Rascal

Mission Overview Document

Document Number: RCL-O-CMQA2

12/9/2013

Revision: -

Prepared for: Prepared by:

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**SAINT LOUIS
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REVISION SUMMARY

REV	RELEASE DATE	BRIEF DESCRIPTION/REASON FOR CHANGE	Author	Approval	EFFECTIVE PAGES
-	12/09/2013	Original Draft	TAM	NJR	All

1   Executive Summary

The Rascal mission consists of a demonstration of proximity operations within the architecture of a small spacecraft, including safe navigation within a 10-50 meter distance of a target spacecraft (stationkeeping), the performance of a collision avoidance maneuver relative to the same spacecraft out to at least 100 meters, and rendezvous to within 50 meters of the same spacecraft.

The mission elements consist of two 3U spacecraft (Jade and Nephrite) that each have identical subsystems and are capable of demonstrating mission success. **Mission success is defined as demonstrating stationkeeping by maintaining a relative distance of 10-75 meters between Jade and Nephrite for at least 5 orbits, demonstrating collision avoidance by increasing the relative distance between Jade and Nephrite to at least 100 meters within 1 orbit, and demonstrating rendezvous by decreasing the relative distance between Jade and Nephrite to at least 50 meters for at least 5 orbits.** This will be accomplished by only necessitating one of the spacecraft to execute the mission requirements defined above, thus reducing the risk associated with flying a custom designed propulsion system into orbit for the first time.

The mission is worth pursuing as it falls within the scope of NASA's strategic goals, specifically, those associated with demonstrating critical technologies that will make NASA's exploration, science, and discovery missions more affordable and more capable. It will also help add to the growing amount of data on the performance of proximity operations through the use of small spacecraft, aiding in the development of such systems for use in satellite inspection and repair in the years to come.

Contents

2   Program Introduction

Rascal is a spacecraft mission that seeks to demonstrate the performance of in-orbit proximity operations within a small spacecraft architecture. Proximity operations are defined as the performance of orbital maneuvers, such as Stationkeeping, Rendezvous, and Collision Avoidance, relative to a resident space object (As Defined in Table 1-1).

Table 1-1. Key Proximity Operations Definitions

Proximity Operation Terms	Definition
Stationkeeping	Maintaining a set relative displacement between two space objects for a period of several orbits
Collision Avoidance	Performing an orbital maneuver that increases the relative displacement between two space objects, as to avoid on-orbit collisions and potential orbital debris creation.
Rendezvous	Performing an orbital maneuver that decreases the relative displacement between two space objects within a set distance for a period of several orbits.
Resident Space Object	Any satellite or object residing in space

Proximity operations have been designated by the NASA Innovative Advanced Concepts (NSPIRES) program as one of many transformative ideas that will help enable new aeronautics and space systems capabilities. If successful in demonstrating the performance of such operations, Rascal would act as a stepping stone to future development and refinement of the technologies and processes involved with the performance of proximity operations, potentially leading to the creation of small satellites that are capable of inspecting, or even repairing, damaged satellites or crew capsules, saving millions of dollars and man hours associated with the replacement of said systems that would normally have no cost-effective means of being repaired in-orbit.

This document serves to elaborate on the relevance and feasibility of proximity operations demonstrations for small spacecraft from historical, analytical, and operational perspectives, as well as outline the mission requirements, success criteria, and design flow-downs for the Rascal mission itself.

3   Mission Relevance and Justification

3.1   Relation to NASA Objectives

The Rascal mission relates directly to NASA Strategic Goal 3.3 (As Outlined in *NASA's FY 2011 and FY 2012 Annual Performance Plans*), which states that missions should be pursued that "Develop and demonstrate the critical technologies that will make NASA's exploration, science, and discovery missions more affordable and more capable."

As a CubeSat mission seeking to demonstrate proximity operations that have not been performed on a system of equal scale (More On This in Section 3.2), the Racal mission meets both the requirements of demonstrating critical technologies within an affordable spacecraft system. As such, missions such as Rascal's (Including both PONSFD and ARAPAIMA, as Discussed in Section 3.3) are highly desirable from a NASA development perspective. The reason for this rests in the potential of these types of systems

to conduct inspections and maintenance on dying or decommissioned satellites, potentially saving satellite developers millions of dollars in costs associated with replacing such satellites that were previously unrecoverable.

3.2   *Historical Proximity Operations Relevance*

Rendezvous and proximity operations (RPO) missions have a long history in human spaceflight dating back to the first Gemini missions. It was not until the previous decade did interest arise in approaching RPO missions with purely robotic systems. For the most part, RPO missions have been solely under the purview of NASA and the military; only recently have private companies and universities made inroads in this area. Each mission has taken a different approach to RPO and has ranged from small CubeSats to massive multi-million dollar satellites. The successes and failures of these missions have helped drive the constraints of the Rascal Mission (Discussed in Section 5.2.6). A summary of theses missions, as well as the success, cost, and lessons learned from their execution, are listed in Table 3-1.

Many previous RPO missions have been large million dollar satellites, each of which approached their mission in many different ways in an attempt to demonstrate many different RPO capabilities. Out of these missions, three were selected for more analysis based on the types of RPO capabilities that they demonstrated.

The first of these spacecraft is the Demonstration for Autonomous Rendezvous Technology (DART) mission, built by Orbital Sciences Corporation for NASA in an attempt to develop and demonstrate autonomous navigation and rendezvous capabilities on a microsatellite platform. Its mission involved attempting to dock with an experimental communication satellite. The primary objectives of the mission were to navigate autonomously using GPS and rendezvous using an Advanced Video Guidance Sensor. Within a few hours of launch, it was able to reach its target, but experienced a malfunction as it began its approach, resulting in a soft collision between it and the target vehicle, which lead NASA to end the mission and begin the effort to find the cause of the malfunction. Though not publically released, the soft collision was likely a result of the chaser satellite approaching the target in a manner that the navigation algorithms used to control its propulsion system did not account for. This prevented the Advanced Video Guidance Sensor from switching to its fine tracking mode from its course mode, leading the chaser to think it was further from the target than it actually was, eventually causing the collision. The total cost of the mission was $98 million. The main lesson to take away from this mission is that even when a large amount of resources and money are used to develop and test a mission, the risk associated with its execution never completely goes away. A secondary lesson that can be taken from the mission is that the method of tracking relative position between two objects is complicated and prone to risk, thus making it a key point of investigation, development, and testing for any RPO mission.

The next mission that is to be discussed is Orbital Express, which was built by Boeing and Ball Aerospace and managed by the Defense Advanced Research Projects Agency *(*DARPA*)* and the Marshall Spaceflight Center. The Orbital Express mission was meant to demonstrate several servicing operations as well as rendezvous and proximity operations. It consisted of two spacecraft, with one being the target and another being the servicing module. The primary spacecraft was able to refuel and replace the batteries of the target spacecraft. The total cost of the mission was $300 million. The main lesson from this mission is that demonstration of extremely complicated RPO maneuvers is possible, but requires a large amount of resources, development time, and testing, likely more than a university-class spacecraft can achieve. Thus, it is necessary to limit the scope of Rascal mission to a level where it can actually be achieved while still being able to demonstrate RPO maneuvers that are of use to the grater aerospace community.

The final large-scale spacecraft mission that was analyzed was the Micro-satellite Technology Experiment (MiTEx) mission. This mission consisted of three spacecraft working in geostationary orbit, with one serving as an experimental satellite and the other two as inspection satellites. The inspection

satellites, with masses of 225 kg each, were technology demonstration satellites capable of maneuvering in relation to other satellites and providing platforms to inspect other satellites without detection. The satellites demonstrated autonomous operations, maneuvering, and station-keeping capabilities. They were built by Lockheed Martin and Orbital Sciences and managed by DARPA. They were able to complete their mission with the experimental satellite, and then moved to inspect a failed missile detection satellite to try to find the cause of the failure. The total cost of the mission was $24.6 million. The lessons learned from this mission are similar to those learned from the Orbital Express mission, with the extra edition of the usefulness of allowing for extended satellite operations when selecting the amount of propellant to fly with an RPO mission.

More and more private institutions are starting to move into conducting RPO missions with smaller spacecraft. Currently the missions done by private institutions have been primarily proximity operations, though they still demonstrate technologies that could be used on future RPO missions.

