A University-based Distributed Satellite Mission Control Network for Operating Professional Space Missions

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Abstract – For more than a decade, Santa Clara University’s Robotic Systems Laboratory has operated a unique, distributed, internet-based command and control network for providing professional satellite mission control services for a variety of government and industry space missions. The system has been developed and is operated by students who become critical members of the mission teams throughout the development, test, and on-orbit phases of these missions. The mission control system also supports research in satellite control technology and hands-on student aerospace education. This system serves as a benchmark for its comprehensive nature, its student-centric nature, its ability to support NASA and industry space missions, and its longevity in providing a consistent level of professional services. This paper highlights the unique features of this program, reviews the network’s design and the supported spacecraft missions, and describes the critical programmatic features of the program that support the control of professional space missions.

Key Words: Spacecraft mission operations, groundstation, nanosatellite, CubeSat

1. Introduction

Distributed satellite mission control networks are in use by a variety of governments and companies in order to support payload operation and health management of their spacecraft. These networks are characterized by being capable of supporting multiple missions around the clock, hosting numerous mission/science/payload operations centers, and having geographically-distributed communication/tracking stations. They also provide networked command and data handling services, database-driven command and telemetry software that consolidates mission data independent of the operations center and communication station used, and modular mission-unique software for satellite-specific processing tasks. Beyond having such equipment and infrastructure, these networks are also characterized by having highly trained personnel and well-defined processes for conducting operational tasks. Although such networks can be costly to support, they offer redundancy, dramatically expanded space-to-ground communications availability, robustness to local service interruptions, and a sharing of infrastructure costs over dozens of space missions.

One example of this type of system is the NASA Deep Space Network (DSN) [1], operated by the Jet Propulsion Laboratory and routinely used to control more than 30 on-orbit spacecraft. In operation for more than 50 years, the DSN specializes in the control of deep space probes, housing the world’s most sensitive telecommunications equipment. The Network has a central network control center with distributed mission-specific operations centers, and it includes more than a dozen large scale antennae ranging in sizes up to 70 meters in diameter and deployed primarily at three sites around the world [2]. The U.S. Air Force Satellite Control Network (AFSCN) is used to operate more than 150 ongoing missions for the U.S. government [3]. It has two operational control nodes and nearly 20 antenna systems ranging in sizes up to 18 meters in diameter at 9 locations throughout the world [4]. The European Space Agency operates 10 communication stations throughout the world with antenna ranging in sizes up

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to 35 meters in diameter. More than a dozen missions are typically supported at any one time from the central mission center in Darmstadt, Germany [5].

Within the university community, many schools have established single student-developed/staffed rooms that serve as a combined mission control room and communications station. These are ideally suited to support educational missions, such as many CubeSat-class spacecraft, that are developed and ultimately operated by students. To improve availability, proposals to implement university-class ground station networks began as early as the mid-1990s, just as universities began to develop small spacecraft, and prior to the introduction of CubeSats [6]. Since that time, there have been several examples of coordinated activity in which operators external to a mission control team can collect data as a courtesy and e-mail files to the control center for that mission; these external operators are often students from collaborating universities or amateur satellite operators. More integrated versions of this have been implemented in which collected data is submitted post-pass via the web to a centralized mission database [7] or where external operators link their communication stations to a control center server during realtime data collection [8]. Even more sophisticated in design is the GENSO (Global Educational Network for Satellite Operations) initiative, which has an objective of establishing a worldwide network of groundstations that can be shared/borrowed via the internet for conducting remote contacts. Focused primarily on the use of amateur radio frequencies, the GENSO system has been in development for the past 8 years with contributions by several universities (such as the University of Vigo in Spain, the University of Tokyo in Japan, and the University of Texas Austin in the U.S). Furthermore, project coordination and systems engineering are being provided by the European Space Agency's Education Office and industry partner the Vega Group PLC, and the European amateur radio group AMSAT-UK is assisting with several technical development activities. Several GENSO groundstations have been operational over the past three years, with one station supporting 227 contacts over a 20 month period [9]. Other recently launched efforts continue to evolve, such as the SATNet initiative from Cal Poly [10], the MIT Open System of Agile Ground Stations program [11], and the University of Stuttgart's Distributed Ground Station Network project [12]. In general, all of these groundstation networking initiatives are distinguished in two ways. First, they are intended to be used primarily to support student-built educational/experimental satellites as opposed to professional-class government or industry missions. Second, they focus on networked ground communication stations, which are only a subset of the infrastructure in a complete satellite control network; furthermore, they generally lack the personnel and process components of professional networks.

