health monitoring and spacecraft operations). These are described, below.

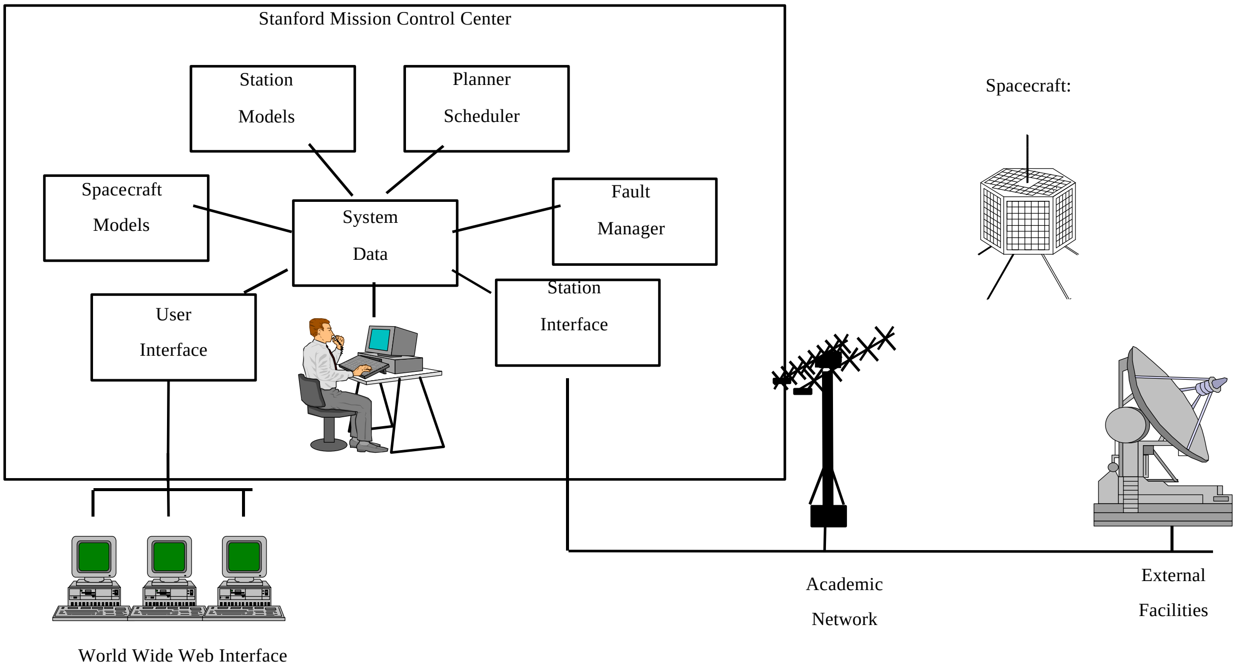


Figure 5 ASSET System Architecture

AMATEUR PAYLOAD MISSIONS

Digital Camera

Students were interested in taking pictures from space, since power, mass, computation and schedule margins existed, this experiment was added. The Logitech Fotoman Plus 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. As commanded by the spacecraft CPU, the Fotoman takes a picture and the image is stored in CPU memory. Expected resolution of the black-and-white camera is 1 km.

Camera requirements include the ability to view the Earth, power for the component, and interfaces with the CPU to handle data storage. The principal investigators for this mission are the SAPPHIRE team.

The Fotoman comes as a self-contained package, weighing about 450 grams and consuming 0.8 Watts on average. Flight modification required potting, coating, and repackaging the electronics, disabling the flash assembly, and adding a power switch. Software modifications permit reloading the Fotoman RAM code in case of radiation upset. The Fotoman takes 496x360 pixel images using 256 gray levels. JPEG compression is used to reduce each photo to about 23 Kbytes.

Voice Synthesizer

Voice synthesizers accept ASCII text strings, phonetically translate the strings, and generate an analog audio output equivalent to human speech. This is another student-motivated payload, and could provide interest to the Amateur Radio community as well. The RC Systems v8600 model was selected to provide this function due to its ease of use and interfacing, quality of voice output, and cost.

The voice synthesizer requires an interface to the CPU, power for the unit, and a means for an FM broadcast. It is intended, but not required, that voice broadcasts will be audible using a handheld radio. The principal investigators for this mission are the SAPPHIRE team.