The first of these was SNAP-1 developed by Surrey Satellite Technology Ltd and the University of Surrey. The 6 kg nanosatellite was to approach and rendezvous with Tsinghua-1, anther spacecraft that was integrated into the same launch vehicle. After launch SNAP-1 ended up in an orbit below that of Tsinghua-1 and, being relatively light, suffered more from the effects of atmospheric drag than the much heavier Tsinghua-1 microsatellite. As a result, the two spacecraft became more separated, and, at their worst, Tsinghua-1 and SNAP-1 were about 15,000 km apart. However, SNAP-1 eventually brought itself within 2000 km of Tsinghua-1 by means of propulsion maneuvers. Thus, while a true rendezvous was not achieved, SNAP-1 was able to demonstrate the agility and maneuverability of its propulsive system under automatic control. In stark contrast to the previously discussed missions, the mission cost of SNAP-1 came in at less than $1 million. This (relatively) small price-tag shows that it is possible to demonstrate proximity operations within a small spacecraft architecture. However, the quick separation between the target and chaser satellite indicate that there are large risks associated with attempting proximity operations demonstrations between two spacecraft that enter orbit with even slightly different initial conditions. In terms of the Rascal mission, it is absolutely necessary to mitigate this risk to the fullest extent possible, as its occurrence would result in the failure of the mission as a whole.

The next mission looked at was Aerocube-4, which was developed and operated by the Aerospace Corporation. It consisted of 3 1U CubeSats that each had solar panel wings that closed and opened in an attempt to alter the ballistic coefficient (Relation That Indicates the Effect of Drag on a Given Spacecraft) of each spacecraft, thus allowing for efficient formation flying (Maintenance of Small Relative Distances Between Each Spacecraft). Each satellite included three-axis attitude control to 1 degree absolute accuracy, a 0.3-square-meter deployable deorbit device, and sub-miniature reaction wheels. The satellite also carried a launch environment data logger that recorded ascent accelerations, vibration, pressure and temperature. In order to efficiently manage the formation of each spacecraft, a new three-node automated ground system network was developed. High-precision orbit determination (OD) was made possible by a GPS receiver installed on each satellite that collected fixes on a regular basis and delivered the measurements of the satellites' position and velocity. The ultimate cost of the mission was around $200,000. Lessons learned from this mission include the importance of knowing and recording the exact location of spacecraft conducting RPO missions, whether accomplished by position/velocity motion sensors, GPS, or ground based tracking, and that high precision formation flying (or stationkeeping) can be accomplished through the implementation of relatively simple attitude control systems.

The final mission looked at was DRAGONsat, a partnership between University of Texas-Austin and Texas A&M. It consisted of two 1U spacecraft, one developed by UT Austin (PARADIGM) and the other

one developed by Texas A&M (Aggiesat2). They were each deployed at the same time, with an objective of collecting two orbits worth of GPS data to determine how far apart the spacecraft separated from each other. The mission was ultimately a success and data was collected from both satellites on the general change in relative displacement between each of the spacecraft. The mission cost around $100,000. The lessons learned from this mission include further demonstration of the reliability and usefulness of GPS data for proximity operation missions.

Though other RPO missions beyond the ones discussed here have been conducted after the past 10-15 years, none have approached the demonstration of RPO maneuvers in the manner that the Rascal mission is set out to demonstrate. DART may have demonstrated the use of image navigation for rendezvous, while SNAP-1 showed the potential of CubeSat sized propulsion systems for relative position changes, and Aerocube-4 proved that stationkeeping can be maintained when precise satellite location tracking is made available, no single spacecraft mission has attempted to address each of these issues and more in the way that Rascal seeks to demonstrate for the costs typically associated with developing a CubeSat mission. Figure 3-1 consists of a comparison of the weight of a given RPO mission vs the cost associated with its development and launch, as well as whether or not each mission was considered a success.
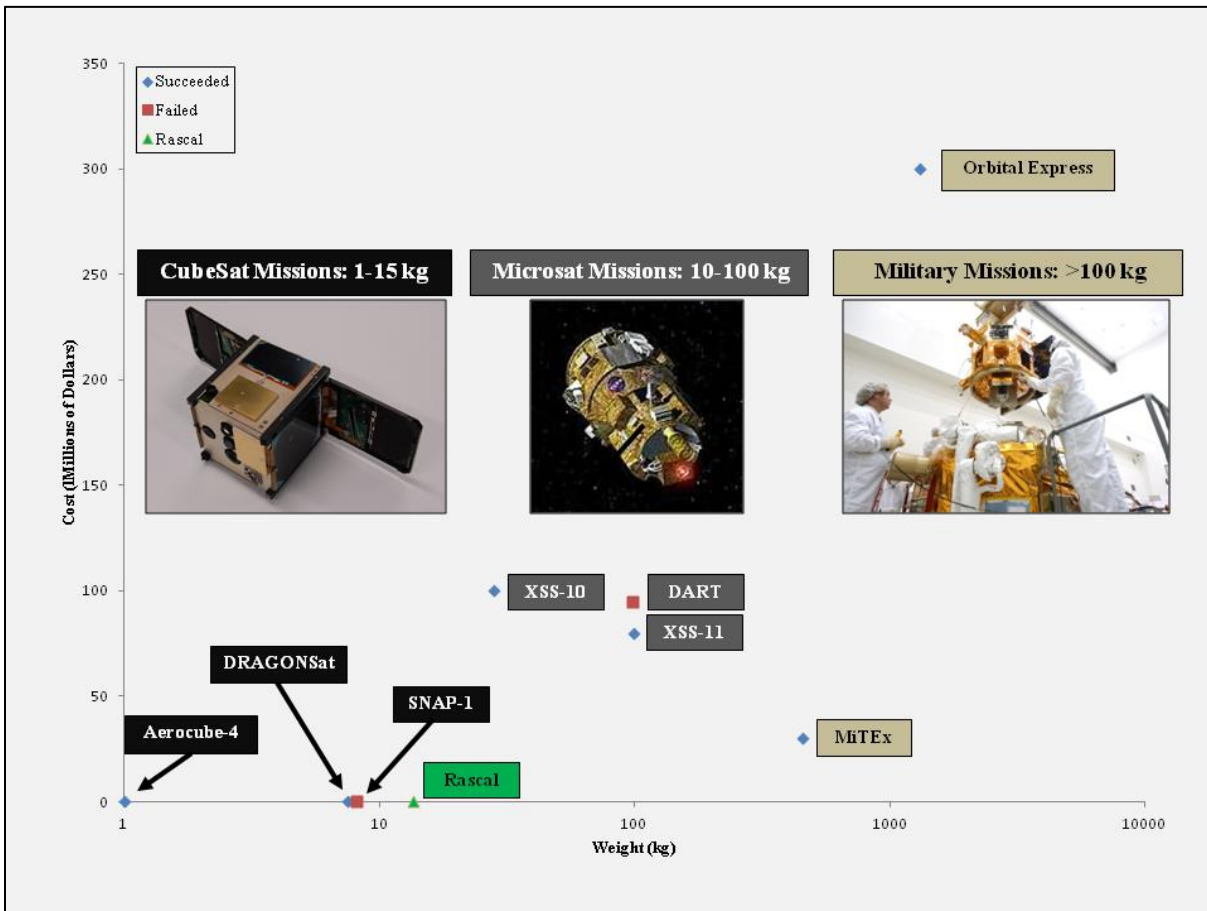

Figure 3-1. Comparison between the Cost, Mass, and Success of Historical RPO Missions

As can be seen from the figure, Rascal falls into a nice gap between its small-scale CubeSat and large-scale microsatellite and military satellite RPO mission counterparts of the past. It carries the benefit of having a low price tag associated with its development, as well as being able to demonstrate proximity

operations the types of which have not been seen on such a small scale, with the foresight gained from previous mission failures and successes going into its mission design. Even with these missions in mind, there is still a large amount of risk associated with the Rascal mission itself. However, the historical perspective provided by each of the discussed missions offers great insight into how exactly these type of missions can fail, and thus, what part of the mission to focus on in this early development stage.

