Rascal: Proximity Operations on a University CubeSat

In response to the 2012 NASA CubeSat Launch Initiative
(NNH12SOMD001L)

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Abstract

Proximity operations (safe maneuvering of one spacecraft within meters of another space object) have been identified by NASA as an enabling technology for future NASA missions. NASA and other organizations are sponsoring CubeSat-class proximity operations missions with notional flight dates in 2015. There is room in the design space to explore other configurations for proximity operations.

The Space Systems Research Laboratory (SSRL) at Saint Louis University proposes to fly **Rascal**, a two-spacecraft mission to demonstrate key technologies for proximity operations: infrared and visible image-based navigation, precision six-degree-of-freedom control using cold-gas thrusters, and navigation algorithms optimized to work with those technologies. Rascal will leverage CubeSat systems developed by SSRL: COPPER (8/2013) and Argus (10/2013) are manifested to fly under the CubeSat Launch Initiative. Rascal will use the core spacecraft subsystems from both missions and the infrared imager from COPPER, allowing the design team to focus on the attitude and propulsion systems. The propulsion system will be based on the RAMPART mission and the Bandit mission previously developed by SSRL.

Rascal will launch as a single 6U CubeSat mission and can operate at any altitude above 300 km and inclination above 40°. It will be ready for delivery in January 2015. The Rascal scientific merit review was completed in August 2012. The Rascal technical merit review was completed in September 2012, but will be reviewed every three months from now until delivery. Results from both reviews will be incorporated into the Rascal final design.

1 Introduction

In 2012, NASA awarded $17.1 million to two organizations to develop and demonstrate enabling technologies for proximity operations of CubeSat-class spacecraft. For this proposal, proximity operations are defined as the safe, controlled navigation of one spacecraft within 1-100 meters of another, possibly non-cooperating space object. We believe that the design space for proximity operations technologies is broader than can be demonstrated in two flight experiments. Therefore, the Space Systems Research Laboratory (SSRL) of Saint Louis University (SLU) proposes the 6U Rascal mission to fly under NASA's CubeSat Launch Initiative. **The mission of Rascal is to demonstrate key proximity operations technologies on CubeSat class spacecraft: infrared/visible navigation, 6DOF propulsion and the navigation algorithms to use these capabilities**. This mission will be accomplished by launching one 6U spacecraft that will separate on-orbit into two 3U spacecraft and an instrumented baseplate. One 3U spacecraft will be released, drift beyond 100 meters, and then navigate back to within 10 meters of the spacecraft/baseplate combination. This activity will be repeated until propellant is exhausted, at which point the other 3U spacecraft will release, drift away and then rendezvous.

Rascal is a 6U CubeSat (Table 1, Table 2) with a target orbit of 500 km altitude and high inclination (> 40°), although any altitude above 300 km is acceptable. The mission can be accomplished in as little as 30 days, although 6 months is the preferred mission duration. The Rascal spacecraft architecture and subsystems are based on COPPER and Argus, SSRL CubeSats that will fly in August 2013 and September 2013, respectively, under NASA's ELaNa program. With the exception of the propulsion hardware and pointing control, all other subsystems are duplicates of those flown on COPPER; Argus' bus is identical save for the imaging system. The propulsion and pointing control are based on a previous SSRL design (Bandit) and a CubeSat mission flying next year (RAMPART). Rascal is an in-house mission developed by the faculty and a team of graduate and undergraduate students. This team has collaborated on the two SSRL missions described above.

Table 1. CubeSat Mission Parameters

Mission Name	Mass	Cube Size	Desired Orbit		Acceptable Orbit Range	325 km @ 51.6° Acceptable?	Readiness Date	Desired Mission Life
Rascal	8 kg	6U	Altitude	500 km	300 – 900 km 40° - 100°	Yes	Jan 2015	6 mos
			Inclination	40°				

Table 2. CubeSat Project Details

Focus Area	Student Involvement	NASA Funding		Sponsor	Proposal Collaboration	
					Yes/No	International
Primary: Technology Demo Secondary: Education	Students are managing, building, testing, operating both bus and payload	Yes	Missouri Space Grant	Finaish/Haug	No	No

The mission overview and merit reviews will be discussed in the next section; in Section 3, the satellite and ground system descriptions are provided along with the feasibility review. The proposal body concludes in section 4 with the management plan, project schedule and funding. Five appendices are attached: the PI and Co-I resumes (A), references (B), the funding commitment letter (C), proof of accreditation (D) and compliance checklist (E).

2 Mission Overview

2.1 Technology Overview and Justification

Of the many technologies involved in proximity operations, Rascal will demonstrate four:

- **CubeSat-class technologies**. These proximity operations technologies will be demonstrated on two 3U-class spacecraft.
- **Image-based navigation**. Using infrared and visible imagers, each Rascal spacecraft will detect the other, determining distance and pose.
- **Six degree of freedom (6DOF) precision maneuvering**. As space objects maneuver within a few meters of one another, it is essential that the maneuvering craft be capable of instantaneous position and orientation change in any arbitrary direction. For these missions, "precision" means centimeter-level control.
- **Navigation algorithms**. The Rascal mission will integrate image-based navigation sensing and 6DOF control into a unified, automated flight control system.

2.1.1 Related Activity in Proximity Operations

NASA has demonstrated a funding commitment to CubeSat-class proximity operations through the selection of two missions for the 2012 Small Spacecraft Technology Program: NASA selected Tyvak Nano-Satellite Systems to develop and fly a two-3U mission to perform on-orbit rendezvous and docking, as well as The Aerospace Corporation to develop and fly proximity sensors on CubeSat-class mission [1]. Details of the propulsion and docking systems have not been released.

Surrey Satellites and the University of Surrey are collaborating on a proximity operations demonstration, STRaND-2, also using two 3U spacecraft for relative maneuvering and magnetic docking [2]. STRaND-2 will use LIDAR and image processing and an isobutene propulsion system.

With these two missions in development, why should Rascal fly? First, as with all space projects, there is no guarantee that either of these missions will proceed from concept to flight, nor that they will meet their flight objectives. Second, Rascal is pursuing a reduced set of proximity operations objectives (i.e., no docking) with a different set of technologies (R134a and imagers), and thus will provide complementary data, even if all three missions succeed. In addition, Rascal has a strong education element to its mission.

The RAMPART mission is a 2U CubeSat that will demonstrate hot gas (heated R134a) propulsion for orbit raising/lowering. RAMPART is the first U.S. CubeSat to carry propulsion, and it is acting as a risk-reduction pathfinder for propulsion-carrying CubeSats to follow. We have been in contact with the RAMPART team, and we will incorporate lessons learned from RAMPART into the Rascal design.