Date	**Event**
April 1994	Project Start
December 1995	Operational vacuum testing
March 1996	Flight spacecraft vibration testing
May 1996	Flight software overhaul begins
June 1996	Development of tertiary missions
July 1997	Full component integration
	Engineering model upgrades
October 1997	Thermal design implementation
December 1997	Thermal vacuum test
April 1998	Flight software delivery
	Antenna test
May 1998	*Solar panel flash test*
	Final calibration
June 1998	*Operational verification*
July 10, 1998	*SAPPHIRE Delivery*

Table 4 SAPPHIRE Mission Timeline

Modifications consisted of structurally mounting the board in a shielding box and replacing and coating low confidence electronic components. Student designed reset circuitry simplified the board's interface with the bus computer. The flight unit weighs 220 grams and consumes less than 0.2 Watts.

STUDENT EXPERIMENT MISSIONS

Health Monitoring Beacon

One of the new approaches towards reducing spacecraft operations costs is to automate routine functions such as health monitoring. In this concept, the spacecraft is responsible for monitoring its own telemetry and making assessments as to its state of health. SSDL has initiated a new space system technology initiative in order to develop, demonstrate, and validate a beacon-based health monitoring system for spacecraft. This system consists of automated fault detection on board a spacecraft, a state of health beacon signal broadcast by the spacecraft, a ground based monitoring network, and a mission control center capable of efficiently integrating this health assessment strategy into its operating architecture.

SAPPHIRE will monitor its own telemetry sensors, comparing measured values with commandable entries in a state-dependent limit table. These modest steps provide SAPPHIRE with an anomaly detection system far more mature than most spacecraft. Depending on the seriousness of the limit violation, the spacecraft health is assessed to be one of four values. SAPPHIRE’s main transmitter transmits the health beacon. SSDL has partnerships with universities in Alabama, Montana, and Sweden to develop a simple receive-only system for health monitoring. These stations will listen for SAPPHIRE beacon transmissions and notify mission control of the results by electronic mail. It is intended to put these stations at locations around the world, giving SAPPHIRE near-global coverage for health monitoring. The Signal flow diagram in Figure 6 illustrates the sequence of events that occur for the beacon health monitoring.

In this manner, all spacecraft sensor data is compacted into a few bits that tells an operator whether or not SAPPHIRE can continue to perform its mission. And while such information once had to be collected over time for eventual download and processing at mission control, spacecraft health is now continuously monitored and available anytime the spacecraft is within range of a low-cost receiving station. Once mission control receives a beacon monitoring update from a remote station, it logs this information and then takes appropriate action. Depending on the health assessment, there are varied responses, from storing the update in the system database to paging the operator on call and rescheduling the network to contact and recover a failed satellite.

Beacon monitoring will be a commandable function on board the spacecraft. SAPPHIRE will operate for a time with and without the beacon, keeping track of the amount of operator time required for health monitoring under each condition. It is expected that beacon monitoring will significantly reduce the man-hours of spacecraft operations.

Attitude Determination & Control (ADC) Subsystem

The primary ADC 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 alternate configurations, passive magnetic 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. This approach