Table 3-1. RPO Mission Summaries and Lessons Learned

Mission Name	Institution	Satellite Type	RPO Demonstrations	Cost	Success	Lessons Learned
DART	NASA	Micro	Rendezvous	$98 Million	No	RPO Missions Have Many Failure Modes, Navigation Algorithms Must be Robust
Orbital Express	DARPA	Military	Rendezvous, Refueling, Component Exchange,	$300 Million	Yes	Mission Scope As a Factor of Available Resources is Important
MiTEx	DARPA	Military	Inspection, Station Keeping, Rendezvous	$28 Million	Yes	Extended Operations Can Demonstrate as Much Use as Primary Mission
SNAP-1	SST	CubeSat	Rendezvous	$1 Million	Partial	Initial Conditions are Important in Determining the Success of a Low-Cost RPO Mission
Aerocube-4	Aero Corp	CubeSat	Stationkeeping	$200 Thousand	Yes	Position Tracking is Crucial in a Successful RPO Mission, Useful Maneuvers can be Demonstrated with Small Spacecraft
DRAGONsat	UT Austin/ Texas A&M	CubeSat	Position Tracking	$100 Thousand	Yes	Spacecraft Separation can Occur Quickly Even with Similar Initial Conditions

3.3 *Related Activity in Proximity Operations*

Several private institutions are developing RPO missions using the CubeSat architecture while getting funding from NASA to do so. Each of these potential missions were studied as to differentiate Rascal from the back and further justify its flight. Also, based on the types of problems that these particular missions are attempting to address can help identify areas of the Rascal mission that will need to be focused on in the future, as well as those that need to be further reviewed.

The first mission that was considered was the Proximity Operations Nano-Satellite Flight Demonstration (PONSFD) mission that is currently under development by Tyvak Nano-Satellite Systems LLC and sponsored by NASA Ames Research Center. It consists of a set of two 3U spacecraft and seeks to demonstrate rendezvous and proximity operations. The concept of operations of the mission will consist of simultaneous deployment from the same spacecraft, after which an initial health check will be performed on each 3U. The mission then enters its main rendezvous and proximity operations flight

demonstration phase. The spacecraft then enters an orbit in which it can maneuver to an initial proximity distance and maintain a set distance from the other, otherwise known as formation flying. Cube-sat one will perform rendezvous and proximity operations relative to Cube-sat two. Then the roles are reversed. The mission then enters increased and decreased range rendezvous and proximity operations scenarios. The mission ends when the spacecraft deorbit. This mission has received $17 million in funding from NASA and has the support of NASA Ames in its development, further high-lighting the interest of NASA in these types of missions. Even though PONSFD's mission seeks to demonstrate proximity operations similar to those that Rascal seeks to demonstrate, it is in no way guaranteed to A) Launch and B) Achieve mission success. Thus, it is still worth pursuing the Rascal mission, as both its and PONSFD's success would further support the validity of proximity operation systems on small-scale spacecraft and further advance NASA's Strategic Goal 3.3, as discussed in Section 3.1.

The next mission that was considered was the Application for RSO Automated Proximity Analysis and Imaging (ARAPAIMA) spacecraft, under development at Embry-Riddle Aeronautical University, the University of Arkansas, and Red Sky Research LLC. Its mission consists of a 6U spacecraft that will autonomously maneuver into close proximity of a resident space object. The concept of operations of the mission begins with the ejection of the spacecraft in orbit, at which point its solar panels will be partially deployed. After this, it utilizes a sun tracker to point at the sun and completely deploys its panels, as to expose the mission payload. The vehicle then under goes orbit and system checkouts, which upon passing, allow it to approach a selected resident space object. Finally, the mission then enters science operations, which consist of proximity operations being performed relative to said object. Based on the missions discussed in the previous section, as well as the general cost associated with tracking and reaching a resident space object (Which has only previously been accomplished by MiTEx), this mission is highly resource intensive and vastly complex in comparison to most CubeSat missions. However, this mission has also received the support of NASA, further underlining the usefulness of such missions.

The final mission analysis looked into the Glint Analyzing Data Observation Satellite (GLADOS), which is under development at the University of Buffalo. GLADOS is a satellite designed to evaluate the size of space debris through the use of cameras capable of observing the reflection of light off of small-scale orbital debris, as to calculate the size, mass, shape, spin, and possibly the path that a given piece of orbital debris is on. The spacecraft has the capability to help in predicting the path of space debris several months in advance, which might prevent orbital collisions. Though not explicitly a proximity operations mission, GLADOS shows that it is possible to observe and analyze RSO's in a statistically significant manner, potentially allowing for the use of such systems in performing proximity operations relative to another satellite.

4 Mission Objectives

4.1 Baseline Mission

The main objective of the Rascal mission is to demonstrate proximity operations on a small-satellite architecture.

With this in mind, Rascal's baseline mission involves first being launched to and released in orbit. Once Rascal is released from its rocket and achieves stabilization, it will enter standby mode. During checkout the ground crew establishes contact with Rascal, confirming that each of its subsystems is working properly. Once confirmed this has been confirmed, a command will be issued for Rascal to initiate its

separation sequence, at which point Rascal would separate into the Jade and Nephrite 3U spacecraft. During and after separation, the spacecraft will perform thrust maneuvers in an attempt to reduce their initial relative velocities. Once it has been verified that each satellite has achieved stability relative to each other, the actual primary mission can begin, which involves the performance of stationkeeping, collision avoidance, and rendezvous maneuvers relative to each other, the success criteria of which are defined in Section 4.2. Once the baseline mission has been completed relative to one of the satellites, extended operations would involve performing the same maneuvers relative to the other spacecraft. Once all of the propellant has been used on each spacecraft, the mission will be considered complete and the satellites would either be decommissioned or put into standby mode until deorbiting and burning up upon re-entry into Earth's atmosphere.

4.2 Success Criteria

In order to achieve full mission success, the Rascal mission shall demonstrate the performance of the following proximity operations relative to either the Jade or Nephrite spacecraft, as defined in the Team Bravo Request for Proposal (RFP):

1. Stationkeeping within a 10-75 m sphere of a resident space object for at least 5 orbits.

2. A Collision Avoidance maneuver by performing an orbital maneuver that intentionally increases the final relative displacement between the mission spacecraft and a resident space object to at least 100 meters in a maximum time of 1 orbit.

3. Rendezvous by performing an orbital maneuver that intentionally decreases the final relative displacement between the mission spacecraft and a resident space object to within 50 m for a period of time of at least 5 orbits.

5 Requirements Verification

5.1 Rationale and Taxonomy

Requirements Verification is the method of verifying that mission success has been fully met by a given mission. This mission success is determined by the ability of a mission developer's design to meet a checklist of primary requirements that have been issued by a potential customer (Such as NASA, Boeing, the DoD, Etc). If these top-level mission requirements are not met, it is within the customer's judgment to determine whether or not their requirements were too strict, their desired mission is too impractical, or if their selection of mission developer is at fault. If it is the latter case, it is within the potential customer's power to part ways with the mission developer, thus making any effort that went into the development of the mission a waste of time, money, and resources.

Hence, one of the most important portions of the preliminary stages of spacecraft mission design is properly defining mission requirements. In the case of the Rascal mission, the main source of these requirements is the Team Bravo Request for Proposal (RFP). This document describes both the type of mission that is to be attempted, as well as the success criteria associated with said mission, and thus is the main driver of mission design going forward. Implicit in these requirements is the need to remotely verify their successful completion when it comes time for the actual mission; otherwise the relevance of the Rascal mission would be moot and the rationale for its launch would be non-existent. Finally, even if the Rascal mission is designed to meet all of these requirements, and can demonstrate as much, it would be completely unreasonable for said mission to take an extended amount of time to be completed. The longer

a mission takes to run out, the more resources have to be utilized in its operation and the more likely that it will experience a failure before mission success can be met. Thus, mission lifetime is a key factor in defining the mission success as a whole.

From these requirements (Known as the Primary Requirements) would then come all other requirements associated with designing a successful mission. Such requirements could be as simple as stating that the spacecraft must have a particular subsystem, or as specific as stating the force required to secure a bolt on the final spacecraft. Regardless, any of such requirements form a subset of one or more of the larger requirements above it.

The representation of the various types of requirements takes the form of a matrix consisting of the definition of each requirement, the method(s) with which it will be verified, the reason that such a requirement exists, and a requirement number for future reference.

