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Engineering Notes

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Sapphire: Case Study for Student-Built Spacecraft

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Introduction

FROM 2000–2005, universities put in orbit more than 35 student-built spacecraft; spacecraft where training of student engineers was the primary/only mission objective, and where the students themselves were primary agents of design, fabrication, test, and operations [1]. Nearly 20 more are scheduled to launch in the next two years. Not only is this a significant increase from the 20 launched between 1981–2000 [2–6], but the pool of "spacefaring" universities grew from 21 in 2000 to 34 in 2005, with at least 10 more scheduled to join that group by 2007. Because these educational projects demand significant resources from the universities, their students, and their government/industry sponsors, it is useful to review student-built space missions for both their educational and technical merit. For this Note, we examine Sapphire, the first spacecraft built by the Space Systems Development Laboratory (SSDL) at Stanford University. We review the Sapphire design approach on both its educational and technical merits to provide lessons learned for other universities and the industrial partners that would sponsor their activities.

The authors managed SSDL's first three orbital spacecraft: Sapphire, Opal [7], and QuakeSat. In the early 1990s, SSDL was among the first U.S. schools to attempt a sustained student-built spacecraft program [8], others included Arizona State University [7,9], Weber State University [10], and the U.S. service academies [10,11]. Like most student-built spacecraft, Sapphire is a modestly performing small satellite that does not push the bounds of space technology. And yet, this is precisely why we believe it to be a good case study; there was nothing special about the mission, nor did SSDL enjoy extraordinary sponsorship from government, industry, or even the university. Thus, lessons learned from Sapphire can benefit almost any student satellite project. Despite its modest technical performance, Sapphire was used to demonstrate new research in spacecraft operations, to educate more than 100 students at three different universities, and to found one of the few sustained student satellite programs.

Sapphire Overview

The Sapphire project began in 1994; the major flight components were integrated and operated in 1995, and the spacecraft was completed in 1998. In 2000, the vehicle was transported to Washington University in St. Louis (WU) for final prelaunch preparations and, in September 2001, Sapphire and three other spacecraft launched on a Lockheed Martin Athena 1 rocket as part of the Kodiak Star flight (Fig. 1). Sapphire's launch was supported by the U.S. Naval Academy and the Department of Defense's Space Test Program.

Sapphire is a 20 kg hexagonal prism 27 cm tall and 44 cm across, with average daily generated power of 8 W, and 5 W required average power. The major components are modified and extensively tested commercial products, including its microcontroller main processor, 70 cm band transmitter, 2 m receiver, 1200 baud terminal node controller, and DC–DC converters. Student-built electronics boards monitor telemetry and manage power, and students fabricated the aluminum honeycomb structure. Space-rated NiCad batteries, GaAs solar cells, and radiation-hardened memory are strategically included to improve on-orbit lifetime. The spacecraft is passively stabilized by a combination of body-mounted permanent magnets and a radiometer spin caused by alternating black and white paint on the turnstile transmit antennae. Passive thermal management is achieved through coatings to create an isothermal interior and structurally isolating sensitive components.

Sapphire met all mission objectives during its six years of ground testing and 30 months of full operations. The primary mission was to collect first-flight data for a fixed, narrow field-of-view horizon-crossing instrument [12,13]. Operational data was returned from two instruments each containing two Stanford/Jet Propulsion Laboratory (JPL) micromachined tunneling horizon detectors (THDs). Sapphire also captured Earth images using a commercial digital camera, supported Amateur radio with digital and voice communications, and, most importantly, provided a significant student education and research platform. Sapphire was used several times as a demonstration vehicle for autonomy research; in ground tests, student researchers provided the first verification of beacon monitoring technology for low Earth orbits (LEOs) [14], developed a suite of performance metrics, and used those metrics to validate the cost-effectiveness of the technology for a niche of LEO missions [15]. On-orbit, Sapphire was used in an end-to-end demonstration of model-based anomaly management algorithms [16]. Finally, Sapphire had two unplanned on-orbit uses: store and forward communications for the amateur community, and ground station calibration for other universities.