Operation of professional-class space missions does occur in university environments. One example of such operations is work at the University of Colorado Boulder's Laboratory for Atmospheric and Space Physics (LASP), which operates several Mission Operations Centers and Science Operations Centers for NASA satellites and spacecraft payloads. LASP routinely controls multiple spacecraft, and students are routinely certified as operators; however, LASP generally does not manage its own groundstation network, and the majority of their operation is run by professional staff [13]. The Johns Hopkins University Applied Physics Laboratory (APL) also provides professional-level satellite operations services for PI-led NASA science and other missions; these services, however often use external ground networks like the DSN, rely on professional staff for conducting operational activities, and focus on payload operations [14].

In contrast to these university-based systems, Santa Clara University's Robotic Systems Laboratory has developed and operates a comprehensive distributed satellite control network appropriate for supporting multiple, professional-class spacecraft missions. Compared to the DSN and AFSCN, this network is simple in design and low-cost in terms of its components, but it has proven to be quite capable of supporting simple small spacecraft missions. Compared to the professionally-capable activities at centers such as LASP and APL, this activity is comprehensive in operational scope and is staffed almost completely by students at both the undergraduate and graduate level; this includes not just contact operations positions but also positions as vehicle and network leads. Compared to many of the other university-based activities, this program strictly adheres to many professional requirements and norms. These include adherence to US government technology transfer and information security requirements, NASA project management and systems engineering directives, NASA and industrial configuration control requirements, the use of procedural techniques with an emphasis on checklist discipline, the formality and separation of operator training and certification, and so on. Finally, we point out that this network has evolved from one of the first such academic initiatives in this area [6], and it has been in operation for professional-class services for more than a decade. As such, it is now routinely used to support NASA and industry satellite missions, and it is also used to perform controlled experimentation for novel research in satellite teleoperation and mission control technology.

Section 2 of this paper describes the technical aspects of the Santa Clara University system, and Section 3 summarizes the missions supported by this system. Section 4 describes the process and personnel aspects of providing professional-class services within an academic framework, and Section 5 reviews some of the auxiliary research and education projects that have contributed to the use of the system. Finally, Section 6 summarizes the main elements of the network and highlights its contributions to the aerospace field.

2. Satellite Control Network Design

Figure 1 depicts the facility-level architecture for the mission control network [15]. During contact operations, one or more geographically distributed communication stations are teleoperated via a secure internet link from a Control Node by human operators or an automated control program; given mission requirements, non-SCU communication stations may also be remotely configured and operated by SCU students from a Control Node. The current array of communication stations wirelessly exchange commands and telemetry data with supported spacecraft using frequencies in the VHF, UHF and S-Band ranges; support in other bands is possible and easily accommodated through the modular installation of new equipment. Interaction with external entities, such as mission managers/scientists/engineers, is conducted from the Control Node through phone/videoconference communications for realtime coordination and via web/ftp sites for asynchronous exchange of data products. For spacecraft using an amateur radio beacon system, data packets collected by external stations, such as those operated by university students and amateur radio enthusiasts, may be submitted to a searchable public database. While this system has been developed by and is extended, maintained and operated by students, it is operated in a way to meet all professional norms, codes, and requirements of professional science-class NASA missions, as described in Section 4.4.