There exist four different verification methods for each requirement can be verified:

1. **Test**: Requirements that necessitate some form of testing in order to be verified. Testing includes subjecting a component or system to vibration testing, verifying the amount of delta V that can be produced by the propulsion system, conducting thermal testing on the spacecraft system to verify that it can survive an on-orbit environment, etc. Each test will be documented in a testing document, which will in turn be used to verify that a particular requirement has been met.

2. **Analysis**: Requirements that can only be verified through computational analyses and not through physical measurement or testing. Requirements that fall under this category include calculating the thermal profile of the spacecraft system, determining the expected roll rates that can be achieved with its attitude determination an control system, finding the amount of propellant necessary to perform the mission itself, etc. Each analysis will have its own document associated with it that will be used to verify the successful completion of its corresponding requirement.

3. **Demo**: Requirements that involve demonstration in order to verify their successful completion. Requirements that fall under this category include showing that deployables will not be released until some amount of time after on-orbit ejection, that inhibits successfully cut power off to the entire spacecraft, and that the satellite communications system does not transmit during dispenser integration. Each demo requirement will be verified through test demonstration documentation prior to the actual demonstration of their completion before any organization that seeks to observe

4. **Examine**: Requirements that are verified through either visual inspection or physical measurement. Requirements that fall under this category include dimension constraints associated with the spacecraft's external structure, the total mass of the spacecraft, etc. Each examine requirement will be verified though documentation supporting that the examination has been performed.

Each requirement will have one or more of these methods associated with its verification, as indicated by an X under its corresponding verification method column.

Each requirement will also have a brief rationale section associated with it. The rationale for each requirement will either be an extension of requirements higher up in the matrix or from constraints that have been imposed on the mission as a whole, as discussed in the next section.

5.2 Mission Constraints

Mission constraints for the Rascal mission stem from many sources, ranging from limits on the physical size of the spacecraft used to complete it, the monetary restrictions associated with the development and integration of such a spacecraft, and the risk associated with its execution. Each of these constraints and more are described in detail in the following sections and are each crucial in both restricting the scope of the Rascal mission and allowing for its successful execution.

5.2.1 Launch Vehicle Integration

One of the most important (and difficult) parts of any spacecraft mission is actually getting it off of the Earth's surface and into orbit. Regardless of the work that is done preparing and developing the mission, if it isn't able to be integrated into one of the currently available rockets, it will have no way of reaching orbit, and thus, no way of achieving its mission goal. Thus, it is key that whichever structure is designed to protect and encapsulate the spacecraft has the dimensions and mechanical interface necessary for it to be integrated into currently available satellite adapters.

Due to the shear amount of small spacecraft that have been launched over the past few decades, standards now exist for the integration of spacecraft into pretty much any currently available launch vehicle. Thus, if a mission follows any of these standards, it will be capable of integrating into a wide variety of launch vehicles without having to make any changes whatsoever in its integration method.

The type of adapter that a particular satellite architecture that a mission follows depends on the type of satellite that is to be integrated. Currently, there exist two major satellite classifications that any particular mission falls into: nano and micro-satellites. The following sections will discuss the definitions of each of the satellites that fall under each of these categories, as well as the pros and cons associated with each type.

5.2.1.1 Nanosatellite Classification

Nanosatellite class spacecraft (AKA CubeSats) are those satellites that have a mass of under 1.33 kg per 10 cm x 10 cm x 10 cm volume (AKA, One Standard Unit, or 1U). This satellite classification was developed at California Polytechnic State University (Cal Poly) in 1999 as a means of standardizing small satellite architectures across the entire small satellite industry. This served to facilitate reduced costs and time associated with the development of small satellite missions, thus allowing for organizations that would have previously not been able to develop and launch small spacecraft (Such as Universities and Privately Funded Corporations) to launch scientifically significant, impactful, low-cost missions. Nanosatellites come in several different sizes, ranging from 1U to 6U. An example of a 1U nanosatellite architecture, as defined by the *CubeSat Design Specification Document, Rev 12* is shown in Figure 5-1. Though the vertical dimension of each particular configuration depends on its type, the width of any CubeSat is limited to 100 mm, thus imposing a limit on the size that a given nanosatellite can occupy.
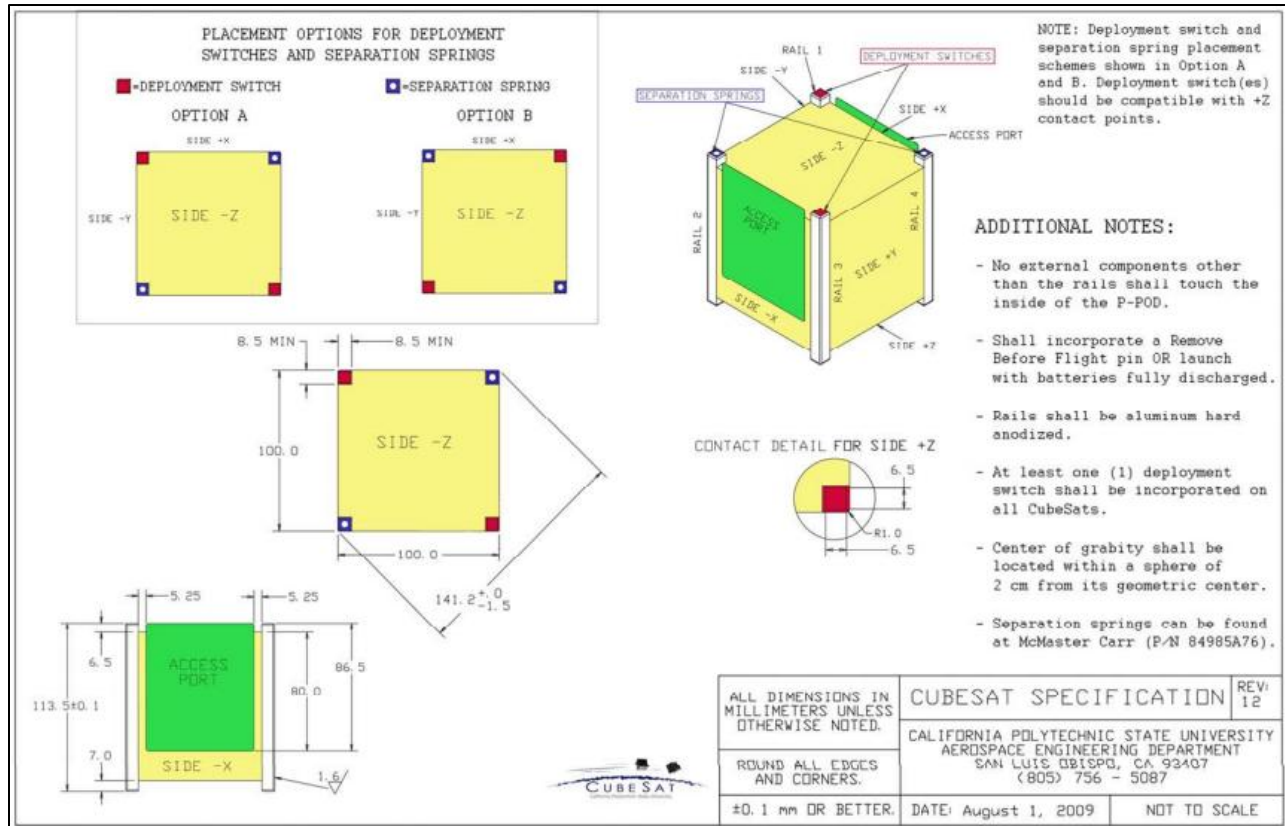
Figure 5-1. CubeSat 1U Architecture

