OPAL: Smaller, Simpler, and Just Plain Luckier

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Abstract – On January 26, 2000 at 7:03PM PST, Stanford University's first student built satellite, OPAL – the Orbiting Picosatellite Automated Launcher, roared into space on a modified Minuteman II missile. Students from the Space Systems Development Laboratory spent four years designing, fabricating, and testing the OPAL satellite in preparation for the launch. OPAL's primary mission objectives were to explore a new mothership/daughtership mission architecture for distributed sensing, to characterize an off-the-shelf magnetometer, and to characterize a suite of off-the-shelf accelerometers. Six DARPA sponsored daughterships, also known as picosatellites, were deployed from OPAL. They were built by The Aerospace Corporation, Santa Clara University, and a team of amateur radio operators. The OPAL satellite completely achieved its mission goals and is now in extended mission operations. Long-term characterization of the satellite bus, magnetometer, and accelerometers are underway. OPAL has demonstrated that low cost, albeit high risk, university satellites offer an excellent platform for experimental space testbeds. AMSAT assigned OPAL an amateur satellite number of OO-38. OPAL will soon be accessible to non-Stanford users for educational and research purposes.

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1. INTRODUCTION

The cost benefits of smaller spacecraft and the advancements in component miniaturization are enabling smaller spacecraft that are equivalent in functionality to larger spacecraft. Current research is driving designs smaller with greater functionality through fundamentally new mission architectures. Realistically, how small can a useful spacecraft be built? The OPAL mission from the Space Systems Development Laboratory (SSDL) at Stanford University is exploring this issue.

Launched in January of 2000, OPAL is a completely student built satellite operating as an experimental testbed in a sun-synchronous 750 km low Earth orbit. As a project, OPAL's high-level objectives are to develop SSDL infrastructure for satellite manufacture, provide educational opportunities for Stanford students, and conduct satellite payload experiments. The OPAL project began in April of 1995.

The primary payload of OPAL is an end-to-end demonstration of a mothership/daughtership mission architecture. OPAL stored and deployed six daughterships, called picosatellites, built by The Aerospace Corporation, Santa Clara University, and a team of amateur radio operators (HAMs). Each of these satellites weighed under a kilogram. Picosatellites, at the forefront of nanotechnology research, are spacecraft weighing less than one kilogram. Also on board are two long-term experiments to characterize commercial-off-the-shelf accelerometers and a magnetometer. All mission goals have been achieved with 100% success and OPAL is in the extended mission operations phase.

This paper describes the OPAL mission and the successful operation of the satellite in orbit. It details the mission concepts and flight results. It concludes with some of the hard learned lessons OPAL taught us and with an outline of future work.

2. SSDL OVERVIEW

The Space Systems Development Laboratory provides graduate degree students with world-class education and research opportunities in the field of space system design, technology, and operation. Through a balanced program of classroom instruction, research work, and project experience, SSDL students are exposed to the full space system life cycle, from concept through operation. The program stresses team-based systems engineering and rapid prototyping.

SSDL is actively engaged in a number of advanced space system research projects. Several of the research projects include:

Formation Flying – As part of the University Nanosatellite Program [1], SSDL is exploring GPS-based formation flying with its Emerald and Orion missions [2].

Operations Research –A comprehensive operations testbed is under development to explore high-level product definition, system health management, and Internet-based operations [3] [4].

Colloid Micro Thrusters - A promising new technology in the field of small spacecraft propulsion is under research under cooperation with the Stanford Plasma Dynamics Laboratory [5].

The core of the SSDL educational program is the Satellite Quick Research Testbed (SQUIRT). The goal of the SQUIRT program is to produce student-engineered microsatellites capable of servicing state-of-the-art research payloads [6]. SQUIRT satellites are completely managed, designed, and implemented by students with only high-level advising from SSDL staff. This program exposes graduate engineering students to space system design by providing hands-on technical and managerial experience in the following areas: conceptual design, requirements formulation, subsystem analysis, detailed design, fabrication, integration, test, launch and operations.

OPAL is SSDL's second SQUIRT satellite, and the first to be launched. The first SQUIRT satellite, Sapphire, is awaiting a potential launch in late 2000 [7].

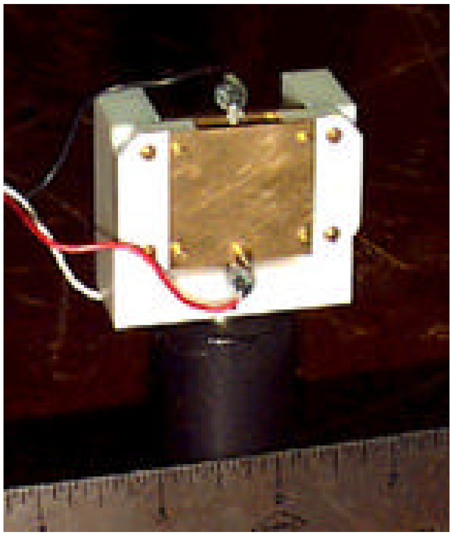

Figure 1 – Prototype of colloid thruster.