Figure 1. The RSL Satellite Command and Control Network Architecture

2.1 Control Nodes

Mission operations are directed by human operators or automated programs executing at a Control Node location. Four primary Control Nodes are currently operating: two on the SCU campus (one for operating NASA missions, shown in Figure 2a, and the other for operating industry missions), one at an SCU lab location in the NASA Research Park, Moffett Field, CA, and a mobile trailer that combines Control Node and communication functions, shown in Figure 2b. Although not currently used due to cost, the NASA Ames Multi-Mission Operations Center (MMOC) has also been used as a Control Node, with SCU equipment and software hosted within the MMOC

facilities. Each SCU communication station is also capable of supporting Control Node operations; this has been used in the past for early orbit operations as well as for contingency operations when internet connectivity between facilities has been compromised. The distributed architecture of the network allows Control Node functions to be performed at any location with an internet connection; as a matter of policy, however, most operations during the primary phase of any mission are conducted in the Control Nodes as a means of ensuring requirements regarding configuration control and data security.

Physically, Control Nodes consist of a suite of workstations, displays, and communications/networking equipment. Workstations run a variety of software in order to perform functions such as command and telemetry processing, orbit planning and analysis, performance analysis, resource scheduling, anomaly management, and report generation; mission specific payload processing capabilities are also often included. Software consists of commercial, open-source, and student-developed packages. The core command and telemetry processing software was originally developed by students as an undergraduate project and consisted of more than 10,000 lines of code, written in Java. Over the past decade, this system has been enhanced and extended by students and staff to improve efficiency, security and extensibility. This software interfaces with an open source MySQL database, which centralizes data for any one mission regardless of the Control Nodes and communication stations used for contact operations. Most telemetry analysis, decision support, display, and reporting software exists as student-developed programs, executed in Matlab/Simulink.

Figure 2. Mission Control Network Facilities

2.2 Communication Stations

The SCU network uses a general communication station equipment architecture capable of supporting a variety of mission-specific communication needs. To date, this has resulted in multiple installations of three distinct types of antenna systems. The first type is a 3-meter diameter programmed track parabolic dish configured for S-Band communications. This system has a 35.4 dB gain and is capable of $6+^{\circ}/\text{sec}$ azimuth rates, which is ideal for Low Earth Orbiting (LEO) spacecraft. The second type is an OSCAR-class VHF/UHF dual-Yagi antenna with gains of 14.4 dB and 18 dB, respectively and also operating as a programmed track system with a $6+^{\circ}/\text{sec}$ azimuth rate capability. The third type of antenna is a non-tracking low gain antenna, typically pointed straight up and used for receive-only reception of low data rate amateur radio beacon transmissions. For specialty operations, the network also includes two 4.5-meter dishes, one of which is static for Geosynchronous Earth Orbit (GEO) spacecraft operations and the other being installed as a programmed track system for LEO operations. In addition, the mobile trailer facility includes a programmed track 2.4-meter dish configured for S-Band operations as well as a programmed tracked 7-element Yagi antenna for UHF amateur radio operations (it also includes several communication systems supporting unmanned aerial vehicle systems and applications).

Apart from the antenna and tracking subsystem, several typical communication equipment suites are used to support mission-specific communications. Many of the supported spacecraft use a COTS ISM-band transceiver, the Microhard MHX2400/2420, for command and control; a similar unit is available at the SCU stations and serves as a synchronization master for such communication. For VHF/UHF amateur radio communications, both for beacon reception and command and control, a multi-band ICOM IC-910H transceiver with Doppler compensation is used; this is generally used in conjunction with a Kantronics KPC-3+ or KPC-9612+ packet modem. To date, the

aforementioned transceivers have been sufficient for all missions operated and manifested to date. The modular design of the communication stations, however, allows for other transceivers to be easily accommodated; this has been done as part of the development phase for several as of yet unmanifested missions, to include space-grade software defined radios as well as more traditional communications equipment from several aerospace vendors. Stations also include workstations for computational support, internet-commandable power strips for remote configuration control, test transmitters for loop-back tests, cameras for remote viewing of the antennae, and networking/communications equipment.