This standardization of CubeSat sizes has allowed companies such as Clyde Space, Pumpkin, Tyvak, and Astrodev to produce commercially available CubeSat electrical power systems, batteries, motherboards, operating systems, and radios that can be integrated into virtually any CubeSat system with relative ease. This in turn allows for a greater concentration of effort in designing, building, and testing those components associated with the execution of a satellite's primary mission, as opposed to focusing on the systems that indirectly support said components. As a result, these Commercially Off the Shelf (COTS) components have greatly reduced the time and resources required to design, build, and fly a small satellite mission.
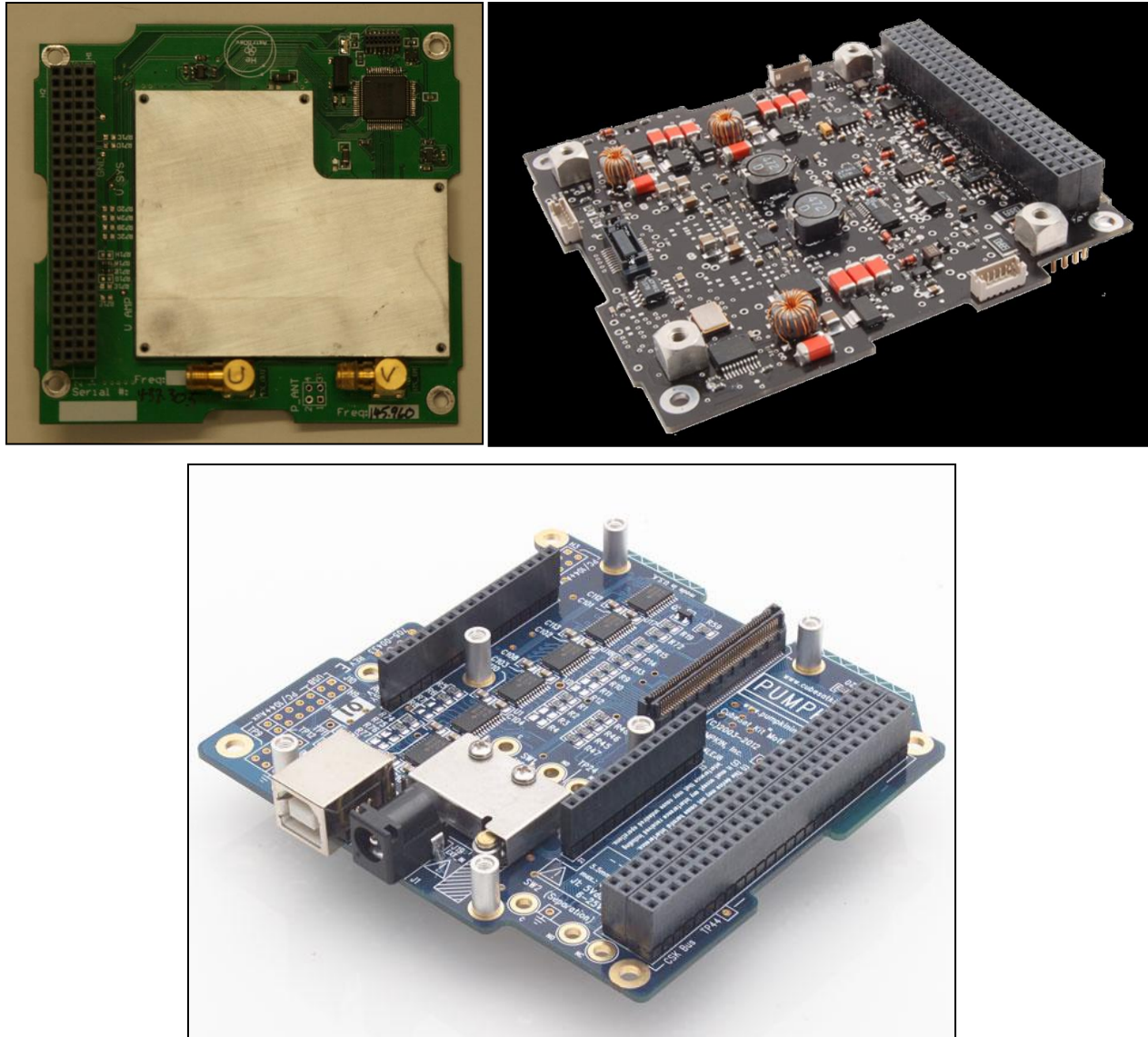
Figure 5-2. (Clockwise from Top Left) Astrodev Helium Radio, Clyde Space Electrical Power System, Pumpkin Motherboard Rev A

Another advantage of following standardized satellite architecture is that it allows for the development of standard satellite deployers, the structures that hold nanosatellites during launch and ultimately eject them into space upon reaching orbit. These deployers, such as the Poly-Picosatellite Orbital Deployer (P-POD), Nanosatellite Launch Adapter System (NLAS), Canisterized Satellite Deployer (CSD) (Each Shown in Figure 5-3), allow for a given nanosatellite design to be integrated into almost any currently available launch vehicle, making it much more likely for a given CubeSat system to get launched than a corresponding Microsatellite mission (More on that in Section 5.2.1.3).
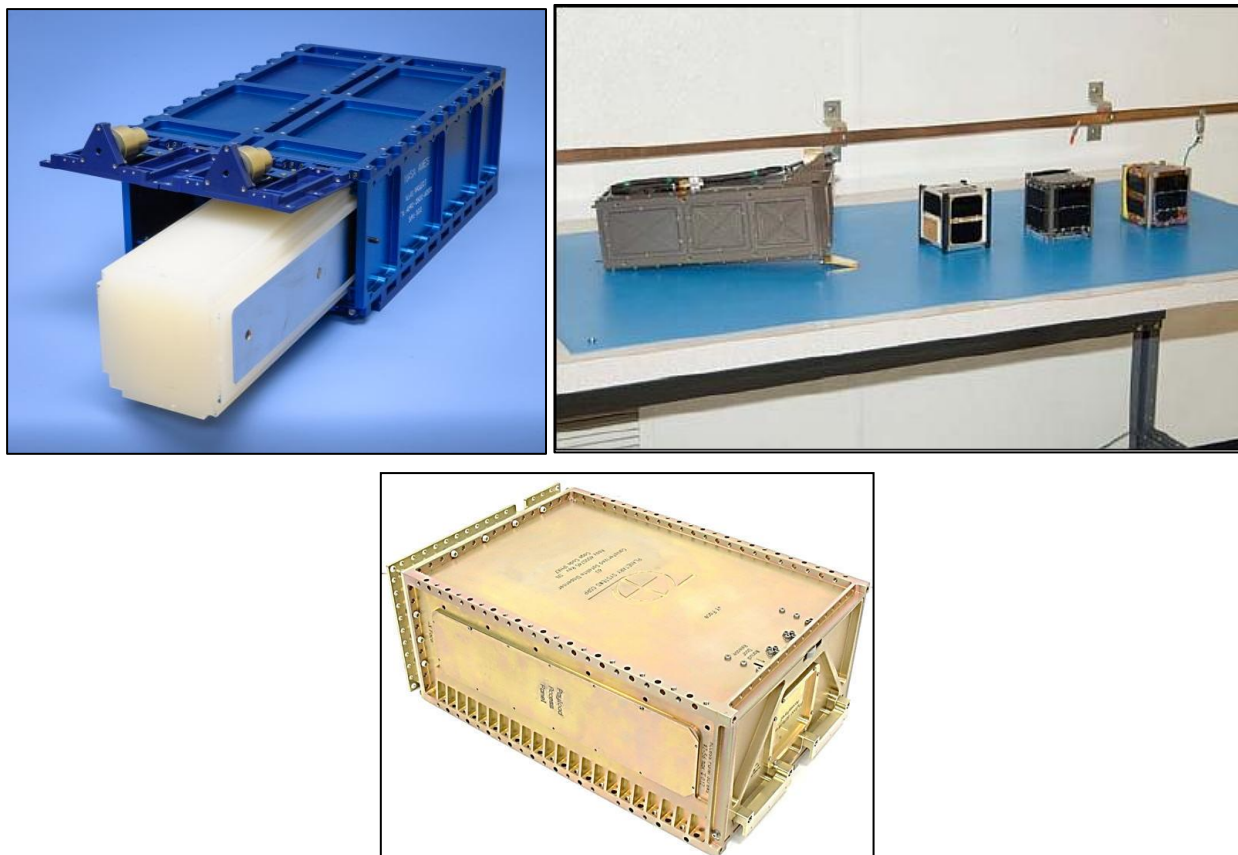
Figure 5-3. (Clockwise from Top Left) NLAS, P-POD, and CSD Nanosatellite Dispensers

Thus, for a CubeSat mission, the ultimate constraint on its launch vehicle integration is whether or not it can integrate into currently available deployers (And Subsequently Survive Launch). Even though such deployers are similar in principal (In that they allow for the easy integration of CubeSat payloads), each deployer has different restrictions and dimensions associated with its use, as shown in Table 5-1. From this list of deployers, as well as the other constraints listed in this document, one will be selected on which to base the design of the Rascal mission as a whole.