Although it did not fly, the PI led the development of the Bandit proximity operations mission from 2003-2009; Bandit was a 5-kg CubeSat-class spacecraft that would release from, maneuver around and re-dock with a 50-kg host spacecraft [3-7]. The image processing algorithms and propulsion system from Bandit are being adapted for Rascal.

2.1.2 Relation to NASA Objectives

Rascal supports NASA Strategic Goal 3.3: "Develop and demonstrate the critical technologies that will make NASA's exploration, science, and discovery." This mission supports this NASA goal by demonstrating proximity operations navigation technologies on CubeSat-class spacecraft.

2.2 Payload Description

The Rascal imaging system consists of two devices, operated by an SSRL-developed video interface board. The primary imager is the FLIR Tau 320 Microbolometer Array (Figure 1), which is sensitive in the 7-13 micron band. This imager and the interface board will fly on COPPER in 2013. The visible-band imager will be a COTS device to be determined in early 2013.

Figure 1. FLIR Tau Microbolometer [courtesy FLIR]

The imagers use a dedicated field-programmable gate array (FPGA) to operate the devices and buffer the images for storage. The FPGA development is being led by Mitchell and the EE students as part of their degree coursework.

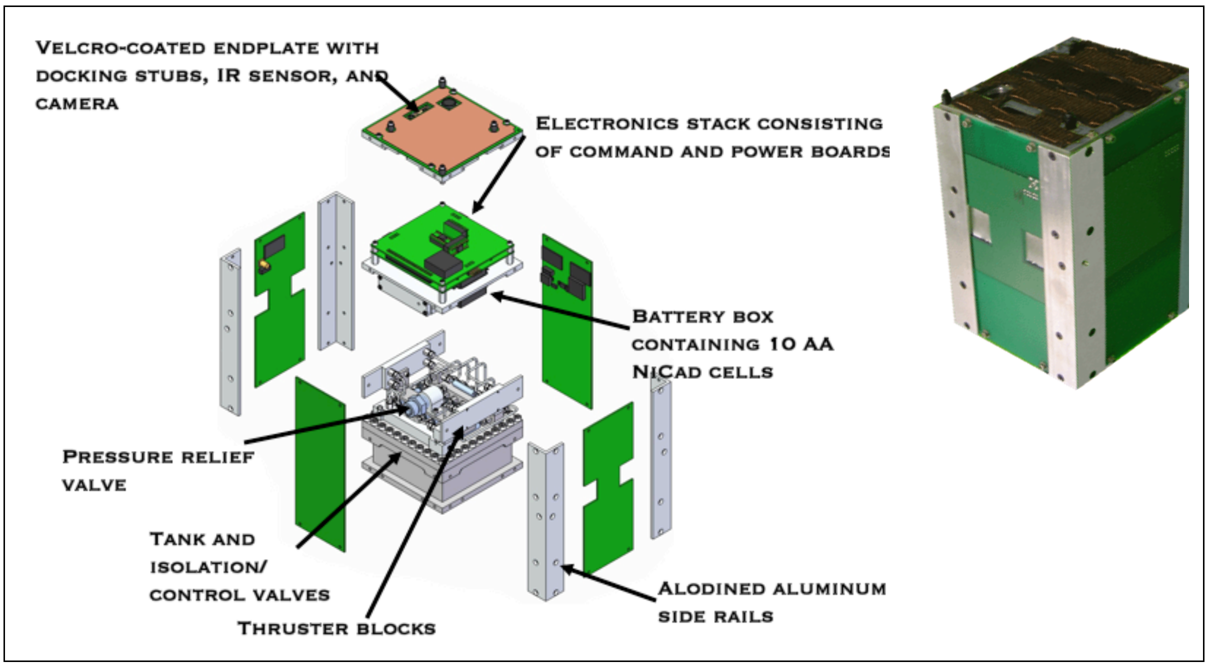

Figure 2. Bandit

The 6DOF propulsion system will be based on the Bandit design (Figure 2). It consists of a single tank of R134a feeding a common manifold. Three isolation valves inhibit hazardous operation, and the manifold routes propellant to the eight valves controlling the eight thrusters. The thrusters are oriented to provide 6DOF control (direct translation/rotation in the orthogonal axes, coupled motion off-axis). The Bandit tank was milled out of a solid block of aluminum; Rascal will follow the example of RAMPART and integrate the tank, manifold and valves into a monolithic block using additive manufacturing (i.e., "3D printing").

2.3 Secondary Mission: Education

Rascal has a secondary focus area: to train SLU undergraduate and graduate students in the entire spacecraft lifecycle (i.e., design, analysis, fabrication, test, launch and operations). This hands-on process for space systems engineering has proven to create uniquely motivated and capable students who are in great demand in the aerospace industry. This proposed work is strongly aligned with the NASA Missouri Space Grant Consortium; the COPPER and Argus missions were partially sponsored by the Missouri Consortium in FY2010-12 because of the educational activities it supported. The secondary mission is achieved through our process of involving students in every part of the lifecycle; students make system-level design trades, manage the day-to-day development of the missions, conduct environmental testing and interface with NASA professionals during integration and launch campaigns.

Thus, Rascal is strongly aligned with NASA Strategic Goals 6.1 (“Improve retention of students in STEM disciplines by providing opportunities and activities along the full length of the education pipeline”) and 6.2 (“Promote STEM literacy through strategic partnerships with formal and informal organizations”).

2.4 Merit Review

The Rascal merit review was conducted by the SSRL investigators in August 2012.

2.4.1 Review Process

The review team examined the announced proximity operations missions (e.g., Tyvak and STRaND-2) as well as past programs (XSS-10 [8], XSS-11, DART [9], Orbital Express [10]). They identified NASA objectives for proximity operations and compared them against these missions.

2.4.2 Results and Response

NASA was identified as strongly supporting proximity operations; more than half the funding of the 2012 Small Satellite Technology Program went to CubeSat-based proximity operations missions. The reviewers identified position sensing, propulsion, navigation algorithms and docking as the key technologies. Docking was eliminated as being too complicated for a student mission (see the Feasibility Review, below). The other three elements were identified as being feasible (though challenging) for a student mission.

3 System Description

3.1 Concept of Operations

The Rascal mission consists of four on-orbit phases as listed in Table 3 and shown in Figure 3.

Table 3. Rascal Mission Phases

Phase	Key Events
1 (launch sep)	Launch sep Detumble / checkout
2 (3U release)	Release of 3U and drift to > 100 m Imager observation Propellant firing
3 (rendezvous)	Maneuver from >100 m to 10 m Imager observation Propellant firing
4 (extended)	Release/observe baseplate Repeat elements of Phase 3

Phase 1 (launch vehicle ejection/checkout – two weeks): Forty-five minutes after ejection, Rascal will be detumbled and all systems tested.