Combinations of these communication stations are installed at various physical locations, as summarized in Table A. The antenna suite on the SCU campus, shown in part in Figure 2c, includes two 3-meter S-Band parabolics, the 4.5-meter GEO parabolic, and one UHF/VHF Yagi station. The combination of a single 3-meter S-Band station and a single VHF/UHF dual-Yagi station is installed at two locations: the SCU facility in the NASA Research Park at Moffett Field, CA, and on the campus of partner institution Universidad Centroamericana Jose Simeon Canas in El Salvador (located at 9° latitude, and installed there to support low-inclination missions). Beacon receive stations operate automatically and are installed on the SCU campus, at the SCU facility at Moffett Field, and at locations across the United States in Texas, Missouri, Pennsylvania, and Massachusetts. The mobile station has a practical range throughout North America and can be deployed at a location based on mission needs. In addition, a separate equipment suite consisting of a 3-meter S-Band station and VHF/UHF dual-Yagi station is maintained as a deployable station. Although not packaged as a mobile station, this can be shipped to and installed at a location of interest for temporary operations as has been done, for example, to support launch operations from Kwajalein Atoll.

The SCU network is also capable of linking Control Nodes to externally provided communication stations. This has been done with an 18-meter dish owned by SRI in Palo Alto, CA (through a lease arrangement, an SCU student team refurbished this station and then operated it for two NASA missions) as well as with a quad-Yagi station owned by Canopus, Ltd at Moffett Field, CA (operated in support of mission operations for two Canopus satellites).

Table A – Communication Station Installations

Station	Location	Equipment
Santa Clara Univ	Santa Clara, CA	4.5m (x2), 3m S-Band (x2), VHF/UHF dual-Yagi, Beacon receive (x2)
NASA Ames	Moffett Field, CA	3m S-Band, VHF/UHF dual-Yagi, Beacon receive
Baylor Univ	Waco, Texas	Beacon receive
St. Louis Univ	St. Louis, Missouri	Beacon receive
Worcester Polytech	Worcester, MA	Beacon receive
Green Ridge	Newville, PA	Beacon receive
Universidad Centro	San Salvador, El Salvador	3m S-Band, VHF/UHF dual-Yagi
Mobile Station	Parked, Moffett Field, CA	2.4m S-Band, VHF/UHF dual-Yagi, Beacon receive
Deployable Station	Stored, Moffett Field, CA	3m S-Band, VHF/UHF dual-Yagi, Beacon receive

2.3 Internet-Based Data Connectivity

The SCU network routes realtime contact data between Control Nodes and communication stations via the public internet. The coupling of this innovation (which has become routine for academic small satellite missions) with the ability to maintain security and configuration control to NASA standards has been instrumental in providing low-cost and flexible operational services. Command and telemetry data flow between the Control Nodes and the communication stations use an open source channel-based data streaming server known as the DataTurbine. The command and telemetry Control Node application and a transceiver data routing application at the communication station both subscribe to appropriate DataTurbine channels, posting and retrieving data from these channels accordingly; SSH tunneling is used to ensure data security. During pre-pass contact operations, subscribing applications are simply configured with the IP address for the workstation running the DataTurbine service; overall, this architecture enhances modularity of the software and makes it very straightforward to deploy new stations, to migrate application upgrades from a single test computer to distributed operational workstations, etc. Latency

between applications through this system is typically under 200 msec, which easily meets the “realtime” requirements of the supported spacecraft.

Apart from the Control Node to communication station connection, two other internet-based communication links are used. First, the command and telemetry processing application connects over TCP/IP to a mission-specific database in order to use validated commands and to store received telemetry. Given this network link, the location of the mission database can be in the Control Node or at any other location. For some NASA missions, there has been a requirement to locate the mission database in the Ames MMOC even though the Control Node has been at another location in order make it easier for students to conduct operations. Second, data products are typically exchanged between the operations team and mission engineers, scientists and managers via the internet. For example, post-pass science data products and telemetry reports are typically posted to a secure FTP site within 15 minutes of the completion of a pass. In addition, a popular “mission dashboard” web page is used for NASA missions in order summarize mission progress and the status of payload, bus and ground segment systems.