Table 5-1. CubeSat Deployer Fact Sheet

Deployer	Allowable Sizes	Maximum Mass	Specifications	Extra Integration Requirements
P-POD	0.5U, 1U, 1.5U, 2U, 3U	8 kg	*CubeSat Design Specifications, Rev 12*	Separation Springs
CSD	3U, 6U	12 kg	*Payload Specification for 3U, 6U, and 27U*	Clamp Tabs
Wallops	3U, 6U	12 kg	*Wallops 6U CubeSat Deployer Specifications*	Separation Springs
NLAS	3U, 6U	14 kg	Not Available (Though Based on CDS)	Not Available
ISIPOD	1U,2U, 3U	6 kg	*CubeSat Design Specifications, Rev 12*	Separation Springs

5.2.1.2 Microsatellite Classification

Microsatellite class spacecraft are those that have a mass between 10 and 100 kg. Beyond this limit, an industry wide definition of what exactly constitutes a microsatellite does not exist. Thus, it is not possible to purchase standard parts for microsatellites in the same manner that can be done for CubeSats, nor do their exist standard specifications that hold true across different launch vehicles, meaning that along with having to be designed for a particular launch vehicle adapter, every microsatellite mission must be designed for a specific launch vehicle, vastly limiting such a mission's launch opportunities.

However, there do exist two standard microsatellite adapters that are available for use of most microsatellite missions: the Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) ring and the Mark II Lightband system.

The ESPA ring consists, as the name implies, of a ring of six different integration points for various types of spacecraft (An Example of one particular ESPA ring is shown in Figure 5-4). Many different sizes of ESPA rings exist for different sized spacecraft, but the integration bolt hole size, diameter, and arrangement between each ring iteration is constant, meaning that only one method of integration needs to be considered when designing a microsatellite for integration into any ESPA ring.

Figure 5-4. Example of a Flight Revision ESPA Ring

However, beyond a standardized bolt pattern, no other standards exist for the type of microsatellite that can be integrated into such a system. This lack of restriction can be either good or bad: good, because it offers much more flexibility in the architecture used to accomplish a given microsatellite mission. Bad because, depending on the restrictions imposed by a given launch vehicle, one particular microsatellite design may be able to integrate into one launch vehicle and not the other; this, in turn, adds developmental risk to any given microsatellite mission that would have to be addressed early in the design phase.

The Lightband Mark II system (Shown in Figure 5-5) is even more limited in its flexibility, only offering the ability to integrate one microsatellite per system. Beyond this limit, integrating into the Lightband system is essentially the same as integrating into the ESPA ring, just with slightly different bolt dimensions.
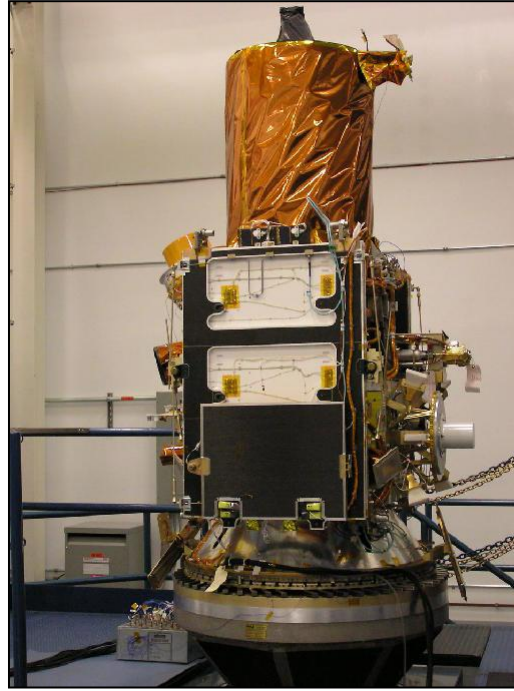

Figure 5-5. Example of a Microsatellite Integrated into a Lightband Mark II System

Beyond these limitations though, recent university microsatellite launches have experienced a relatively large amount of success and have been able to demonstrate both scientifically and practically significant missions that have contributed much to the small satellite community as a whole. Thus, if the resources, time, and money are available, microsatellite missions are worth pursuing.

5.2.1.3 Recent Nanosatellite and Microsatellite Launch Comparisons

In order to compare the feasibility of launching Rascal as either a CubeSat or microsatellite mission, a survey of manifested spacecraft missions over the past three years (2010-2013) was conducted. This was accomplished by recording instances of launches with manifested CubeSat or microsatellite missions and then comparing the number of each type of mission relative to the total number of satellites manifested for said launches. The results of this process are shown in Figure 5-6. When parsing the data, one notices two distinct trends: the number of satellites manifested per launch is increasing rapidly and that CubeSats are the cause of said increase, with CubeSats accounting for 70% of said missions. This indicates that for a given mission, a spacecraft is much more likely to launch if it is of aCubeSat architecture.

This assertion is further supported when limiting the CubeSat and microsatellite missions to those that were developed principally by a student-led university team. When looking at these missions (As Shown in Figure 5-7), the disparity between launched CubeSat and microsatellite missions increases even more, with 86% of launched missions falling under the CubeSat category. Thus, for a given mission, it is significantly more likely for it to be manifested for a launch if it follows the CubeSat, as opposed to microsatellite, architecture.
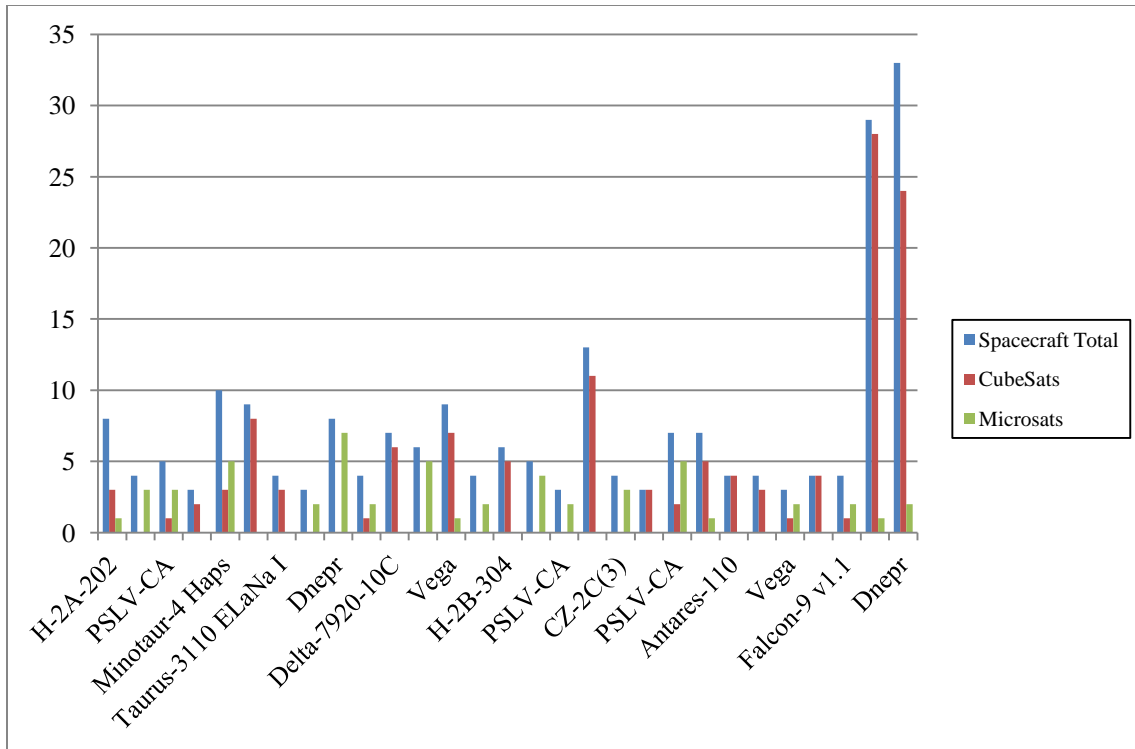
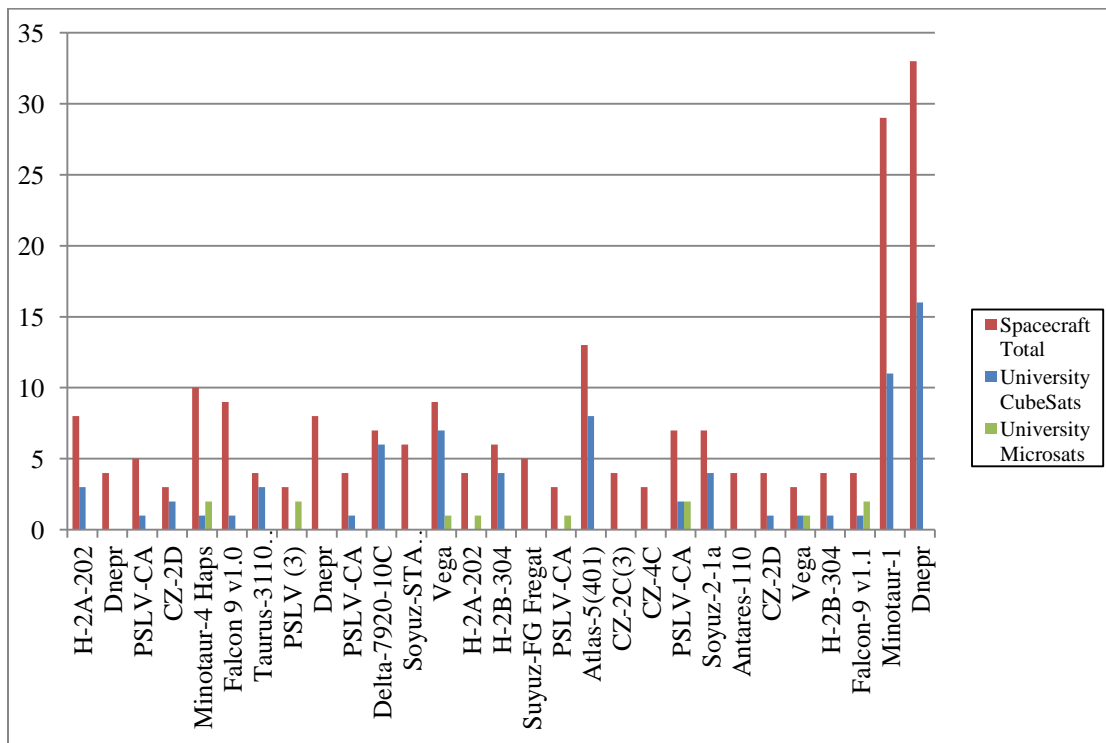**Figure 5-6. Comparison of Manifested CubeSat and Microsatellite Missions Per Launch Vehicle from 2010-2013**