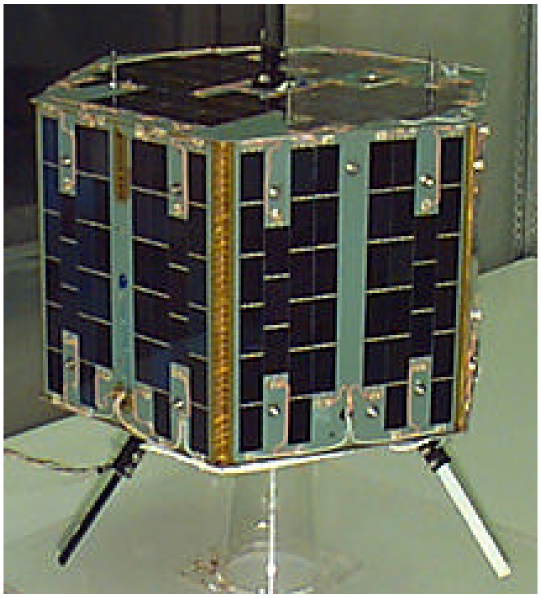

Figure 2 – SSDL's first satellite, Sapphire.

3 MISSION OBJECTIVES

OPAL has three primary payloads: the mothership/daughtership mission, the magnetometer testbed, and the accelerometer testbed.

3.1 Mothership/Daughtership Testbed

Traditional point measurements of spacecraft are limited by their maneuverability in mapping complex fields that vary rapidly over time and space. Scientists are looking towards distributed sensing techniques to better measure and study these complex fields.

OPAL explores a new mission architecture to perform distributed sensing in space. In this architecture, a main spacecraft, or "mothership", deploys a number of smaller spacecraft, or "daughterships" to remote locations of interest to perform the required distributed sensing. An example of this is the free-flying magnetometer mission [8]. Hundreds of small, dedicated spacecraft would be deployed to measure the Earth's magnetic field.

To date, several missions have placed one or two sensors in interesting locations, such as the Galileo probe to Jupiter [9], but placing dozens or hundreds of them remains a challenge. Due to increased interest in distributed sensing and the mothership architecture, new technologies require development. The mothership technologies include daughtership storage, deployment, communication, and retrieval or disposal. The daughtership technologies include all the necessary miniaturizations of current satellite technology to the smaller daughtership scale.

OPAL validates this mission architecture and provides a basic testbed to develop the mothership and daughtership technologies. The OPAL design team focused on mothership technology development. A mothership system was developed to address the storage and deployment technologies. The system was designed for reliability, scalability, and manufacturability. OPAL contained six daughterships that were built by The Aerospace Corporation, Santa Clara University, and a team of HAMs.

3.2 Magnetometer Testbed

The primary objective of the magnetometer testbed is to characterize the functionality and operation of the APS533, a miniature 3-axis fluxgate magnetometer fabricated by Applied Physics Systems. Characterization of the magnetometer is defined as determining short-term magnetometer performance degradation due to launch and initial exposure to the space environment and determining long-term magnetometer performance degradation due to extended exposure to the space environment.

Magnetometer performance will be measured by comparing the vector magnitude of the earth's magnetic field as measured by the sensor to the predicted vector magnitude of standard geomagnetic modeling software. The principal investigator is Jim Lockhart from the Gravity Probe-B mission [14].

3.3 Accelerometer Testbed

The primary mission objective of the accelerometer testbed is to characterize the functionality and operation of several commercial-off-the-shelf (COTS) accelerometers during flight in space. The following COTS devices (each representing a different sensor technology) will be tested:

1. A capacitive sensor, the ADXLO5 from Analog Devices.
2. A piezoelectric sensor, the PCB 336M27 from PCB Piezotronics.
3. An inductive sensor, the GS-11D and GS-30CT from GeoSpace Corporation.

Characterization of the accelerometers is defined as determining short-term sensor degradation due to launch and initial exposure to the space environment and determining long-term sensor degradation due to extended exposure to the space environment. The OPAL satellite will provide a stimulation source for the accelerometers with which to monitor sensor performance. Ground testing of the accelerometer testbed will provide a set of control data with which to compare recorded flight data. The principal investigator is Prof. Tom Kenny from Stanford University.

4 SATELLITE IMPLEMENTATION

The design of OPAL began in April of 1995 and was completed in May of 1999 when delivered for launch integration. The following is an overview of the design and implementation of OPAL.