3. Spacecraft Missions Operated

To date, eleven satellites have been operated using the SCU Network, as detailed in Table B; two additional spacecraft were integrated but failed to reach orbit due to a launch vehicle mishap. Over the course of the next year, another eleven manifested satellites will be operated.

Table B – Spacecraft Missions Operated Using the SCU Satellite Control Network

Mission	Developer	Launch Date/Site/Rocket	Primary Operations
Sapphire [16]	Stanford Univ.	9/2001, Kodiak, Athena 1	Health analysis experiments
GeneSat-1 [17]	NASA/Ames	12/2006, Wallops, Minotaur	Bio-payload tech demo
PharmaSat [18]	NASA/Ames	5/2009, Wallops, Minotaur	Antifungal microgravity exp
MAST [19]	Tethers Unlimited	4/2007, Baikonur, Dnepr	Health analysis, tether ops
PreSat	NASA/Ames	8/2008, Kwajalein, Falcon 1	Failed to reach orbit
NanoSail-D	NASA/Marshall	8/2008, Kwajalein, Falcon 1	Failed to reach orbit
O/OREOS [20]	NASA/Ames	11/2010, Kodiak, Minotaur IV	Micro-organism survivability
NanoSail-D2[21]	NASA/Marshall	11/2010, Kodiak, Minotaur IV	Sail test; De-orbit behavior
PhoneSat 2.4	NASA/Ames	11/2013, Wallops, Minotaur	COTS tech demo
SporeSat	NASA/Ames	4/2014, KSC, Falcon 9	Bio-gravitational response
PhoneSat 2.5	NASA/Ames	4/2014, KSC, Falcon 9	COTS tech demo
Perseus (2 satellites)	Canopus	6/2014, Yasny, Dnepr	Bus performance, AIS data
NODES (2 satellites)	NASA/Ames	* 2/2015, ISS, Nanoracks	Inter-satellite ops
EDSN (8 satellites)	NASA/Ames	* 7/2015, Kauai, Super Strypi	Inter-satellite ops
EcAMSat	NASA/Ames	* 9/2015, KSC, Falcon 9	Antimicrobial experiment
SporeSat-2	NASA/Ames	* 3/2016, ISS, Nanoracks	Bio-gravitational response
* = vehicle is manifested for launch on the indicated vehicle			

These spacecraft, all but one of which are CubeSat-class satellites, include both peer-reviewed NASA science missions as well as technology demonstration missions. GeneSat-1, PharmaSat, PreSat, O/OREOS, SporeSat, SporeSat-2 and EcAMSat are all part of a line of astrobiological spacecraft developed by NASA Ames Research Center. These satellites contain small automated labs for supporting biological entities (such as E. coli, yeast cells, etc.) and studying their behavior in the space environment. Technology demonstration satellites included Sapphire (which verified the operation of MEMS IR sensors in space), the two NanoSail-D satellites (which verified the packaging, deployment, operation of a solar/drag sail), the two PhoneSats (exploring the use of cell phone technology as low-cost satellite components), and the 10 manifested EDSN/NODES spacecraft (exploring networks of small spacecraft). MAST (which tested a satellite tether inspection mechanism) and the two Perseus-M satellites (verifying the operation of the Perseus bus and demonstrating AIS service capabilities) were industry technology demonstration satellites.

Nearly all of the satellites operated to date have used S-Band communications (with a version of the Microhard 2400/2420 radio) with the exception of Sapphire (which used student-built VHF/UHF amateur radios) and the two Perseus-M satellites (which used a 400 MHz Lithium radio). Every satellite except for MAST also had a UHF radio beacon to support tracking, health analysis, and student/public outreach. All of these satellites were LEO missions with initial altitudes in the range of 350-650 km; PreSat and NanoSail-D were in a 9° inclination orbit (requiring the deployable communication station to be temporarily installed at Kwajalein as well as use of the station in El Salvador), O/OREOS and the Perseus spacecraft were near-polar, and the rest have all been in the 40-55° inclination range.