Figure 5-6. Comparison of Manifested University CubeSat and Microsatellite Missions Per Launch Vehicle from 2010-2013

5.2.1.4 Nanosatellite vs Microsatellite Architecture Selection

Based on the discussion laid out in Sections 5.2.1.1-5.2.1.3, launch is the number one obstacle for the success of any mission, regardless of its scope or complexity. Reasons for this are to a certain extent related to finding integration space on currently available launch vehicles, but more concretely related to finding funding for said integration space. For microsatellite missions, no agency currently exists (Other than the University Nanosatellite Program) that is willing to or able to cover their launch cost, as said costs can approach $1 million per spacecraft. For those microsatellites that do get funding from the University Nanosatellite Program, their post award funding development time often runs up to 3-4 years, as demonstrated by the CUsat and DANDEE missions. Thus, even when a microsatellite manages to find funding for launch, it still manages to have a difficult time to ever actually reach orbit.

For CubeSats, however, the opposite is the case. Both the CubeSat Launch Initiative (CSLI) and the Educational Launch of Nanosatellites (ELaNa) have been funding university nanosatellite missions since 2006. Thus, if a nanosatellite mission is capable of demonstrating relevance to NASA objectives while offering education to university students in space systems engineering; it can guarantee a launch spot on pretty much any currently available launch vehicle. Hence, if a mission is capable of fitting within a CubeSat architecture (Like to Rascal Mission Can, as Discussed in Section 5.2.2), it is in its best interest to do so.

With all of these factors in mind, the first constraint to be imposed on the Rascal mission is that it utilizes CubeSat architecture.

5.2.2 Volume

With the discussion in Section 5.2.1 in mind, and CubeSat architecture selected for the Rascal mission, the next most important constraint on its design is that of volume. This constraints stems both from the necessity to integrate into one of the currently available nanosatellite deployers (As Listed in Table 5-1) and the need to make enough space available to execute the mission as a whole. The former constraint is enforced externally and thus cannot be altered beyond selecting a particular deployer to design the mission around. The latter stems from the volume necessary to contain all of the subsystems of the Rascal spacecraft, as determined by a preliminary analysis of the propellant necessary to execute the mission and a historical understanding of the volume required to contain each of the supporting subsystems of a CubeSat system.