Phase 2 (controlled separation/baseline mission success – one day): At the start of this phase, one 3U is released from the baseplate and allowed to drift away (nominally at a few centimeters per second). Each spacecraft will perform a detumble/slew maneuver to fix its imagers on the other, observing continuously as the two systems drift out to 100 meters (3-4 orbits). Also during this phase, short, zero-net thrust bursts of R134a will be released at known intervals by each spacecraft to be observed by the other.

Phase 3 (rendezvous/complete mission success – two weeks). When the two spacecraft have reached sufficient distance, one spacecraft will be commanded to activate its propulsion system to automatically maneuver to rendezvous back within 10 meters of the other spacecraft (with a goal of 1 meter). The "sufficient distance" for drift is nominally 100 meters, but this distance could be increased or (more likely) reduced based on the performance of the various sensors and navigation systems. During the rendezvous portion of Phase 3, the propulsion observations conducted in Phase 2 will be repeated. After the spacecraft are returned within 10 meters for at least one orbit, the separation and rendezvous phases may be repeated to provide additional data-collection opportunities.

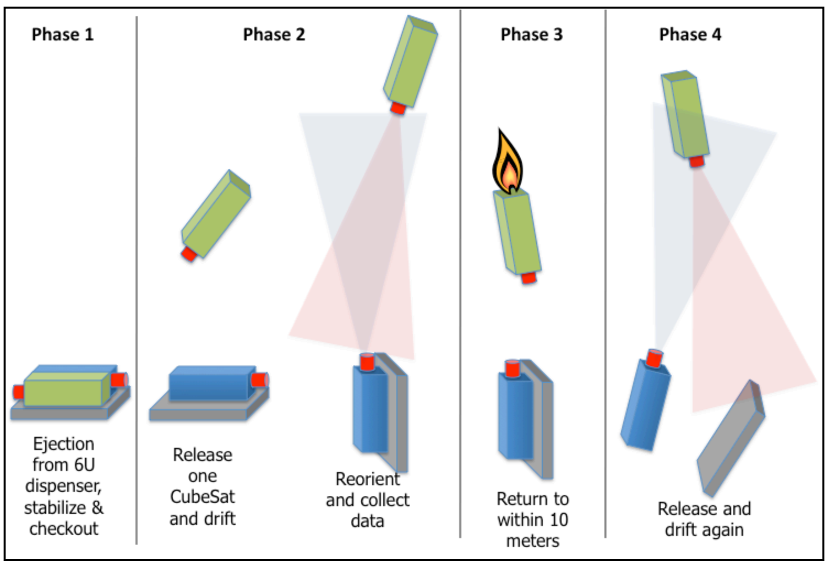

Figure 3. On-Orbit Phases of the Rascal Mission.

We recognize that this Phase carries significant risk, since orbit rendezvous from these distances has not been demonstrated for CubeSat-class spacecraft. We will mitigate this risk by including GPS receivers and communications crosslinks on each spacecraft, allowing navigation data sharing to improve relative performance. One of the critical objectives of the Spring 2013 design phase is to perform a detailed risk/mitigation analysis of Phase 3, including options such as altering the target distances.

Phase 4 (extended operations – 3+ months): Once Phase 3 has been completed, Phase 4 begins with the release of the second spacecraft from the baseplate, providing another object for imaging. The objects all drift away from one other while data is collected. The newly-released spacecraft will attempt to rendezvous with the other 3U and the baseplate.

Phase 4 ends when both spacecraft are out of propellant, or when the mission managers choose to suspend further rendezvous attempts. All three space elements will passively and safely deorbit within 25 years of the end of the mission.

3.2 Spacecraft Components

The science spacecraft consists two identical 3U CubeSats on a 6U-compatible baseplate. Each 3U holds the sensor payloads described above in a supporting spacecraft bus (Figure 4). Rascal is based on the SLU Core Aerospace Research Applications Bus (SCARAB), a common set of CubeSat-class subsystems that make up the COPPER and Argus missions (Table 4).

Table 4. Notional Spacecraft Components for Rascal 3U.

Subsystem	Notional Component(s)	SSRL Experience/Heritage
ADCS / Nav	Rate gyros Reaction wheels GPS unit	COPPER, Argus - -
CDH	CubeSat Kit PIC24-based system Salvo RTOS	COPPER, Argus COPPER, Argus
Power	Clyde Space 3U EPS Clyde Space Lithium Battery Spectrolab UTJ body-mounted solar cells	COPPER, Argus (1U version) COPPER, Argus COPPER, Argus
Comm	AstroDev Helium UHF/VHF transceiver	COPPER, Argus
Structure / Mechanisms	CubeSat Kit 3U Structure TiNi ERM-500 Release Mechanism	COPPER (1U), Argus (2U) -
Thermal	Passive	-
Propulsion	R134a-based 6-axis propulsion system Additive-manufacturing propellant tank/plumbing	Bandit - (will fly on RAMPART)
Imaging	Flir Tau 320 LWIR imager COTS visible camera	COPPER -

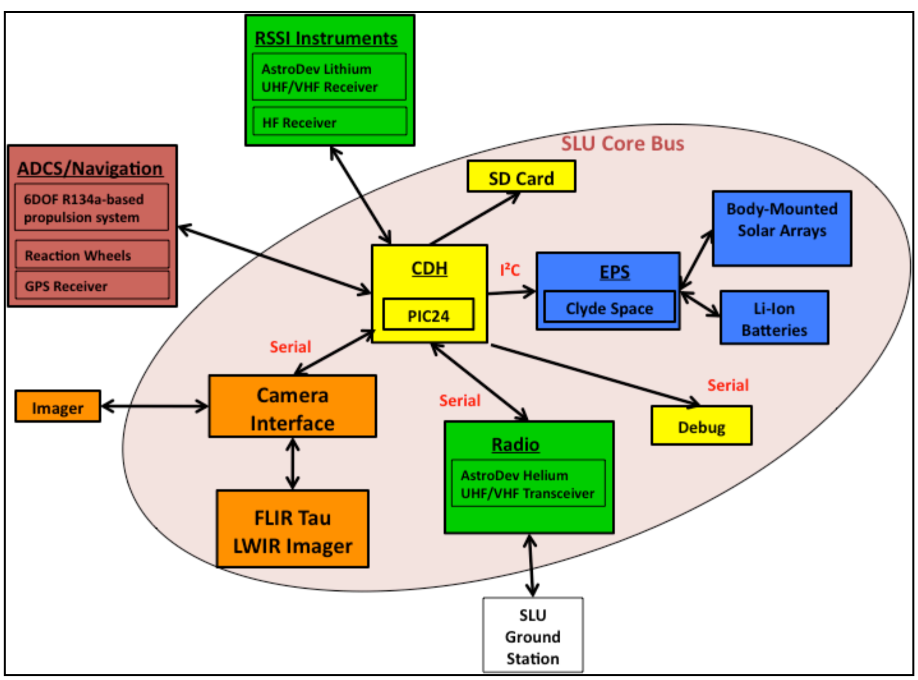

Figure 4. Rascal Block Diagram

Structure and Mechanisms. Each spacecraft is based on the skeletonized CubeSat Kit 3U (10 x 10 x 33 cm) aluminum structure. Components will be stacked in the common configuration. Use of the 6U frame allows for 3U spacecraft on the order of 4 kg. The SCARAB components will occupy the middle 0.75U, with propulsion and ADCS systems in the bottom 1.25U and the imaging/RF systems in the upper 1U. The 3U structure will be held to the baseplate using a TiNi ERM-500 actuator, which will allow for a low-force separation from the baseplate on orbit. These actuators are available in-house.