Primary operational phases for these missions have ranged from weeks to 16 months, during which time more than 1 contact per day is routinely conducted on average. After primary operations are concluded, the remaining lifetime for these satellites is used to support student education and research projects. As an example of the volume of contacts conducted, during the first year of primary operations for the NASA O/OREOS mission, more than 500 S-Band contacts were executed for science purposes, with more than 100 additional OSCAR contacts conducted for educational and training purposes. In addition, more than 80,000 beacon packets were received by external operators during this time. During this time, the SCU student team also conducted operations for the NanoSail-D spacecraft, and there have been numerous occasions with a variety of missions in which simultaneous contacts have been executed.

4. Processes and Personnel

Nearly all standard satellite operations tasks are routinely conducted within the SCU satellite control network. This includes contact operations, ground segment control, satellite performance analysis, system health management and anomaly management, service and contact planning, resource allocation and scheduling, and mission-specific payload activities. For most of these activities, formal procedures and processes have been defined, and student operators are drilled in order to efficiently perform procedures with demonstrated acumen in checklist discipline.

4.1 Orbit Determination

The one significant task that has not been a routine part of activities is orbit determination. To date, missions have been run using NORAD/JSpOC-generated orbit estimates. Although this poses challenges during early orbit operations (particularly when multiple small spacecraft are launched from the same launch vehicle), NORAD/JSpOC data has proven to be sufficient for operational planning and antenna control given the orbits and communication profiles used by the spacecraft that have been supported to date. For several upcoming missions, the orbit determination task will be brought in-house due to the needs of specific missions and the availability of on-board GPS receivers. For example, several NASA missions manifested for launch over the course of the next year have very short mission durations and need to establish a routine command and telemetry link as soon as possible. These spacecraft will beacon on-board GPS data to the ground from which orbit estimates will be generated by the SCU team, with NASA support until the process is validated, in order to support precise tracking and successful high bandwidth communications. Standard NASA orbit determination software tools will be used for this process.

4.2 Pre-launch Functional Test

Although not a typical element of mission operations, pre-launch satellite beta testing is a function routinely provided through the SCU satellite control network. For the NASA Ames missions that have been supported and which are currently manifested for launch, SCU personnel work with medium-to-high fidelity satellite engineering units in order to beta test satellite functionality from an operational perspective. In doing so, command and telemetry operations with the engineering units are routinely conducted through the control network using operational control node / communication station facilities and software. This promotes a test-as-you-fly capability during the development process. Furthermore, as the satellite is beta tested, SCU developers simultaneously ensure compatibility with the network, validate commands, verify telemetry parsing and calibration functions, and certify the validity of contact procedures. It is worth noting that, in the opinion of the authors and lead NASA managers, this combined satellite beta testing / control network development process is a major contributor to mission success and the ability to effectively operate professional missions as a student-centered university enterprise.

4.3 Personnel

Students are the primary system engineers and satellite operators within the SCU satellite control network; one part-time staff member maintains critical software and database content and oversees development tasks, and one faculty member spends a portion of his time managing the program and overseeing student research and training. The students involved range from freshman to doctoral students and are typically in a mechanical, electrical or computer engineering program (although students from other programs occasionally join the team).

Students generally enter the program by taking a novel, formalized, 1-unit satellite operations course. They then become members of the contact operations team by going through additional on-console training with more senior students and then successfully undergoing one or more certification evaluations for the tasks they will be performing. Initial certification is typically given for conducting routine tracking and data download operations. Examples of specialty operations requiring delta training and certification include running critical biological experiments and conducting some contingency procedures. During early orbit and/or critical commanding operations, it is typical to have three student operators staff a contact: one command operator, one satellite analyst, and one ground segment / tracking operator. For routine operations, a single operator and/or an automated contact execution program is typically used. It is not uncommon to have more operators on console than required, not due to mission requirements but because students participate as part of their training/education program.