Design Approach and Assessment

Because projects such as Sapphire depend on untrained students for subsystem design and development, the design scope of these satellites must fit the abilities of the team. Three approaches to

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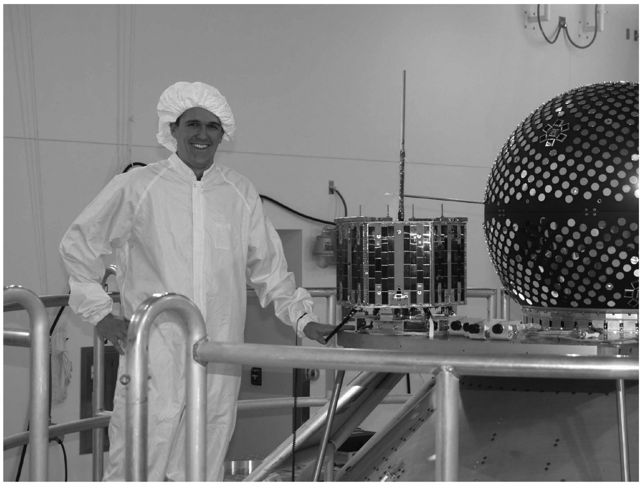

Fig. 1 Sapphire on Athena Payload Upper Deck (photo courtesy NASA).

managing scope were particularly important to Sapphire's success: operational robustness, payload/component definition, and modular architecture. Conversely, the project's approach to managing schedule and securing a launch are lessons to avoid repeating.

Operational Robustness

In retrospect, the most important self-imposed design guideline was to require all parts of the mission to be robust to operations-time errors such as incorrect commands, loss of communication, or loss of data; this requirement also mandated large mass, power, and communications margins. Such "operational robustness" greatly simplified the overall design and made the spacecraft an ideal training tool; most Sapphire operators were students or radio amateurs with little or no training, and yet no operator command or environmental disturbance permanently disabled or damaged the spacecraft.

Operational robustness protected the mission against hardware failures. Two THDs failed during subsystem integration, and a third stopped returning telemetry within a few weeks of reaching orbit. The decision to fly two dual-redundant THDs meant that a fourth sensor was still available, and it functioned throughout the mission. Similarly, in the three years from integration of the flight solar panels to launch, handling and workmanship errors rendered three strings inoperable. The management team decided against repairing these strings because of the prohibitive cost and schedule delays. This decision was made possible by Sapphire's significant power margin, which only required 12 of 20 strings to meet minimum operational requirements. It is not an exaggeration to state that this operational robustness saved the Sapphire mission; if Sapphire had to be disassembled to correct either problem, the schedule slip would have certainly caused the project to lose its slot on Kodiak Star, permanently grounding it.

Payload Selection

Student satellites exist to serve student education, and thus the flight payload is often selected after the team decides to build a spacecraft. Sapphire was no exception. Because of this inverted design process and the limited resources of student projects, the payloads were selected based on student interest, compatibility with an operationally robust design, and because they represented fundamental payload types: science instrument, communications relay, and remote sensing. From an education standpoint, this spectrum of types forced students to manage conflicting payload requirements and difficult integration problems.

Modular Architecture

Sapphire was designed as a set of modular trays; although all components had to fit within the envelope and connect to a common wire harness, complete freedom was given to arrange components within the tray. This modular approach aided design by allowing each subsystem to continuously iterate without affecting other components. Modularity aided the process of creating a sustainable university program by allowing future student teams to modify only a few subsystems to meet their new mission; for example, Opal used a nearly identical power subsystem tray.

Although the modular structure was very weight-inefficient, weight was deliberately sacrificed to improve integration, test, and survivability. The benefits of modularity were repeatedly enjoyed during fabrication and early testing, because one or two students could quickly swap out components and even trays to troubleshoot faulty systems.

Launch Sponsorship

Sapphire was built under the assumption that ample low-cost secondary opportunities would be available, based on the 1990s expectation of dozens (or hundreds) of satellites launched for communications constellations (Iridium, Globalstar, Teledesic, etc.). When those missions stalled, the cost of secondary opportunities rose (or went away), and Sapphire was left without a launch. This had the obvious negative effect on student productivity, project reputation, and schedule. By contrast, the Opal [17] mission had Defense Advanced Research Projects Agency sponsorship and was launched within a year of completion; QuakeSat was a sponsored remote sensing demonstration and took less than 18 months from concept to operations.