4.1 Satellite Bus

The OPAL satellite bus was based heavily off of SSDL's first SQUIRT, Sapphire [7]. Estimated out of pocket cost for the spacecraft is less than $70,000. This does not include generous corporate donations of many components such as solar cells. Due to a limited budget, students designed OPAL with non-space rated off-the-shelf components. The only space rated components were flight code EEPROMS from SEI and nonexplosive actuators from NEA. OPAL's primary bus subsystems are described below.

Figure 3 – Front view of completed OPAL.

Figure 4 – OPAL complete with picosatellite in launch tube.

Communication System
OPAL uses packet radio protocols (AX.25) over amateur radio frequencies. It operates half duplex on 437.100 MHz at 9600 baud. Four omni directional antennas are located on OPAL's exterior, and the radio is a packet radio from EJ Johnson. A typical OSCAR (orbiting satellite carrying amateur radio) class ground station is sufficient to communicate with OPAL.

Attitude Determination/Control
Since mission objectives did not require attitude control, none was implemented on OPAL. Rough attitude information will be determined from the magnetometer measurements and solar panel currents [13].

Power
The average power consumption of OPAL is 2.4W. Primary power is supplied via gallium arsenide solar panels mounted on seven of OPAL's eight external sides. Maximum power provided by the panels is approximately 12W. Secondary power is provided by a nickel-cadmium battery pack. No charge regulation circuitry exists on OPAL. The secondary power system was designed to safely dissipate any surplus power generated by the solar panels.

Command and Data Handling
OPAL's CDH system is based on the Motorola 68332 microcontroller running at 16 MHz with 1 MB of onboard RAM. The OPAL Operating System

(OOS) processes real time events and schedules payload/telemetry data events. OOS is open source software written by Stanford students.

Structure
OPAL is a hexagonal prism, made of quarter-inch aluminum honeycomb panels. The spacecraft uses a modular, three-tray approach.

Mass: 25kg
Height: 23.5cm (without antennas)
Outside radius: 21.0 cm

4.2 The Mothership System

The original OPAL mothership system was designed for a free-flying magnetometer (FFM) mission sponsored by JPL. The daughterships carried precision magnetometers and were similar in shape to a hockey-puck [8]. Due to the lack of funding and the lack of picosatellite delivery, the OPAL design team reevaluated the FFM mission.

New sponsors were found for the picosatellite mission. DARPA funded The Aerospace Corporation to develop picosatellite technology. The old FFM launcher was redesigned to be more reliable, scalable, and manufacturable. The complex moving parts, the stepper motors, and the brushless DC motor of the original were all replaced with a simpler spring based design. A full description of the mothership system is beyond the scope of this paper so therefore a smaller overview is given.

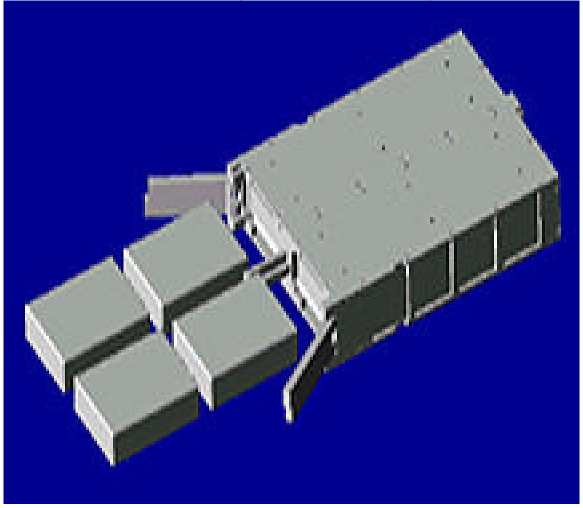

Figure 5 – Rendering of two launch tubes.

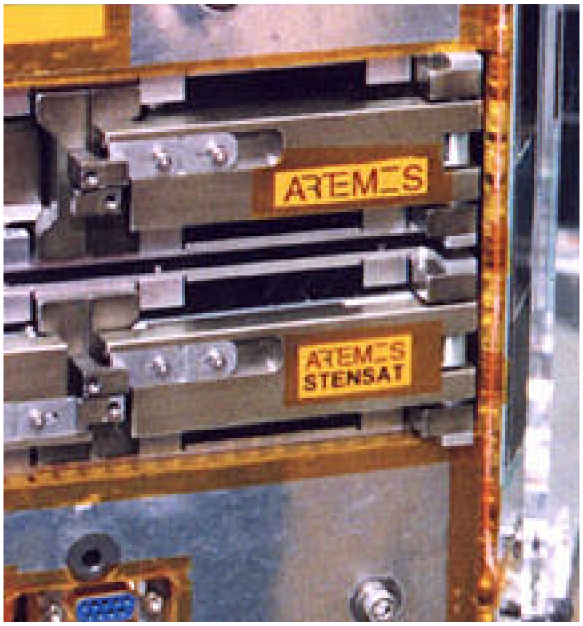

Figure 6 – Head on view of two picosatellite tubes.