As their knowledge of the system increases, student operators often become interested in becoming more involved, either as operations managers or network developers. As managers, they move into positions such as becoming the operations coordinator/lead for a specific satellite/mission, the manager of communication station configuration and maintenance, a resource scheduler, and/or part of the team to work with the customer to understand their needs and to develop budgets/proposals. As developers, student help to upgrade or improve the control network through design or research projects; in many cases, the motivation for their projects is based on their knowledge of the control network and the identification of a new need for or opportunity to enhance services. At the undergraduate level, these projects are often completed as part of capstone projects, independent study projects or internships; in the past, these projects have included the development of the command and telemetry software, of communication stations, and of test apparatus. At the graduate level, projects often become the basis for an experimental capstone, thesis, or dissertation; these projects have included the development of modeling tools/environments and the evolution of advanced anomaly management techniques.

4.4 Professional Practices

In executing a professional-class space mission, there are certainly practices that must be followed that are more intensive and restricting than those followed in a typical university satellite program. From a security perspective, this includes the use of technologies and practices relevant to physical, communications, and data security and compliant with FISMA (Federal Information Security Management Act) requirements. In practice, this includes the use of encrypted internet and wireless communication links, strong password policies, double layers of physical access control, etc. In addition, strict configuration control policies compliant with NASA space mission requirements are enforced, requiring configuration lock-downs, an off-line system upgrade verification process, explicit configuration change reviews, etc. Compliance with these FISMA and configuration control standards are verified through a formal, multi-step review process embedded in each of the NASA missions. ITAR compliance must be explicitly demonstrated and proactively enforced; the practical effects of this range from a selective policy for the students who may participate in this program to documentation control and dissemination policies. Adherence to these criteria is ensured through an annual review by Santa Clara's own research compliance office. Finally, for NASA missions, all project management requirements and protocols relating to the execution of Class D space missions are followed; this is ensured through periodic, formal design reviews.

5. Associated Research, Education and Outreach Initiatives

In addition to having the capability to support professional-class government and industry missions, the SCU satellite control network is used as an experimental testbed to explore and evaluate new satellite control technologies. Indeed, it is this capability that has motivated the majority of financial support for development of the network. As a completely SCU-owned and operated system subject to strict configuration control policies, it provides an outstanding environment for conducting verifiable technology performance experimentation using comparative and/or action research norms. Given that real-world missions are supported, technology validation metrics can also be collected in order to evaluate the ultimate utility of innovations.

One example of a design innovation is the use of the public internet for routinely controlling professional-class satellite missions; a decade ago, this was dismissed as an approach that would never gain traction, even for NASA Class D missions. Our experience has shown that this approach, coupled with the operate-anywhere capability and the modular software architecture, has been a significant element in providing low-cost and flexible operational services given the distributed nature of the control network. Another design initiative to achieve cost-effective operations is the use of beacon broadcasts to support health operations; this has been shown to reduce operational costs during quiescent mission phases and to improve response times for responding to anomalous conditions [7]. Finally, the network has been used to explore new approaches and systems for managing operational anomalies, both on board a spacecraft as well as in the control network. This work has focused primarily in the area of model-based reasoning approaches, and a new theoretical framework has been developed and implemented in which a variety of anomaly types are managed (faults, hazards, and misconfigurations) and for which a unified algorithmic approach to detecting, diagnosing and resolving these anomalies has been developed [22].

Educationally, students obtain academic credit for participation in design and research projects. Such activity often begins with the 1-unit satellite operations course, which is a novel offering in a university environment. The class covers the concepts and procedures involved in performing tracking, commanding and telemetry analysis activities; it is supported by a hands-on laboratory exercise that has been adopted by the IEEE Real-World Engineering Projects program. This formalized training program, combined with a separate, formally-conducted certification process is atypical in an academic environment. In addition, the fact that students can work their way up within the program to become operational vehicle leads for NASA and industry spacecraft (responsible for leading efforts to characterize vehicle status and to manage operational planning) is fairly unique. These distinct features are one reason why this program has been honored as an exemplar Real-World Engineering program by the National Academy of Engineering given the institutionalization of this unique student-centered enterprise.