Sapphire reached orbit by being donated to the U.S. Naval Academy as an operations training tool, then through sponsorship of the Space Test Program. Although it is generally true that flight-ready student spacecraft eventually find a launch, we do not recommend this approach; it has a deleterious effect on student morale and technical relevance.

Schedule

The obvious drawback to an open schedule is that the schedule will inevitably slip. The program originally envisioned a one-year development cycle, but with no firm launch. Sapphire was built over a period of four years, with another three years to secure a launch and enter orbit. One advantage of an uncertain schedule was that management could trade schedule against cost or performance. For example, the solar panels were prohibitively expensive to purchase; Sapphire's solar panels were assembled from donated cells using the facilities and assistance of Lockheed Martin on a time-available basis.

Still, timeliness (or the lack thereof) has three significant drawbacks for university-class missions. First, these projects face significant student turnover problems, leading to further delays. Second, turnover erodes the project's educational value, as few students (if any) participate in the entire design life cycle; this problem is mitigated by the fact that more students get to participate in the project. Finally, cutting-edge university research becomes less relevant. The THD was a relatively new technology at the start of the project, but in the seven-year gap from conception to flight data, the THD had become old technology and, more importantly, the payload principal investigator had shifted his research focus to terrestrial applications. Therefore, although the flight data validated the basic design of the sensor, the delay hampered the data's relevance.

Mission Assessment

Sapphire was designed and built by more than 70 students at Stanford University, readied for flight by more than 30 students at Washington University, and operated by students at the U.S. Naval Academy and at Santa Clara University. In addition, Sapphire was used to calibrate ground stations and train student operators for other university programs. The educational benefits of the program are further reflected in the post-project careers of participating students; of the dozen graduate students who invested a year or more in the project, nine hold significant spacecraft systems or management responsibilities with aerospace contractors, the U.S. Air Force, or academia, whereas the other three are involved in systems-based research and management in industrial or government laboratories. Sapphire played a central role in experimental research for two doctoral dissertations and three engineers' projects, and three students founded satellite projects at other schools. Sapphire-heritage parts and processes can be traced to SSDL's Opal and QuakeSat, as well as five other university programs: Santa Clara University's Onyx, Washington University's Akoya [18], San Jose State's Spartnik, the three UNISATs from the University of Rome [19,20], and the three SaudiSats launched by the King Abdulaziz City for Science and Technology, Saudi Arabia.

Sapphire's modest technical performance was hampered by three problems: the THD's lack of relevance driven by schedule slips, a miscalibration of the digital camera rendering it useless in full sunlight, and colder-than-anticipated conditions due to the flight orbit being 300 km higher than the design orbit. Still, the technical simplicity of the project is a program strength; unlike many more ambitious student projects, Sapphire was finished, made available for ground-based research and testing for six years, and functioned for more than two years on-orbit.

Sapphire was very useful as an operations test bed. Since the vehicle carried simple representations of standard payload types, it was a good flight demonstration for ground-based autonomy research in beacon monitoring and model-based health management. Sapphire's lack of technical depth was a benefit to autonomy researchers in two ways: it allowed them to create simple but comprehensive models of the entire vehicle and to have significant access to the vehicle both on the ground and on-orbit.

Design Suggestions to Maximize On-Orbit Utility

Anomalies and mission difficulties are to be expected with any student-built spacecraft; indeed, student labor and nonstandard components carry inherent mission risk. The lower performance and higher risk of student-built spacecraft compared with professionally-built spacecraft tends to restrict students' ability to develop and integrate real-world-relevant missions. Through positive and negative examples, the Sapphire mission demonstrated six methods to guide students towards modestly scoped, useful missions that can be accomplished in the near term with existing hardware.