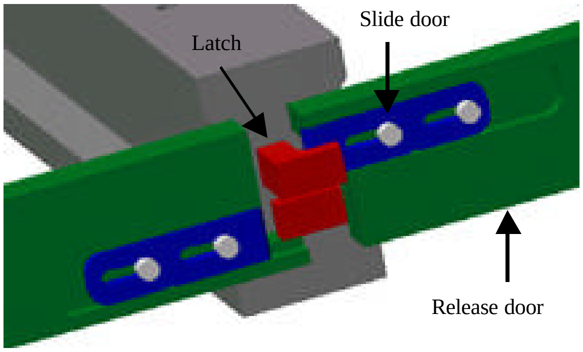

Figure 7 – Close up of two latch/door mechanisms.

Figure 5 is a rendering of two picosatellite launch tubes. OPAL contains four such launch tubes, each capable of holding two short 7.5x10x2.5 cm or one long 7.5x20x2.5 cm picosatellite. Six picosatellites flew on OPAL, four short and two long. The dimensions of the picosatellites were determined by the preexisting structure of OPAL. The launcher itself can be manufactured to support an endless possibility of rectangular shaped picosatellites.

During storage, the picosatellites were confined by their beveled edges as they pressed against beveled support rails on the launcher. The release door in front locked them in place during launch. The door was held by a latch and cable system attached to a nonexplosive actuator. A spring powered push plate inside the tube ejected picosatellites. Each tube could be commanded separately to fire. The launcher was fabricated from aluminum and coated with the dry lubricant Dicronite. Effort was made to minimize constraints on external picosatellite features. Less than five percent of the picosatellite exterior surface was in contact with the launcher mechanism. Figure 6 shows a head on view on the launcher doors.

The latched door was designed with a dual release mechanism. The primary release was through a latch and cable system. It is a single shot release and requires replacement of the nonexplosive actuator for additional releases. Resetting the primary mechanism required de-stacking of the OPAL structure. A secondary release was built to enable insertion or removal of picosatellites without disruption to the primary latch and cable system. Figure 7 shows a close up of this mechanism. The blue door slider enables the red latch to be free of the door. Thus the door can be opened without disturbing the latch. This enabled picosatellites to be inserted after delivery of OPAL to launch providers.

Picosatellite firing was commandable from the ground via the CDH system. A secondary auxiliary receiver and firing circuitry were installed as a redundant firing option. The secondary system was independent of the primary CPU and communication system.

4.3 Daughterships (aka Picosatellites)

A diverse range of picosatellites flew onboard OPAL. From seasoned aerospace professionals to inexperienced college undergraduates, three design teams explored the technological and mission capabilities of the smallest satellites ever launched in space.

The Aerospace Corporation teamed with Rockwell Science Center and was funded by DARPA to explore MEMS (micro electromechanical systems) technology in space. They flew a pair of picosatellites tethered together by a 10-meter tether. The picosatellites carried a testbed to characterize MEMS radio frequency switches. They also carried a communication system based on 900MHz digital phone technology to perform packet-hopping experiments.

Three picosatellites were built a team of undergraduates from Santa Clara University, called Artemis. Two of them contained a VLF (very low frequency 0.2 - 11 kHz) receiver to study VLF emissions from thunderstorms. Their third picosatellite, named JAK, was a simple beacon transmitter designed to test the ground reception ability of space borne picosatellite broadcasts [10].

The last of the OPAL picosatellites was built by a group of amateur radio enthusiasts from the Washington, D.C. area. Their satellite, called STENSAT, is solar powered and intended for use by world wide HAMs as a single channel mode “J” FM voice repeater [11].

4.4 Magnetometer Testbed

The APS533 magnetometer was originally mounted on a 35 cm fixed boom on OPAL’s top panel. Launch vehicle constraints forced us to reduce the boom size to 10 cm. The original boom would have placed the magnetometer outside the rocket fairing.

Resolution of the magnetometer is limited by the OPAL’s 12bit analog-to-digital conversion system. Measurements of 0.25mG increments are possible with a maximum reading of +/- 1 G. The magnetometer can be measured with a frequency up to 1 KHz.

Magnetometer performance will be measured by comparing the vector magnitude of the earth’s magnetic field as measured by the sensor to the predicted vector magnitude of standard geomagnetic modeling software

4.5 Accelerometer Testbed

Two of each of the accelerometers were flown in the testbed. A stimulation source was provided to exercise the accelerometers. Frequency response of the accelerometers will be compared to ground testing. Leakage currents will be measured to determine long-term radiation damage.