Thermal. The thermal control design has not been completed; however, based on the temperature specifications of the selected components and past experience with CubeSats, it is expected that passive control techniques will suffice.

Power. Body-mounted solar arrays will provide sufficient power to operate the spacecraft, with secondary batteries to provide peak power and eclipse functionality. The Clyde Space 3U EPS has been selected as the baseline system with an integrated 30 W-hr Lithium Polymer battery pack. Body-mounted solar arrays will be developed in-house, using on-hand Spectrolab UTJ cells. Expected on-orbit power will be 5 W.

Command and Data Handling (CDH). The CDH subsystem is based on the PIC24-based CubeSat Kit microcontroller using the Pumpkin Salvo Real-Time Operating System. Core software modules for Rascal will fly on COPPER and Argus for operations all of SCARAB components; new modules will be written for the proximity operations activities.

Communications. The AstroDev Helium UHF/VHF transceiver will be used for communications. The transceiver is capable of up to 38400 baud downlink, although Rascal will use it at half that rate. Each 3U will be configured differently; one will be configured for UHF up/VHF down and the other for UHF down/VHF up. This will allow for simultaneous operations of both spacecraft. The Heliums can also be operated in a beacon mode to provide real-time tracking and snapshot health data.

Navigation. To complete mission, the Rascal spacecraft must be pointed at one another; however, given the fields of view and the separation distance, pointing must be maintained only within 20°. The baseline design is to use reaction wheels to stabilize the tumbling of each spacecraft after separation and GPS units so that each spacecraft can orient their imager towards the other. Like all hardware choices, this decision will be reviewed by the design team in the first two quarters. (The capabilities and component selection for Attitude & Navigation is the most significant design activity in Spring 2013.)

3.3 Ground Segment

The primary Earth station at SLU is an omnidirectional UHF/VHF beacon receiver and an OSCAR-class UHF/VHF transceiver with a steerable Yagi antenna. Mission control will be in McDonnell Douglas Hall, the same building that houses SSRL .

3.4 Feasibility Review

Given the student-led nature of this mission, we feel that a single feasibility review would be incomplete. Instead, as noted in Table 5 (see Section 4), feasibility reviews are an ongoing process, with the system evaluated every few months. At each review, the design team will respond to the findings of the previous review, and critical issues are tracked across reviews. The review team evaluates the design team's response and issues new recommendations. For this proposal, we performed two feasibility reviews in August/September 2012.

The August 2012 review covered the suitability of the SCARAB bus to provide power, data, and communications. It was a competitive review for student teams participating in the University Nanosat Competition. The reviews are led by staff and contractors in the Space Vehicles Directorate at the Air Force Research Laboratory; space industry professionals from Lockheed Martin, Boeing, Northrup, Orbital and other AFRL centers participate. The missions are rated on technical relevance and probability of success; the results are informally relayed to the teams on-site by the judges, and formally by written correspondence and a debrief telecon with AFRL.

SCARAB passed its August feasibility review, with the following observations:

- **Power**. SCARAB appears to be underpowered in its 2U configuration, prompting to extend it to 3U for Rascal.
- **Communications**. The panel recommended a review of the communications system (which used the COPPER-baselined MHX2420 transceiver). After further review, the SSRL design team chose the Helium radio as a better fit for both missions.

The September 2012 feasibility review was conducted by a review of SSRL's Nanosat-8 concept by AFRL personnel. While informal and non-binding, the AFRL reviewers indicated that the 6U concept was the lowest-risk (compared to the side-by-side 3U missions proposed by both Tyvak and Surrey). They also identified the re-use of SCARAB as a way to reduce risk.

As noted above, SSRL will conduct regular feasibility reviews through flight hardware delivery.

4 Management Plan

4.1 Management Philosophy

Clearly, cost and schedule are significant drivers and are managed in three ways:

1. **Incremental Design**. Rascal leverages designs and core subsystems used in other SSRL missions (Table 4, above). This decision allows the design team to focus on the enabling technologies for Rascal: propulsion, imaging and flight algorithms. And those devices are based on hardware and software developed for Bandit and COPPER, respectively.
2. **System-level redundancy**. Rascal consists of two identical spacecraft, which simplifies pre-launch processes such as parts management, configuration control, and testing. It also provides system-level redundancy on-orbit (see the flight risks, below).
3. **Schedule margin**. The first two SSRL spacecraft will fly in 2013, giving the SSRL team 18 months to focus on development of Rascal. This appears to be a very short time, except that the core bus and components will have had integrated flight testing in 2013.

4.2 Management Details

The Rascal design team consists of the PI, Co-Is, and the student team (12 students). Because of the teaching arrangements, the PI will have daily contact with the student design team. By leveraging the existing courses for design, fabrication and testing work, the participation of both students and faculty is maximized; the students gain course credit and formal training through their engineering curriculum, and the faculty are able to devote significant unfunded effort through classes they are already teaching.

A student bus manager will be appointed by the PI; this student's responsibilities are to assist the PI in scheduling, action item tracking and in overseeing fabrication and integration activities. In addition to the bus manager, one student will be assigned a lead role in each of spacecraft subsystems. The students are responsible for the analysis, integration and test of the Rascal mission, supervised and assisted by the PI and Co-Is. Students earn course credit for their work through the capstone design course, in addition to outside time they are volunteering. The core students are assisted by a half-dozen more students who participate as volunteers.

The schedule will be discussed, below, but as for cost, all major components listed above are on hand. The remaining costs are a few thousand dollars for various electronic fabrication and test supplies; this work is supported by external grants (NASA Missouri Space Grant).