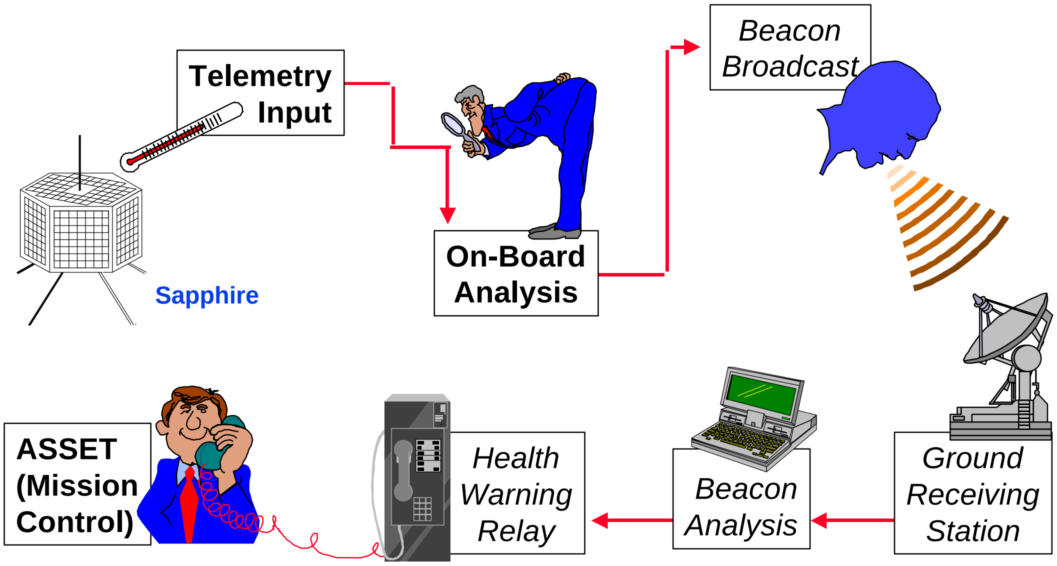


Figure 6 SAPPHIRE Health Beacon Signal Flow

provides what has been called the "controlled tumble", as shown in Figure 7. The spacecraft follows the magnetic field in a North-seeking orientation. The effect is for the Z (top) axis to be nadir pointing in the northern latitudes, zenith pointing in the Southern latitudes, and horizon-pointing in the middle latitudes. This allows camera operations over North America and Europe (the camera points out the top face).

The slow spin required by Thermal Subsystem is accomplished by a radiometer effect on the four transmit antennas; they are alternately coated white and black to be very reflective and very absorptive. Solar pressure creates a very small but constant torque. Attitude sensing is present primary as student interest and for use in future SQUIRTs

Four ALNICO-V bar magnets mounted on the external solar panels, and damping by six hysteresis rods on the CPU tray provide pointing. The slow spin comes from the painted antennas and is also damped by the rods. Additional mass was added to the side panels as ballast to ensure that the maximum moment of inertia was around the Z (spin) axis. Two infrared phototransistors form a simple wide-angle Earth sensor for possible use in determining when to take pictures. In order to assure steady pointing, a study of the magnitudes of the disturbance torques was conducted, summarized in Table 5. Since the orbit is undetermined, the study examines a number of candidate altitudes. Note that though the radiometer torque is extremely small, it has constant effects while in sunlight over time it becomes significant. Meanwhile, the magnet torques are orders of magnitude larger than all disturbances. Thus, SAPPHIRE will be very closely following the magnetic field.

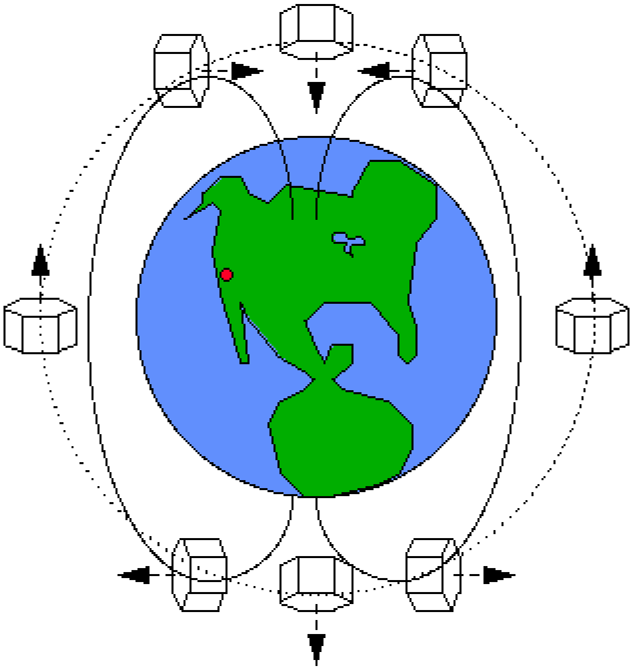


Figure 7 The Controlled Tumble

Altitude	200 km	300 km	400 km	600 km	800 km
Aerodynamic	418	52	13	1.07	0.11
Magnetic	1400	1340	1280	1120	1080
Radiometer	0.05	0.05	0.05	0.05	0.05
Gravity Gradient	0.32	0.30	0.28	0.26	0.24

Table 5 Maximum Magnitude of Expected Torque (dyne-cm)

According to Altitude and Type

All ADC components have been built and are part of the flight structure. The radiometer paints will be added when the thermal design is implemented.