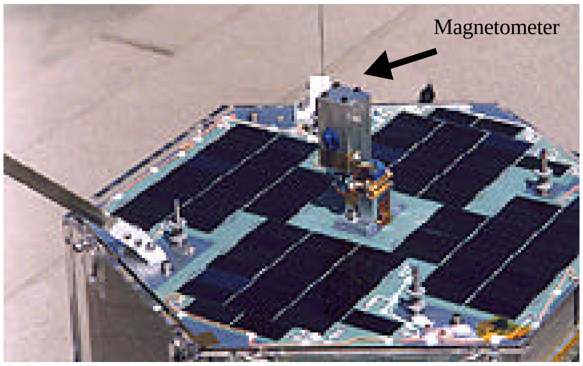

Figure 8 – Externally mounted magnetometer.

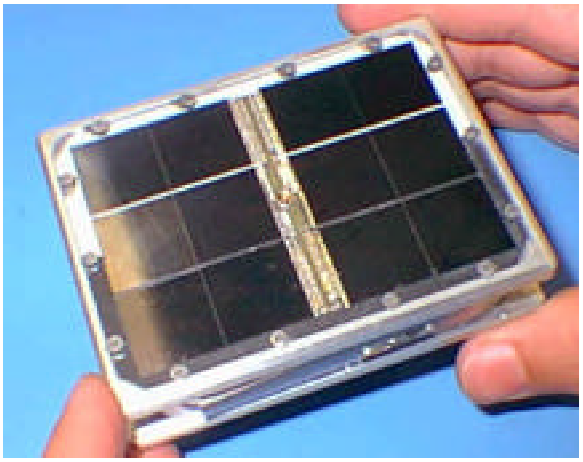

Figure 9 – The STENSAT picosatellite.

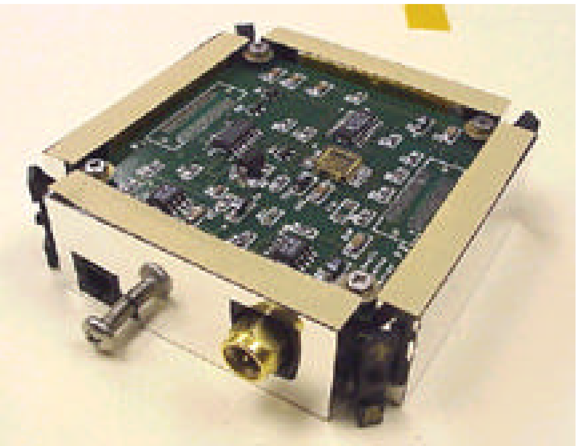

Figure 10 – Inner electronics of an Aerospace picosatellite.

5 MINOTAUR LAUNCH

On January 26, 2000, at 7:03PM PST, OPAL was launched from Vandenberg Air Force Base on the historic launch of the Minotaur I launch vehicle. Attached to a multi-payload adapter, OPAL rode with several other university satellites. All five payloads of the Minotaur were placed in a circular, sun-synchronous orbit at a height of 750 km.

5.1 Minotaur

The Minotaur, also called the Orbital Suborbital Program Space Launch Vehicle, is the first use of a modified Minuteman missile as a launch vehicle. The first two stages are from the Minuteman II ICBM while the last two stages are from the Pegasus launch vehicle. The vehicle can lift 340 kg to a 740 km, sun-synchronous orbit. This is roughly 1.5 times that of the Pegasus vehicle [12]. The U.S. Air Force and Orbital Sciences Corporation performed integration of the rocket components. The second Minotaur mission is scheduled to launch the Air Force Research Laboratory's MightySat II payload in late 2000.

5.2 Multi-Payload Adapter

OPAL was attached to the multi payload adapter built by the One Stop Satellite Solutions of Ogden Utah. The adapter itself was a satellite called JAWSAT, which supported a plasma science experiment and an attitude control experiment [16]. The adapter was attached to the fourth stage of the launch vehicle.

In addition to Opal, three other free flying satellites were attached to the adapter and deployed within minutes of reaching orbital height. These satellites were: Falconsat from the US Air Force Academy [17], ASUSAT1 from Arizona State University [18], and the Optical Calibration Sphere (OCS) from the Air Force Research Laboratory [19].

6 FLIGHT RESULTS

OPAL has achieved all mission goals. All six picosatellites were successfully deployed and the component testbeds are operational. OPAL is now in extended operations with focus on long term characterization of the bus and component testbeds. The Radio Amateur Satellite Corporation (AMSAT) has assigned OPAL an identifier of OO-38.

In the followings section, flight results and data from OPAL operations and payload experiments are summarized.

Figure 11 – The Minotaur rocket on the launch pad.