4.3 Schedule

With two spacecraft being prepared for delivery at SSRL, the Rascal mission will be the lowest priority until Summer 2013, after Argus is delivered. We believe that this arrangement is beneficial to Rascal for two reasons: it gives the design team time to solidify the requirements and design choices, and it allows for the best possible flow of lessons learned from the COPPER, Argus and other CubeSat missions into the development of Rascal.

The milestone-based schedule is shown in Table 5; it is based on the 24-month development schedule of the Air Force University Nanosat Program. The processes developed by the Air Force University Nanosat Program will be followed, specifically all of the requirements, design, analysis, and testing documents specified by the program (see Feasibility Review section). We will use the UNP processes even if not Rascal is not selected for the Nanosat-8 competition.

Table 5. Schedule and Reviews

System Concept Review	• Mission Objectives and Requirements • Program Schedule & Personnel/Resources Budget • Subsystem prototype hardware	Completed in May 2013
Preliminary Design Review (PDR)	• Mission Objectives and Requirements • Requirements Verification Matrix • Preliminary Subsystem Drawings • Mass, Volume, Power, Link, and Computing Budgets • Structural, Thermal, Pressure Profile & EMC Analyses/Models	Completed in August 2013
Critical Design Review (CDR)	• Requirements Verification Matrix • System Drawings • Subsystem Tests on Breadboard and Results • System Test Plans • Materials List • **Flight-Equivalent Engineering Unit**	February 2014
Prototype Qualification Review	• System-level Functional Tests on Engineering Unit • Mass, Volume, Power, Link, and Computing Budgets—Verified • Subsystem Environmental Testing Results • Assembly Procedures • Preliminary Frequency Coordination Documentation • Environmental Test Plan, Operational Test Plan, On-orbit Operations Plan • **Flight Unit Integrated**	August 2014
Integration & Test Review	• 7-day functional demonstration on Flight Unit • End-to-end functional demonstration of Flight Unit • Environmental test results on Engineering Unit • RF compatibility testing of Engineering Unit • Approval to qualify flight unit in test chambers	September 2014
Spacecraft Acceptance Review	• Flight unit environmental test results • 30-day “locked operations” demonstration of Flight Unit • Signed-off verification of Requirements Matrix • **Flight Unit delivered**	January 2015

4.4 Risk Management

Various Risk Factors have been identified and will be reviewed regularly until the flight spacecraft is delivered. For this mission, risk is divided into three categories: **Flight Safety Risk** (i.e. damage to the spacecraft and/or launch vehicle during ascent), **Mission Risk** (i.e., mission objectives not met on-orbit), and **Program Risk** (i.e., the project is not completed in the schedule and budget allowed).

All three categories will be reduced by implementing standard practices of systems engineering, as noted above. A software configuration management process has been instituted using commercially-available version control software (e.g. SVN). Industry partners, faculty and peers and alumni act as the "Red Team" at specified design reviews.

4.4.1 Flight Safety Risk

The CubeSat/P-POD standards are designed to minimize flight safety risks, and the standards have proven effective, with dozens of successful launches against no CubeSat-caused flight safety problems. Therefore, the first approach to minimizing flight safety risk is to strictly adhere to the standards, including (but not limited to) mass, shape, surface coatings, and the kill switch. Still, the launch vehicle and CubeSat standards are formally specified in our requirements document and examined at each design review to ensure compliance. We recognize that propulsion is a hazardous operation; we will follow closely the procedures and design parameters developed for RAMPART to minimize risk.

Flight safety will also be mitigated through functional and environmental testing as discussed in Table 5; the PI and Co-Is manage the college's spacecraft environmental testing laboratories, including a CubeSat-sized vibration table and a vacuum chamber.

4.4.2 Mission Risk

Based on a study of past spacecraft failures, we have concluded that the attempt to extract razor-thin performance margins out of university-class space missions is a leading cause of mission failure. Therefore, our most important risk-reduction methods have been implemented in the design: system-level redundancy, incremental design and margins. These are the same principles applied above to manage cost and schedule.

As noted, the testing plan is structured to perform early functional demonstrations, with repeated intensive demonstrations culminating in the 30-day "locked ops" test. Thus, missed assumptions, bad designs or incorrect assemblies can be identified early in the process.

4.4.3 Program Risk

While every space program is constrained in both funds and schedule, university-built spacecraft are most vulnerable to schedule slips. This is because of the inherent schedule conflicts encountered by students, and because university programs are not used to hard deadlines for complex experiments. Schedule risk is managed with significant margins and external milestones.

The Rascal team has relevant experience in this domain. The PI, Dr. Swartwout, was program manager and lead integrator for the student-built Sapphire satellite, launched by NASA in 2001 as part of the Kodiak Star mission. The SSRL team is also on-schedule to deliver two CubeSat missions in 2013.

Appendix A: Resumes

Swartwout, Michael Alden (PI)

Education/Training

1991	BS, Aerospace Engineering, University of Illinois (Urbana-Champaign)
1992	MS, Aerospace Engineering, University of Illinois (Urbana-Champaign)
2000	PhD, Aeronautics & Astronautics, Stanford University

Positions and Employment

2000-2009	Assistant Professor, Mechanical & Aerospace Engineering, Washington University in St. Louis
2009-	Assistant Professor, Aerospace & Mechanical Engineering, Saint Louis University

Other Experience and Professional Memberships

1992-	Senior Member, AIAA
1994-	Member, IEEE
2001-2004	Automation and Operations Working Group, Universities Space Systems Symposium
2004-2005	Member, NASA Solar Sail Technical Advisory Group
2005-2009	AIAA Emerging Technologies Committee; Space Subcommittee
2006-2009	AIAA Gossamer Spacecraft Technical Committee; Recording Secretary for Education Subcommittee
2009-	SLU Representative to Missouri Space Grant Consortium
2010	Reviewer and Select Review Committee Member, 4th edition of Space Mission Engineering

Missions/Accomplishments

2000-2001	Aria-1 (launched aboard STS-106), Aria-2 (STS-102), Aria-3 (STS-108). Role: Assistant Project Manager, Structures Lead
2001-2004	Sapphire Satellite (launched 30 September 2001; decommissioned 31 March 2004). Role: Project Manager, Launch Integration Lead, Operations Lead
2003-2005	High Altitude Ballooning. Seven helium balloon missions to nearly 100,000 feet and one rideshare on NASA science balloon in Antarctica. Role: Chief Engineer
2003-2013	PI for the Air Force University Nanosat Program, spanning five competitions (NS-3 through NS-7). Second place, three times (NS-3 through NS-5). Only PI to participate in all five competition cycles
2013	Scheduled date for launch of SLU's first CubeSat, COPPER and second, Argus

Selected peer-reviewed publications (in chronological order).