OPERATIONS MISSION

The SAPPHIRE microsatellite is capable of performing three high level functions. These are to collect and filter sensor data, to provide space-based photographs, and to broadcast voice messages. Described below are the various aspects of operating the spacecraft.

Operations phases

Launch Phase - This phase includes all activities from when SAPPHIRE is delivered to the pad until it has ejected from the launch vehicle. Specific attention is given to procedures relating to pad assembly/testing/charging, launch adapter mating, and spacecraft ejection.

Checkout Phase - This phase includes all activities from when SAPPHIRE is ejected until the Mission Operations Team for normal mission activities has approved it.

Mission Operations Phase - This phase includes all activities from when SAPPHIRE is approved for normal mission activities until the Mission Directors decide to terminate normal operations or to transfer mission authority.

Exclusive Mission Operations - This first period of mission operations is controlled such that only SSDL operators and affiliates will have vehicle command capability. This will be done in order to ensure the timely completion of all mission objectives. Once these objectives have been suitably accomplished to the satisfaction of the Mission Directors, SAPPHIRE may enter its public period of mission operations.

Public Mission Operations - This second mission operations period enhances the provision of mission services by permitting properly equipped and certified public operators to directly communicate with SAPPHIRE.

End-of-Life Operations - This phase commences when the Mission Directors decide to terminate normal SSDL-controlled mission activities.

Complete termination of mission services will occur if SAPPHIRE is no longer functional. In this event, end-of-life operations may entail occasional health assessment contacts at the discretion of the Mission Directors. Mission transfer will occur if SAPPHIRE is functional but SSDL no longer desires to maintain the vehicle. Transfer will most likely be made to an SSDL affiliate such as AMSAT or a cooperating educational institution. In this event, SAPPHIRE payload operations may still be conducted as a standard SSDL groundstation activity.

Ground Stations

An OSCAR class amateur satellite ground station has been installed on the top floor of Stanford's Durand Building, the home of SSDL. The configuration of this station permits the operation of the SAPPHIRE spacecraft, future SQUIRT vehicles, and other SSDL and amateur satellites. The center is operated and managed by Stanford students and interested local high school pupils. This facility has already been used to contact orbiting Amateur spacecraft and to participate in SAPPHIRE operational testing. The ground station must operate in mode J, with AFSK modulation. The station uplink frequency is 145.945 MHz and the downlink frequency is 437.100 MHz.

User Operational Interface

Access Control : The SAPPHIRE operating system is a bulletin board system allowing multiple users to be logged in at a single time. Users logon to the spacecraft with a particular password in order to initiate a session. During a session, a user may execute any authorized command (controlled by the password used). Users "disconnect" upon completion of their session.

- To logon to the spacecraft, a connect command using SAPPHIRE's callsign(KE6QMD) is sent in order to establish a TNC link. The user's groundstation software should be properly configured such that his/her callsign or station callsign is included in broadcasts.
- Once connected, a password must be entered in order to initiate a session. Three password levels exist: *admin*, *school*, *guest*. Each password permits a different level of command authority for the vehicle.
    - The password for *admin* and *school* users is controlled through a special program with a controlled distribution. The program takes a passkey of varying length as a variable in order to produce the proper numerical password. The satellite upon connection broadcasts the passkey.
    - The password for *guest* users is "guest".
- Access control-related commands include listing all current users, broadcasting a message to all current users, disconnecting specific users, and setting/checking the total number of user permitted to be logged on at once. Setting/checking the total number of permitted users requires *admin* access). These commands are found in the *os users*... software subsystem (see http://aa.stanford.edu/~ssdl under SAPPHIRE satellite).
- It is interesting to note that the SAPPHIRE software system is always logged on to SAPPHIRE as a distinct, *admin* access user. This arrangement facilitates the programming approach as well as automated platform operation.
- SAPPHIRE is the first user to log onto the bulletin board system. If the total number of permitted users is limited to 2, then only a user with *admin* level access can log in as the second user. This facilitates operational control during anomalous vehicle conditions.
- When done, the user must enter a disconnect command in order to terminate the session. The disconnect command is *disconnect*. Alternatively, if the modem link is disrupted for more than 5 minutes, SAPPHIRE will automatically attempt to verify the link (by sending an "are you there" message ten times every 4 seconds); if the link is not re-established, SAPPHIRE will terminate the session.
- When disconnecting from SAPPHIRE, the CPU sends a "**Goodbye**" message, and the TNC sends "***** DISCONNECTE: KE6QMD**" message. Timing between these events is not controlled. If the TNC sends it's message and disconnects first, then the "**Goodbye**" message from the CPU will not be received by the ground operator. See the example login as a guest in Figure 8.