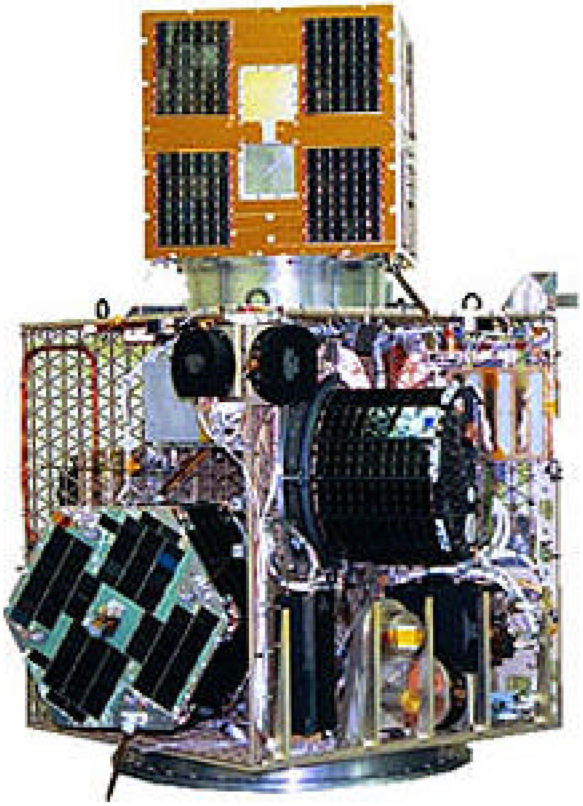

Figure 12 – Payloads attached to the multipayload adapter. Falconsat is on top. OPAL is on the lower left. ASUSAT1 is the larger black cylinder in the middle.

6.1 Operations

The first few days of operations were filled with excitement and tension. OPAL beacons received by HAMs within hours after launch indicated that the OPAL bus was operational.
Jean-Louis Rault F6AGR from Paris, France conducted the first full contact with OPAL and from his data we determined the OPAL bus was indeed fully operational. Malfunctions in the SSDL ground station prevented operators from contacting OPAL. The HAM community was instrumental in delivering OPAL data to SSDL while the SSDL ground station was debugged and fixed.

After several days of unsuccessful operations from SSDL, operations were moved from the SSDL OSCAR ground station to the SRI 50 meter radio telescope facility behind Stanford. Equipment was installed and contact with OPAL was established using the high gain 50 meter antenna. Initial vehicle checkout was performed, preliminary characterization of the testbeds was performed, and all six picosatellites were successfully fired.

Operations returned to the SSDL station after antenna gain and output power issues were resolved. Currently, operations are supported by the SSDL station via Internet based operation techniques [4]. Upon completion of appropriate documentation, access to OPAL will be opened up to allow non-Stanford operation.

6.2 Bus Performance

OPAL's bus performance is better than expected. All systems are operating nominally and telemetry values are within predicted boundaries. Exterior temperatures on the solar panels range from –20° to 75° C. Internal temperatures range from 10° to 35° C. The average internal temperature is 23° C.

The power system is functioning exceptionally well. Average power generation of the panels is 8W. Average consumption is 2.4W. Additional power is dissipated as heat by the battery system. The average bus voltage is 14.5V.

The computer system has performed remarkably well considering the lack of hardened or EDAC (error detection and correction) memory. The spacecraft has reset unintentionally only three times in five months of operation despite orbits through the poles and South Atlantic Anomaly [15]. In the near future, operators plan to upload code to monitor bit flips in OPAL's memory system.

The communication system has been the most troublesome system on OPAL. The link margin is very tight with standard OSCAR station equipment. OPAL's output power is only 1.6W and it has omnidirectional antennas. We are experiencing degraded links as OPAL rotates through nulls in its antenna pattern.

The lack of an attitude control system has challenged the OPAL bus. Figure 13 shows a temperature plot during the second week of OPAL operation. Notice the sharp increase in OPAL's battery temperature. They reached a sustained temperature of 70°+ C. The battery system has a maximum temperature rating of 30° C.

The event that caused the increase in temperature is unknown. We hypothesize that OPAL collided with the Optical Calibration Sphere. Orbital analysis shows that OPAL came within two kilometers of the balloon at this time. The event forced OPAL's bottom solar panel to face the sun for an extended period of time and OPAL rotation stopped. The batteries, attached to the bottom solar panel, heated quickly.

The sharp decrease in temperature immediately followed picosatellite deployment. OPAL recoiled from the launch and once again began spinning. Temperatures returned to normal.

The elevated temperatures were a threat to battery integrity. Although no immediate damage was detected, it is expected that battery lifetime has been shortened. During this time of elevated temperatures, the communication system was also affected. Spurious tones appeared on OPAL's transmissions that rendered data from OPAL unreadable. These tones disappeared when temperatures returned to normal.