1. M.A. Swartwout. Perspectives on Critical Research Areas in Space Systems, Journal of Aviation and Aerospace Perspectives, 2011; 1(1).
2. M.A. Swartwout. The first one hundred university-class spacecraft 1981-2008, IEEE Aerospace and Electronic Systems Magazine, 2009; 24(3).

3. M.A. Swartwout, C.A. Kitts, R.J. Twiggs, T.J. Kenny, B.R. Smith, R.A. Lu, K. Stattenfield, F.K. Pranajaya. Mission results for Sapphire, a student-built satellite. Acta Astronautica, 2008; 62:521–538.
4. M.A. Swartwout, C.A. Kitts, J.W. Cutler. Sapphire: a case study for student-built spacecraft. Journal of Spacecraft and Rockets 2006; 43(55).
5. C.A. Kitts, M.A. Swartwout. Beacon monitoring: reducing the cost of nominal spacecraft operations. Journal of Reducing Space Mission Cost 1998; 1:305-338.

Relevant Conference Publications

6. M.A. Swartwout. A brief history of rideshares. Proceedings of the 2011 IEEE Aerospace Conference, Big Sky, MT, 8 March 2011, paper 1518.
7. M.A. Swartwout. The promise of innovation from university space systems: are we meeting it?, 23rd Annual AIAA/USU Conference on Small Satellites, Logan, UT, 13 August 2009, Paper SSC09-XII-03.
8. M.A. Swartwout, Attack of the CubeSats: a statistical look, 25th Annual AIAA/USU Conference on Small Satellites, Logan, UT, 9 August 2011, Paper SSC11-XI-04.

Honors

2011	Outstanding Faculty of the Year, Parks College
2011, 2012	Student Government Association Faculty Excellence Award

Related, Ongoing Research Support

Swartwout (PI) 11/01/09-04/30/13
NASA Missouri Space Grant/Non-Affiliates' Award
Space Grant Activities at St. Louis University: Hands-On Projects to Improve Retention, Training and Diversity.
This activity brings students into engineering through hands-on engineering projects and peer-to-peer mentoring. This grant has been renewed three times.

Swartwout (PI), Jayaram, Mitchell (co-Is) 02/01/11-01/31/13
AFOSR/University Nanosat-7
Multi-Spacecraft Investigations of Space Situational Awareness
This project is to train undergraduates to design and build a spacecraft to compete in the Air Force University Nanosat-7 competition; the winning school earns a space launch. We are building Argus (see below) through this grant.

Swartwout (PI), Jayaram (co-I) 02/01/11-12/31/13
NASA/CubeSat Launch Initiative
COPPER-Cube: Thermal Imaging on a University CubeSat
NASA has selected SLU to launch its student-built CubeSat, COPPER on the ORS-3 launch in August 2013. SLU will provide the spacecraft and operations.

Swartwout (PI), Jayaram (co-I), Mitchell (co-I), Reed (co-I) 02/01/12-12/31/13
NASA/CubeSat Launch Initiative
Argus: Radiation-Effects Modeling on a University CubeSat
NASA has selected SLU and science partner Vanderbilt to launch their joint CubeSat mission, Argus on ORS-4 in September 2013. SLU will provide the spacecraft and operations; Vanderbilit the science payload and data analysis..

Sanjay Jayaram (Co-Principal Investigator)

Director, Space Systems Research Laboratory
Associate Professor, Aerospace and Mechanical Engineering Department
Saint Louis University

Dr. Jayaram is an Assistant professor in the Department of Aerospace & Mechanical Engineering at Saint Louis University. His research and teaching emphasis is on the design and operations of spacecraft systems, developing high performance components for low cost spacecrafts. He worked as Research Associate at Florida Space Institute for one year. He has peer reviewed journal and conference publications in many sources with a focus on advanced control systems design and spacecraft engineering. Jayaram heads/mentors several student-design spacecraft at Saint Louis University.

Education

- Bachelor of Engineering, Mechanical Engineering, Rashtreeya Vidyalaya College of Engineering, 1994
- Master of Science, Mechanical Engineering, University of Central Florida, 1998
- PhD, Mechanical Engineering, University of Central Florida, 2004.

Appointments

- Assistant professor, Department of Aerospace & Mechanical Engineering at Saint Louis University (2005 – Present)
- Post Doctoral Research Associate/Adjunct professor, Mechanical, Materials and Aerospace Engineering Department, University of Central Florida, (2004-2005)
- Research Associate, Florida Space Institute (1998-1999)

Relevant Publications

- S. Jayaram, "SLUCUBE: Innovative high performance nanosatellite science and technology demonstration mission", Acta Astronautica, Volume 65, Issue 11-12, pp 1804-1812, 2009.
- S. Jayaram, "Spacecraft Engineering Education and Research Overview at Saint Louis University", IEEE Aerospace and Electronics Systems Magazine, Volume 24, Issue 10, pp 12-16, 2009
- S. Jayaram, "Design and Analysis of Nano Momentum Wheel for Picosatellite Attitude Control System", International Journal of Aircraft Engineering and Aerospace Technologies, Volume 81, Issue 5, pp. 424-431, 2009.
- S. Jayaram, R. Johnson, "Robust Fault Tolerant Control Architecture – Actuator Fault Detection and Reconfiguration", Journal of Control and Intelligent Systems Volume 38, Issue 1, pp. 1 – 8, 2010.
- S. Jayaram, "A New Fast Converging Kalman Filter for Sensor Fault Detection and Isolation", Sensor Review, Volume 30, Issue 3, pp. 210 – 224, 2010.
- S. Jayaram, E. Gonzalez, "Design and Construction of a Low-Cost Economical Thermal Vacuum Chamber for Spacecraft Environmental Testing", In Press, To appear in Volume 9, Issue 1, 2010, Journal of Engineering, Design and Technology.
- S. Jayaram, M. McQuilling, "PRO/MECHANICA-based Structural and Random Vibration Analysis of Picosatellite Structure", International Journal of Computer Aided Engineering and Technology, In Press.
- S. Jayaram, M. Swartwout, "A Review of the Role of Student-Built Spacecraft in Workforce Training and Innovation: Ten Years of Significant Change", AIAA 2010-8735, AIAA Space 2010 Conference and Exhibit.

Kyle K Mitchell

Center for Sensors and Sensor Systems
Associate Professor, Department of Electrical and Computer Engineering
Saint Louis University

Dr. Mitchell is an associate professor of Electrical and Computer Engineering at Saint Louis University. His research and teaching on the design of embedded systems with an emphasis on low-power wireless acquisition hardware for infrastructure health monitoring. He currently is developing a platform for wireless data collection from polymer based sensors.

Education

- Bachelor of Science, Electrical Engineering, University of Missouri – Rolla, 1996
- Master of Science, Electrical Engineering, University of Missouri – Rolla, 1999
- PhD, Computer Engineering, University of Missouri – Rolla, 2004.