Rigorous Functional and Environmental Testing

Early vacuum and thermal cycle testing identified discrepancies between manufacturer specifications and actual thermal behavior of key components. More important, a functional prototype is essential for success. Sapphire was extensively operated for months on the ground before launch; every single operating condition and anomaly experienced on-orbit had been identified during ground testing. It is our belief that many student spacecraft fail due to lack of time to correct problems in ground testing, especially in power subsystems.

Large Operational Margins

Student-built spacecraft have an inherently higher risk of design and/or fabrication errors. It is essential to mitigate these errors by building spacecraft with significant margins in mass, power, computation, pointing, and communications; such margins saved the Sapphire mission on several occasions. Alternately, student projects that push the state-of-the-practice in performance need all team members and sponsors to accept a significantly higher risk of failure.

Common Structural Interfaces

The benefits of a modular tray structure were discussed in a preceding section. In addition, the spacecraft-to-launch vehicle interface is one of the most reviewed and risk-prone aspects of a student project. Both cost and reliability are improved through the use of common interfaces across universities. Standard launch interfaces increase the likelihood of successful deployment, decrease the regulatory burden on the design teams, and increase the ability for students to gain practical insight from other schools whose vehicles fit those interfaces. Sapphire's student-led launch interface design was common to Opal and the U.S. Naval Academy's prototype communications satellite (PCSat). In fact, testing irregularities in PCSat's launch interface led to a design improvement in Sapphire's interface, eliminating a potentially mission-ending design flaw. The question of whether these benefits would apply to other aspects of student spacecraft (wiring harness, power systems, data protocols) deserves further study. For example, Santa Clara University adopted a standardized command and data handling system based on the authors' experience with Sapphire [21].

Very Short-Duration Missions

Short-duration missions (90 days or less) have two positive effects. First, reduced orbital lifetimes lead to lower cost/mass components, particularly required battery depth-of-discharge and propellant mass. Secondly, short missions reduce the risks to consumer-grade parts; over a two-week mission, the risk of radiation-induced failures on a commercial microprocessor could be favorably traded against the cost, mass, power, and complexity of integrating a space-rated device. However, the radiation risk for modestly-performing student spacecraft should not be over-estimated. During 30 months of operations, Sapphire's micro-controller experienced three radiation-induced upsets; Opal and QuakeSat had similar experiences.

Well-Scoped Missions

With a lack of compelling payloads and lacking the resources to attract such payloads, most student projects focus almost entirely on training. Clearly, this is a worthwhile objective; many students (including the authors) have benefited from hands-on engineering experience despite the lack of "real" payload. However, this approach is not sustainable. Most programs with education-only satellites succeed in launching only one spacecraft (if they launch any at all); the time, money, personnel, and enthusiasm spent on the first spacecraft was not available for the second, and the program ended.

Rather than attempt to mimic professional spacecraft, student projects should play to their strengths: their tolerance for risk and ability to use their space assets to test revolutionary concepts. The reduced capabilities and simple design inherent to student-built spacecraft makes them ideal for short-term/limited demonstrations of new operations concepts and technologies, such as autonomy, inspection, servicing, robotic assembly, or higher-risk methods for navigation and control. Such mission objectives make it easier for projects to attract outside sponsorship, and it provides students with a more compelling goal. Sapphire's simple design was used to demonstrate complex autonomous operations, and the authors' follow-on missions (Opal, QuakeSat, Onyx, Akoya) have adopted this path.

Conclusion

The Sapphire spacecraft was placed on-orbit in 2001, exceeded its one year design life by 18 months, and most components were strenuously operated for several years before launch. The batteries failed in March 2003, but at the time of this writing, Sapphire is still functional in sunlight. From a program standpoint, the decision to make operational robustness and modest, modular architectures fundamental spacecraft design drivers proved essential to the eventual completion and launch; it also enabled the vehicle to be used for both ground tests and on-orbit activities unexpected during the design process. The project also highlights the need to properly manage system scope and development schedule to maximize technical and educational value. Although Sapphire eventually found a path to orbit, it came at the cost of severe schedule slip and payload obsolescence. To ensure their own mission's launch and operational success, we believe that student satellite projects should seek modest-in-performance but revolutionary-in-concept flight demonstrations of technologies and processes that professional programs are not (yet) ready to adopt.

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