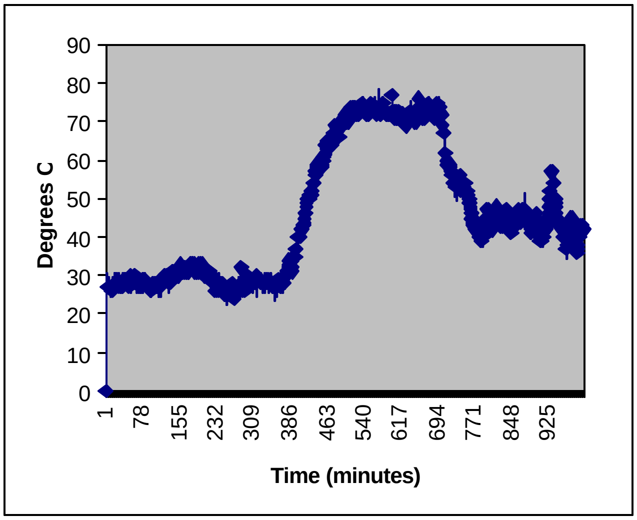

Figure 13 – OPAL battery temperature data

An attitude control system, even a simple one, would have helped alleviate this problem. Especially now, as OPAL's spin rate has decreased since launch from 10 rpm to .1 rpm, there are concerns that OPAL may again see elevated temperatures.

After five months of successful operations, OPAL is expected to operate for several more months. Long term degradation due to space radiation and extreme temperatures will likely result in an eventual system failure. Until then, OPAL will continue in extended operations.

6.3 Picosatellites

OPAL successfully stored and deployed the six picosatellites. Ejection was confirmed through onboard telemetry as well as Space Command tracking of objects near OPAL.

Aerospace successfully operated the world's smallest civilian satellites. Based on satellite log files, the time of launch was approximately 02/06/2000 19:34:16 PST. They achieved their primary mission objective of validating an array of MEMS RF switches. Their batteries were exhausted before the communication hopping experiment could be performed.

STENSAT was successfully fired at approximately 02/10/2000 17:59:13 PST. Unfortunately, no confirmed contacts were made with STENSAT. Reasons for failure are unknown.

The Santa Clara beacon satellite, JAK, was fired with STENSAT. They were housed in the same launch tube. No reception of JAK's beacon was confirmed. Possible partial beacons were heard but they are believed to be from Opal rather than JAK (JAK transmitted at the same frequency of OPAL). Expected output was a Morse code beacon containing a URL. Due to limited battery life, it is believed JAK ceased operating by 02/13/2000.

The VLF picosatellites from Santa Clara were successfully launched at approximately 02/12/00 05:40:19 PST. Possible signals were received but nothing confirmed. No lightning data was downloaded. Due to limited battery life, they ceased operating by 02/15/00.

6.4 Component Testbeds

Operation of the magnetometer testbed is nominal. Figure 14 shows a sample of three-axis magnetometer data taken over one orbit (1000 measurements taken over one hundred minutes). Detailed data analysis is underway.

Operation of the accelerometers is nominal. All accelerometers are functioning as expected. No signal degradation has been detected. Detailed analysis is underway. See figure 15 for a data plot.

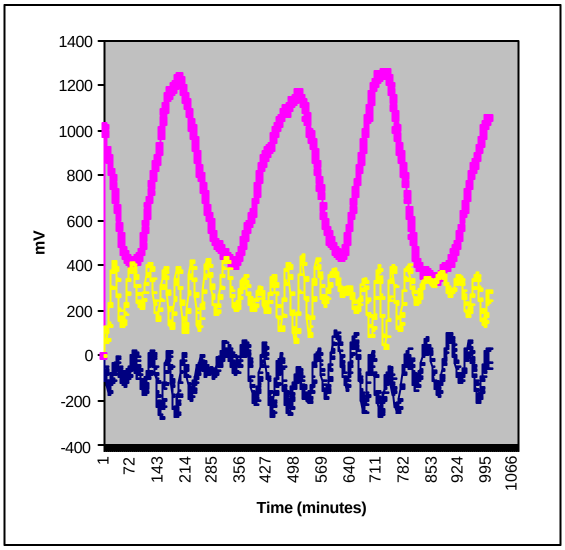

Figure 14 – Magnetometer Data.

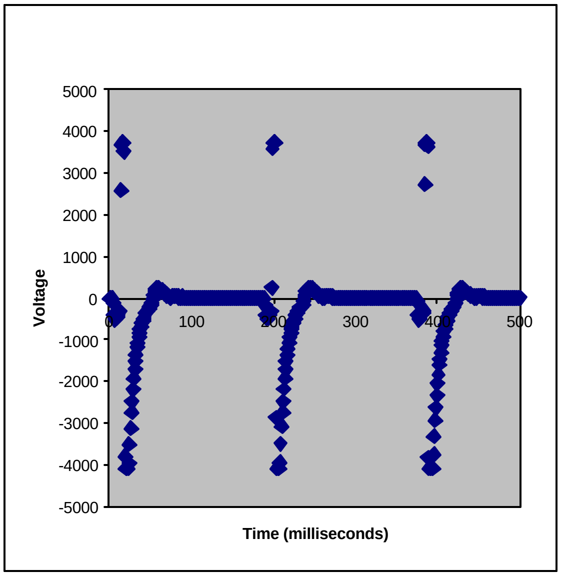

Figure 15 – PCB accelerometer data.