Appointments

- Associate professor, Department of Electrical & Computer Engineering, Saint Louis University (2009-present)
- Assistant professor, Department of Electrical & Computer Engineering, Saint Louis University (2002-2009)
- Degreed Researcher, Intelligent Systems Center, University of Missouri – Rolla (2001-2002)

Relevant Publications

- K. Mitchel, W. Ebel, *Peak Strain Detection in EFPI Sensors Via Direct Phase Difference Synthesis*, Kyle Mitchell, William J. Ebel, 12th International IEEE Conference on Intelligent Transportation Systems, St. Louis, MO, 2009
- K. Mitchell, W. Ebel, S. Watkins, “Hardware Implementation of Neural-Network-Based Peak Strain Detection for Extrinsic Fabry-Perot Interferometric Sensors Under Sinusoidal Excitation”, SPIE, Optical Engineering, 2009
- Banerjee, S. , Mitchell, K., and Sholy, B., *Ultrasonic Wireless Sensor Network and Automated Data Analysis Algorithms for Health Monitoring of Structural Components*, SPIE conference on Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring, March 9-13, San Deigo, CA, 6935-3, 2008.
- Banerjee, S. , Mitchell, K., and Sholy, B., *An Automated Data Analysis Algorithm for Near Real-Time Damage Monitoring of Structural Components*, The 6th International Workshop on Structural Health Monitoring, Stanford, California, Fu-Kuo Chang ed., September 11-13, , pp. 685-692, 2007.
- Mitchell, K., Banerjee, S. and Sholy, B., *Wireless acquisition System for Automated, Near Real-Time Structural Monitoring using Ultrasonic Sensors*, Proceedings of the Sixth International Workshop on Structural Health Monitoring, pp. 746-753, 2007.
- K. Mitchell, B. Sholy, A.J. Stolzer, *Flight Operations Quality Assurance for General Aviation Aircraft: Overcoming the Obstacles,* IEEE Aerospace and Electronic Systems Magazine, 2007
- K. Mitchell, S. E. Watkins, J. W. Fonda, J. Sarangapani, *Embeddable modular hardware for multi-functional sensor networks* , Smart Materials and Structures, Vol 16, Num 5, 2007 , pp. N27-N34(1)

Appendix B: References

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3. S. Scarritt, M. Swartwout, J. Neubauer, “Proximity Navigation of Highly-Constrained Spacecraft,” 20th International Symposium on Space Flight Dynamics, Annapolis, MD, 24 September 2007.

4. M. Swartwout, “Beyond the Beep: Student-Built Satellites with Educational and ‘Real’ Missions,” 21st Annual AIAA/USU Conference on Small Satellites, Logan, UT, 15 August 2007.

5. J. Neubauer, M. Swartwout, “Potential Function Controllers for Proximity Navigation of Underactuated Spacecraft,” 30th Annual AAS Guidance & Control Conference, Breckenridge, CO, 4 February 2007.

6. M. Swartwout, “Bandit: A Platform for Responsive Educational and Research Activities,” 4th Responsive Space Conference, Los Angeles, CA, 26 April 2006.

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8. T. M. Davis and D. Melanson, "XSS-10 micro-satellite flight demonstration program results," Proceedings of SPIE - The International Society for Optical Engineering, vol. 5419, 2004, pp. 16-25.

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10. J. Shoemaker and M. Wright, "Orbital Express Space Operations Architecture Program," Proceedings of SPIE - The International Society for Optical Engineering, vol. 5419, 2004, pp. 57-65.

11. D. Zimpfer, P. Kachmar, and S. Tuohy, "Autonomous rendezvous, capture and in-space assembly: Past, present and future," Proceedings of the 1st Space Exploration Conference: Continuing the Voyage of Discovery, Orlando, FL, United States.

Appendix C: Commitment Letters

Three commitment letters are attached. The first is from the PI, committing the funds and other resources needed to complete the Rascal mission.

The second is an e-mail from the administrator of NASA Missouri Space Grant, confirming that SSRL can use existing Space Grant funds to develop Rascal.

The third is permission from the director of Project RAMPART to use the lessons learned in development of Rascal.

11 November 2012

To the NASA CubeSat Launch Initiative Review Committee:

I am writing to confirm that we have funds committed to complete the Rascal spacecraft, deliver it for launch and operate it for 6 months after launch. The primary source of funds is the NASA Missouri Space Grant through a series of Associate Awards. (Dr. Stephen Haug is the Space Grant manager for Missouri: 573.341.4887, sbhaug@mst.edu.)

At present, we have component spares from the Argus and COPPER missions to construct Rascal, paying for new hardware out of the Space Grant funds. We are also soliciting additional support for the purchase and construction of new flight hardware from the Air Force University Nanosat Program (UNP) through the Nanosat-8 competition. I am the PI for this grant application; award notification is in December 2012. If selected, we will enter Rascal into the Nanosat-8 competition, which will support improved development of the mission and hardware. The UNP Program Manager is aware that we are also submitting Rascal for a NASA launch and he supports this activity. (Dr. David Voss: 505.846.5291, david.voss@kirtland.af.mil).

Sincerely,

Michael Swartwout,
PI

SAINT LOUIS UNIVERSITY

Michael Swartwout <mswartwo@slu.edu>

Two quick (?) questions

Stephen Haug <sbhaug@mst.edu> Fri, Nov 9, 2012 at 10:55 AM
To: Michael Swartwout <mswartwo@slu.edu>

Hi Mike,

For (1), the posters (as would any 'Instructional Media') qualify as 'materials and supplies', so there's budget revision needed on our end. These expenses would be justified as required for the dissemination of your students' work at the conference and are approved for this purpose. Thank you for acknowledging Space Grant support as we have requested for all MOSGC funded projects.

A proposal budget is meant for planning purposes and unanticipated expenses are to be expected (we just try to remember to include them next time!). As long as an expense falls within the proposed budget category/program element you will not be required to submit a budget revision.

For (2), first, congratulations on getting your second flight opportunity confirmed! I know it's been a very long road for you to gain access to space for your students and it looks like all of the hard work and persistence is finally paying off.

Thank you for brining Saint Louis University's newly proposed CubeSat Launch Initiative mission to our attention. Others may wonder, but it comes as no surprise to me that you are ready to start another project. NASA regards these hands-on student activities as being essential to achieving their education priorities and the Consortium is supportive of your efforts. Your presently awarded Missouri Space Grant funds may be used to initiate the development of the Rascal project. Please send a brief summary of the proposed mission at your convenience.

Best wishes for success on Copper, Argus, and now Rascal!

Would you like me to send something more formal for either of these to someone in your accounting or research offices?