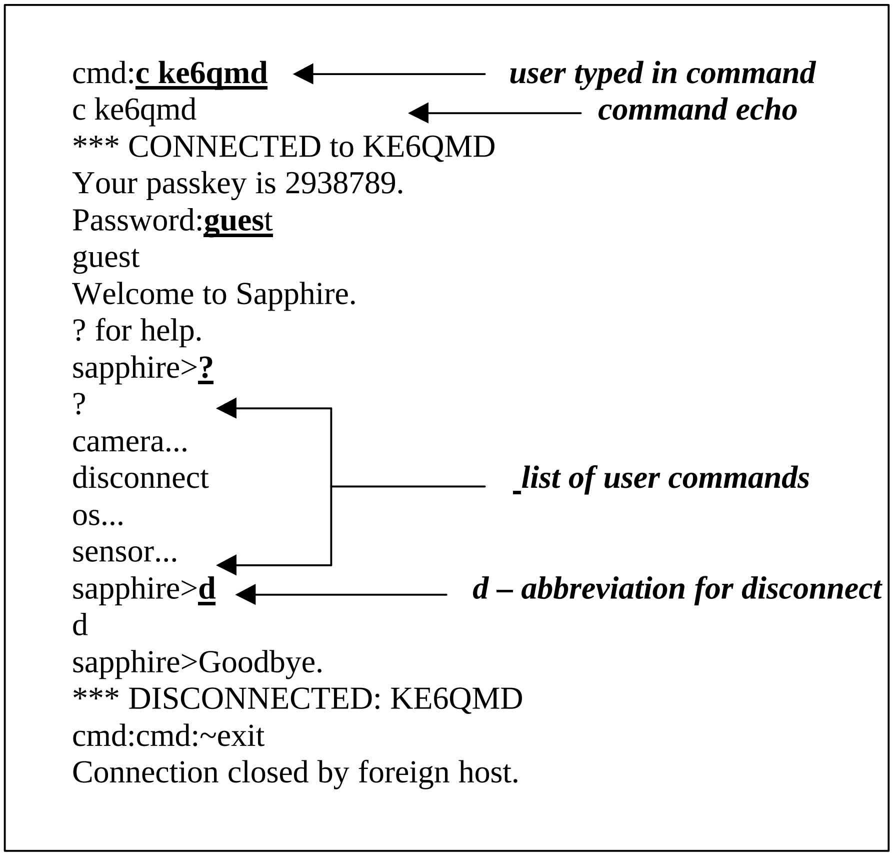
Summary

AMSAT-NA members pioneered a new way to use amateur radio communications through the OSCAR program. With the sift in economic need in industry and government to reduce costs of space access in the last ten years, the “AMSAT way” is now being adopted for space missions outside the amateur community.

Through AMSAT’s association with and interest in education, the university community can use this space access as a valuable education tool. Stanford University joined this growing group of universities in the development of low-cost program to build and operate microsatellites in 1994 with the establishment of the Space Systems Development Laboratory – SSDL.

The first product of this program is the Stanford SAPPHIRE microsatellite that is ready for launch. Stanford expects to have a continual production of new microsatellites from SSDL to educate students and promote OSCAR activities and with ASSET a new means of operating these spacecraft.

AMSAT has been a leader in promoting communications in space education, now the educational community is helping promote AMSAT and its OSCAR activities.



```
cmd:c ke6qmd
c ke6qmd
*** CONNECTED to KE6QMD
Your passkey is 2938789.
Password:guest
guest
Welcome to Sapphire.
? for help.
sapphire>?
?
camera...
disconnect
os...
sensor...
sapphire>d
d
sapphire>Goodbye.
*** DISCONNECTED: KE6QMD
cmd:cmd:~exit
Connection closed by foreign host.
```

user typed in command

command echo

list of user commands

d – abbreviation for disconnect

Figure 8 SAPPHIRE Command Example

References & Acknowledgements

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