6.5 Lessons Learned

The OPAL satellite was engineered entirely by master's level graduate students during their education at Stanford. We learned many things the hard way. Though the following lessons may well be common knowledge to veterans, hopefully they will serve as a good reminder to all.

A well-defined interface is an integrator's dream come true. Integration of OPAL subsystems was hard enough, but external interfaces with the launch vehicle and picosatellite design teams required detailed interface documents. These documents were an excellent tool in ensuring plausible integration as well as a heated source of conversation, consideration, and controversy.

As C.A.R. Hoare, "The unavoidable price of reliability is simplicity." Whenever possible, we simplified our system while still achieving mission goals. A prime example is the power system. No power regulation circuitry was designed. The solar panels were directly wired to the secondary battery system. The battery system was sized large enough that excessive overcharging was not possible.

If at all possible, use a standard and don't reinvent the wheel. Our communication system was based on the AX.25 packet radio protocol from the amateur radio community. OPAL's standard communication system allowed HAMs around the world to aid in downlink of OPAL data and telemetry. This proved vital in determining OPAL's post launch state while SSDL's ground station failed to function.

Flight operations are better planned during design rather than after launch. We discovered during operations that we should change and tweak many things on OPAL. Had we done more extensive operations planning and testing, many of these issues would have surfaced prior to launch. Also, contact times are much smaller than expected. We had planned for 10 minute or longer contact windows. Realistically, we are only able to converse with OPAL approximately 5 minutes a pass.

A good beacon is the needle in the haystack. After launch, orbital elements were inaccurate, and in OPAL's case, they were mislabeled for several weeks. A strong beacon would have helped us find OPAL and aided in characterizing the communication channel. Our beacon, only 800ms in duration, was far too short.

An external power-on indicator is a must. Twice, during final integration, OPAL was inadvertently turned on without anyone knowing and this led to damage of critical flight hardware systems. Fortunately, the systems were repaired but this would not have happened if OPAL had had an external power indicator (i.e. a power-on LED). A corollary to this lesson is having an "alive" indicator to indicate that the CPU and software are functioning properly.

When your memory fails, a telemetry repository will be your greatest asset. All OPAL data is not only archived, but also decoded and published on a public web site. This is done in real time during a contact. Operators can thus search and parse OPAL data with a few simple keystrokes. This has proved an incredible tool during operations for real time data mining. We wish we had such a system in place during pre-launch testing. Our pre-launch records of OPAL telemetry are sparse at best.

Hopefully, these lessons will be useful to others as they venture to build other complex space systems.

7 FUTURE WORK

OPAL has completed its primary mission and is currently under extended operations. Characterization of the bus, the accelerometer testbed, and the magnetometer testbed will continue as long as OPAL is functional and resources are available to operate OPAL. The operations team is currently working to publish operating procedures for OPAL. Once complete, restricted access to OPAL will be disabled thus allowing non-Stanford operation for educational purposes. It is our hope that OPAL will serve as an educational tool for other universities as it provides real world satellite operational experience.

7.1 Internet Based Operations

A current research project at SSDL is Internet based satellite operations. Over 90% of all OPAL contacts are done remotely via the Internet. SSDL is building an infrastructure to enable remote operation of ground station facilities. A software infrastructure is also under development to enable real time reconfigurable multi-user access to distributed data sources (such as satellites) [4].

7.2 Next Generation Picosatellites

The Aerospace design team is launching a second picosatellite mission on MightySat II.1 scheduled to launch in late 2000 on Minotaur II. They have replicated the OPAL mothership system and the tethered picosatellite system. Future Aerospace picosatellites will continue to push the frontier as they explore innovative MEMS technologies such as micro thrusters and gyroscopes.

SSDL is continuing its work through a project called CubeSat. Partnering with several other universities, SSDL will be launching 10cm cube satellites to explore mothership/daughtership mission technologies.

8 CONCLUSIONS

SSDL has successfully launched and operated its first satellite, OPAL. The OPAL satellite has demonstrated that student-built microsatellites can provide an excellent low-cost, though high risk, platform for experimental testbeds.

OPAL provided an end-to-end mission demonstration of the mothership/daughtership architecture by storing, deploying, and launching six picosatellites. This architecture has been proposed to provide better measurement capabilities for distributed sensing. Two of the six picosatellites were successful and conducted experiments on MEMS RF switches. OPAL’s other two payloads are characterizing a magnetometer and a suite of accelerometers.

All OPAL mission goals of have been successfully met. In extended missions operations, OPAL will continue long-term characterization of the bus and payloads. It will also be used as an educational tool for real world satellite operations training.

More detailed information on the OPAL satellite is published online at: http://ssdl.stanford.edu/opal/.

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