I'll be running around a bit today, so if you would like to talk by phone you can call me at 573-587-0343.

Steve

Stephen Haug, Manager
NASA-Missouri Space Grant Consortium
NASA-EPSCoR Missouri
Department of Mechanical & Aerospace Engineering
Missouri University of Science & Technology
573-341-4887
sbhaug@mst.edu
http://web.mst.edu/~spaceg

From: Michael Swartwout [mswartwo@slu.edu]
Sent: Wednesday, November 07, 2012 8:53 PM
To: Stephen Haug
Subject: Two quick (?) questions
[Quoted text hidden]

SAINT LOUIS UNIVERSITY

Michael Swartwout <mswartwo@slu.edu>

Permission to cite RAMPART

GilMoore12@aol.com <GilMoore12@aol.com> Sat, Nov 10, 2012 at 12:49 PM
To: mswartwo@slu.edu
Cc: jim@coloradosatellite.com, phuang@uark.edu

Mike,

You have my permission to pass along our lessons learned on RAMPART in your NASA proposal. I'm sure that Jim White, RAMPART program manager, will be happy to share his communications, encryption and programmatic lessons learned, as I also hope will Dr. Adam Huang of the University of Arkansas, RAMPART propulsion system developer, with respect to his propulsion lessons learned.

In answer to your second question below, we will not be able to meet the delivery schedule for the ORS-3 mission, sue to unresolved propellant leakage issues, so we have voluntarily asked that RAMPART be removed from it.

However, we are on schedule for PrintSat delivery. I agree with you that it's too bad the ORS-4 integration isn't going to be held at Kauai's Barking Sands Test Site. I participated in lots of Sandia multistage sounding rocket launches there in the 1960s and 70s.

Gil Moore
Director, Projects RAMPART, PrintSat and POPACS
3855 Sierra Vista Road
Monument, CO 80132

[Quoted text hidden]

> [Quoted text hidden]
> Department of Aerospace & Mechanical Engineering
> Saint Louis University
> mswartwo@slu.edu --|-- astrolab.slu.edu --|-- 314/977-8214

Appendix D: Accreditation

The accreditation letter for Parks College of Engineering, Aviation and Technology is enclosed.

ABET, Inc.
111 Market Place, Suite 1050
Baltimore, MD 21202
Phone: 410-347-7700
Fax: 410-625-2238
www.abet.org
accreditation@abet.org

Applied Science Accreditation Commission
Computing Accreditation Commission
Engineering Accreditation Commission
Technology Accreditation Commission

August 12, 2009

Manoj Patankar
Dean
Saint Louis University
3450 Lindell Boulevard
St. Louis MO 63103

Dear Dr. Patankar :

Engineering Accreditation Commission (EAC) of ABET recently held its 2009 Summer Meeting to act on the program evaluations conducted during 2008-2009. Each evaluation was summarized in a report to the Commission and was considered by the full Commission before a vote was taken on the accreditation action. The results of the evaluation for Saint Louis University are included in the enclosed Summary of Accreditation Actions. The Final Statement to your institution that discusses the findings on which each action was based is also enclosed.

The policy of ABET is to grant accreditation for a limited number of years, not to exceed six, in all cases. The period of accreditation is not an indication of program quality. Any restriction of the period of accreditation is based upon conditions indicating that compliance with the applicable accreditation criteria must be strengthened. Continuation of accreditation beyond the time specified requires a reevaluation of the program at the request of the institution as noted in the accreditation action. ABET policy prohibits public disclosure of the period for which a program is accredited. For further guidance concerning the public release of accreditation information, please refer to Section II.L. of the 2008-2009 Accreditation Policy and Procedure Manual (available at www.abet.org).

A list of accredited programs is published annually by ABET. Information about ABET accredited programs at your institution will be listed in the forthcoming ABET Accreditation Yearbook and on the ABET web site (www.abet.org).

It is the obligation of the officer responsible for ABET accredited programs at your institution to notify ABET of any significant changes in program title, personnel, curriculum, or other factors which could affect the accreditation status of a program during the period of accreditation.

Please note that appeals are allowed only in the case of Not to Accredit actions. Also, such appeals may be based only on the conditions stated in Section II.G. of the 2008-2009 Accreditation Policy and Procedure Manual (available at www.abet.org).

Sincerely,

John Rutherford, Chair
Engineering Accreditation Commission

Enclosure: Summary of Accreditation Action
Final Statement

cc: Lawrence Biondi, President
J. Gary Bledsoe, Associate Professor, Parks College of Saint Louis University
Muthusamy Krishnamurthy, Report Team Chair

ABET, Inc.

Engineering Accreditation Commission

Summary of Accreditation Actions
for the
2008-2009 Accreditation Cycle

Saint Louis University
St. Louis, MO

Aerospace Engineering (BS)
Biomedical Engineering (BS)
Electrical Engineering (BS)
Mechanical Engineering (BS)

Accredit to September 30, 2013. A request to ABET by January 31, 2012 will be required to initiate a reaccreditation evaluation visit. In preparation for the visit, a Self-Study Report must be submitted to ABET by July 01, 2012. The reaccreditation evaluation will be a comprehensive general review.

Appendix E: Compliance Checklist

✓	Respondent is a NASA center, a U.S. not-for-profit organization, or an accredited U.S. educational organization	Parks College of Engineering, Aviation and Technology at Saint Louis University is an accredited U.S. educational organization (see Appendix D)
✓	Proposal includes demonstration of the benefits to NASA	The mission will improve NASA's ability to perform proximity operations on CubeSat-class missions (Section 2.1). STEM education will be improved through hands-on, industry-relevant training (Section 2.3).
✓	Proposal identifies a project focus area	Rascal is a technology demonstration of navigation technologies for on-orbit proximity operations (see Sections 2.1 and 2.2). The secondary focus area is education (Section 2.3)
✓	Proposal includes a description of the merit review process and outcome	Section 2.4
✓	Proposal includes a description of the feasibility review process and outcome	Section 3.4
✓	Proposal should fully comply with the Launch Services requirements and identify any potential waivers	Rascal will launch as a 6U, and is in compliance with P-POD standards for envelope, mass, inhibits, delayed deployables (see Section 3). Rascal will need a waiver to carry propulsion, but the propulsion system will be based on a propulsive CubeSat flying in 2013 (RAMPART).
✓	Proposal includes a completed Mission Parameters Table.	Table 1 (Section 1)
✓	Proposal includes a completed Project Details Table	Table 2 (Section 1)
✓	Proposal includes a schedule for remaining CubeSat development that supports a launch in 2013-2016	Table 5 (Section 4.3)
✓	Proposal includes funding commitment letters demonstrating sufficient financial support for remaining CubeSat development	Appendix C