From an outreach perspective, the amateur radio beacon that has been included on most of these missions has been the basis of an active public engagement program in which K-12 and university students as well as HAM radio enthusiasts have been able to acquire telemetry, analyze the health of a satellite, and track performance over time. As an example of the popularity of this program, more than 40,000 packets of beacon data were collected and submitted to the SCU network during the first six months alone of the GeneSat-1 mission. Related to this, the previously-described mission dashboard display, originally developed for mission managers, has become a highly popular way for the public to stay abreast of mission activities; it is common for this web page to have tens of thousands of page views during the first few weeks of a mission.

6. Summary and Conclusions

Santa Clara University operates a geographically distributed satellite control network consisting of three active mission Control Nodes and nearly 20 distinct communication stations deployed at seven different locations in addition to mobile and deployable stations that can be located at arbitrary locations. This network uses an internet-based data routing infrastructure that adheres to NASA and industry security and configuration control standards. University students manage and operate the vast majority of network activities, are formally trained and certified as per NASA standards, and provide nearly all standard mission control services. Collectively, this enterprise has been used to successfully conduct on-orbit operations with 11 satellites to date, with 12 more manifested for launch within the next two years.

As a resource within the small satellite community, the SCU satellite control network is an important contribution in several ways. First, it is a student-centered activity that provides outstanding real-world educational opportunities, as evidenced by its recognition by the IEEE and NAE. Second, as a university-based satellite operations system, it is far more than a communication station network; rather, it sets a benchmark for its scope and extent, having multiple Control Nodes and communication stations at a variety of locations. Third, given the use of industry-standard operating norms and procedures, the system has been routinely used for a significant number of diverse, professional-class NASA and industry missions, to include peer-reviewed NASA science missions and critical path technology development missions. Fourth, SCU typically operates under contract with strict deliverables (which is somewhat atypical for student-centered university work, in which “best effort” grants are more common), often competing with other organizations in order to win these opportunities. Finally, the system is valuable to the

research community as a controlled experimental testbed suitable for verifying performance of innovations and validating their value in the context of real aerospace missions.

Reflecting on this work, it is useful to consider the forces that have led to its success. As a satellite control network for professional-class missions, the comprehensive and distributed nature of the network as well as the ability to manage multiple simultaneous missions make it attractive; its enterprise-class design with modular, centralized command and telemetry databases and the ability to easily accommodate mission unique tools are also positive features. Perhaps more importantly, the organizational practices that complement the technical system provide for a mature level of service that is critical to professionally operating government and industry missions. This includes the ability to execute of standard mission operations tasks (command execution, telemetry analysis, mission planning, anomaly management, etc.), to be formally compliant with required requirements and practices (FISMA, configuration control, ITAR, etc.), to operate under contracts rather than grants, and to accommodate test-as-you-fly practices through use of the operational system during spacecraft beta testing.

As for specifically conducting an operation such as this within an academic institution and in a student-centric manner, there are several additional challenges. To start, few if any of the benefits of performing work such as this are directly compatible with the success criteria for typical tenure-stream professors; in fact, the level of work, risk, and costs associated with the creation and operation of a program such as this are typically considered as negative influences for those in such positions. At Santa Clara, several factors, however, have contributed to the achieved level of success. To begin, the first author has significant professional experience operating spacecraft and in managing such systems both in the military and in NASA; furthermore, the current results are a product of working on academic implementations of such systems for more than 20 years. Second, the program is dramatically leveraged – both in time and financially – by programs that exploit the use of the satellite operations network for conducting real-world experimental research and student education. Third, the close proximity and long-term research relationship with key personnel at NASA Ames Research Center has been instrumental; it is noted that when Ames personnel originally considered the execution of low-cost CubeSat-class missions, the authors were approached as operations collaborators given that they had more mission operations experience and small satellite experience than anyone on the Ames team. The combination of these factors have helped ensure the team's ability to sustain this operation for more than a decade.

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