5.2.2.1 Propellant Volume Required

The amount of propellant required to execute the Rascal mission stems from the orbital maneuvers required of it to demonstrate, as described in Section 4.2. Based on these orbital maneuvers, as well as various initial conditions for the relative velocity between the two spacecraft, the relative displacement between each spacecraft for the duration of an orbit can be calculated, as shown in Figure 5-7 and 5-8. As can be seen from each of these figures, two RSO's will drift quite a ways apart within just one orbit for even small initial relative velocities. However, as can also be noted from these figures, there are certain portions of the orbit where the two RSO's drift closer together. Thus, it is crucial that the time at which the orbital maneuvers associated with the primary mission are initiated is one that reduces the total ΔV required for the performance of the mission as a whole. Figure 5-9 emphasizes just how important this particular parameter is, with just a 10 second difference in thrust time leading to a total ΔV difference of 20 m/s (Which is fairly large for a CubeSat mission).
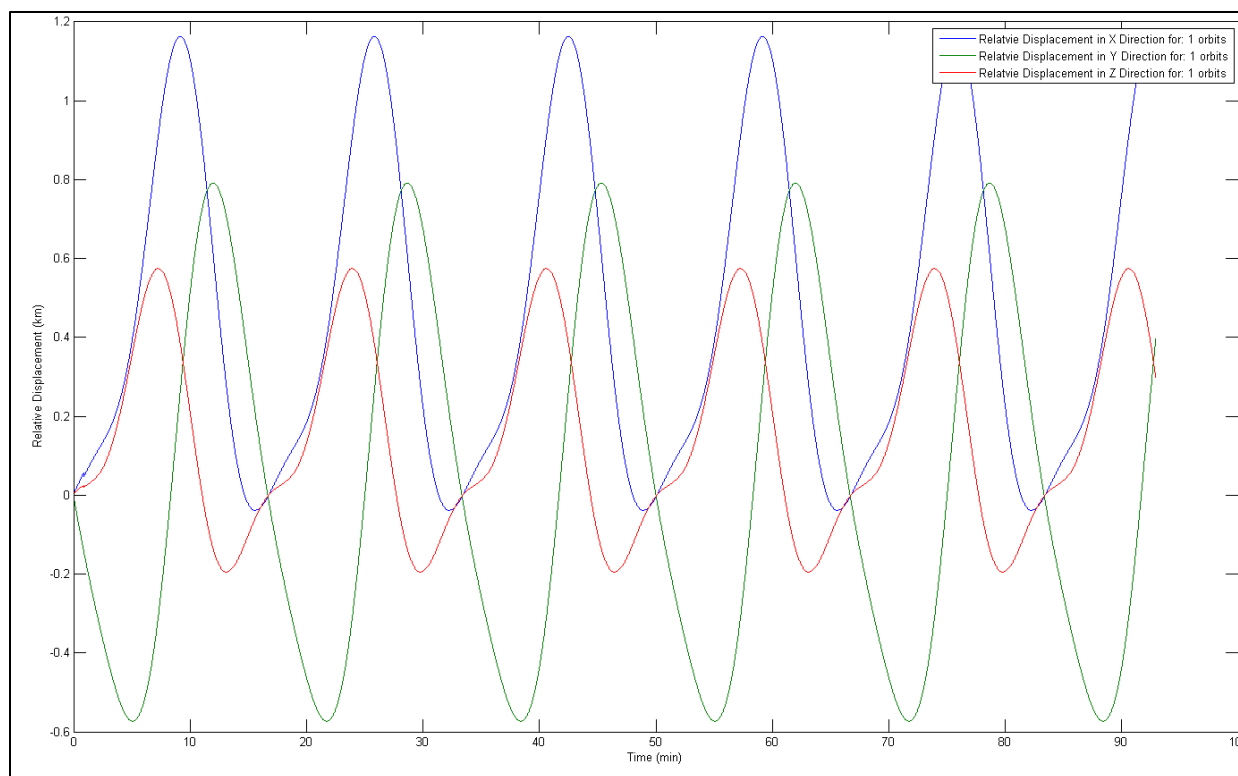
Figure 5-7. Relative Displacement between Two Resident Space Objects on Each Primary Axis for an Initial Relative Velocity of 50 cm/s
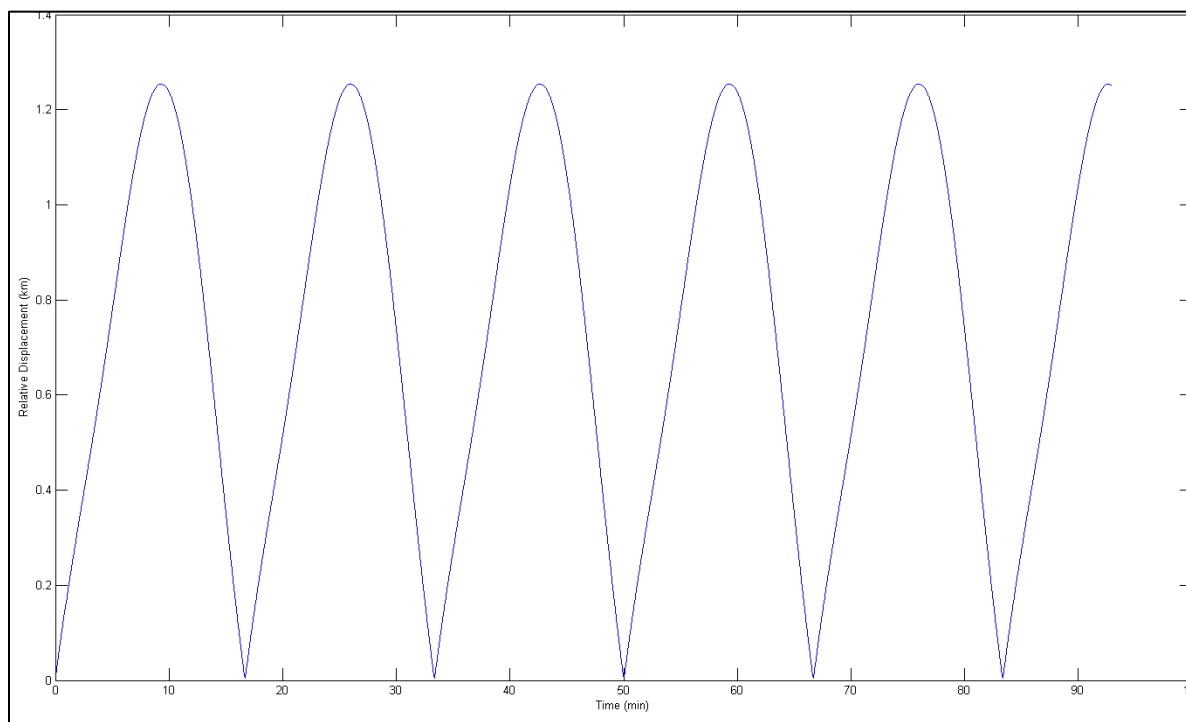

Figure 5-8. Total Relative Displacement between Two Resident Space Objects for an Initial Relative Velocity of 50 cm/s
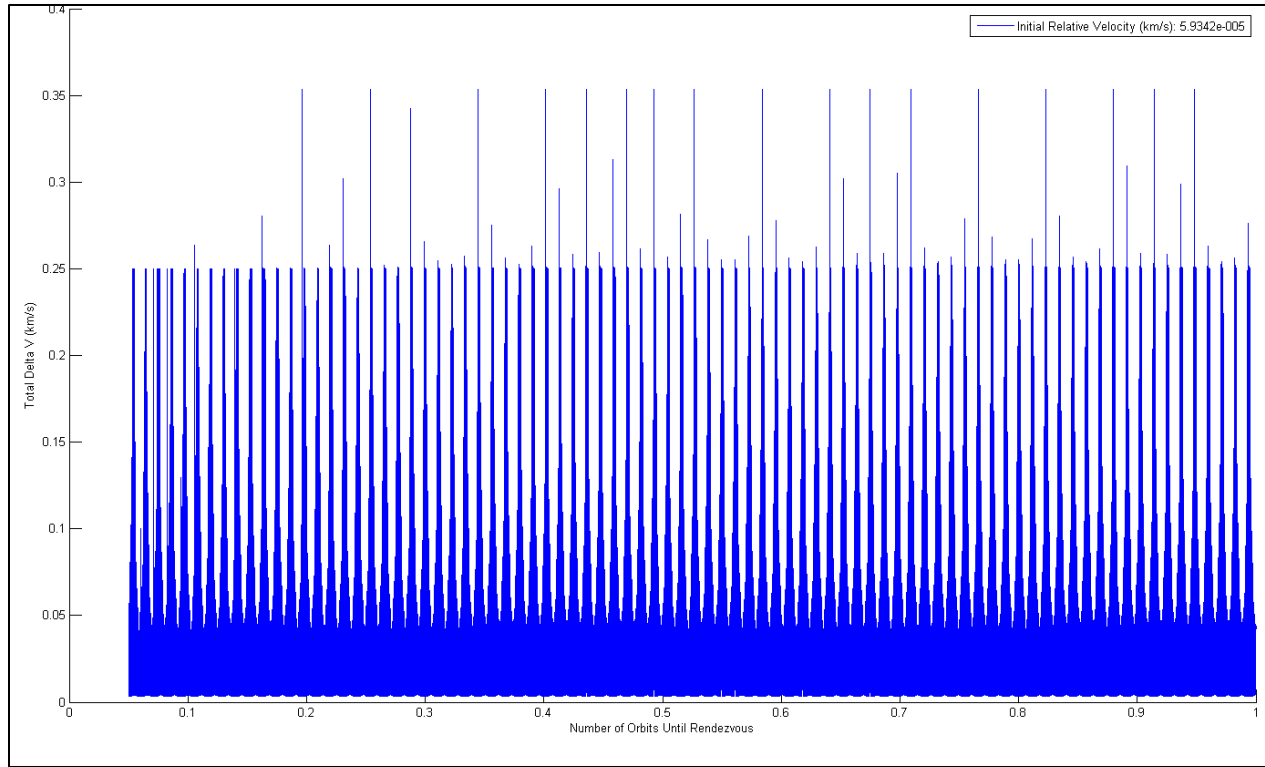
Figure 5-9. Total Delta V Required for Execution of Rascal Mission as a Function of the Orbit Time at Which they are Initiated

With these ΔV ranges in mind, the mass margin of the propellant to the total mass of the spacecraft itself can be found through the use of the standard Rocket Equation, where I_{sp} is the specific thrust of the propellant used in seconds, g_o is the gravitational constant at the Earth's surface, m_{tot} is the total combined mass of the propellant and spacecraft, and m_{prp} is the mass of the propellant. If the specific thrust and required ΔV are known, the percent mass of the propellant relative to the total mass of the spacecraft can be found, as shown in Equation (5-2).

$$\Delta V = I_{sp} g_o \ln \left(\frac{m_{tot}}{m_{tot} - m_{prp}} \right)$$

(5-1)

$$MR = 100 \times \frac{e^{\frac{\Delta V}{I_{sp} g_o}} - 1}{e^{\frac{\Delta V}{I_{sp} g_o}}}$$

(5-2)

With this Equation in mind, one can vary the I_{sp} values associated with the propellants that could potentially be used on small-scale satellite missions with the potential ΔV that the propulsion system must provide. For a preliminary analysis, a low I_{sp} propellant called Refrigerant 134a was selected. Based on previous mission data from the Bandit mission at Washington University and RAMPART, a current RPO mission being developed at Montana State University, 134a can be expected of having a I_{sp} between 20 and 50 seconds. Figure 5-10 shows how changing the I_{sp} between this range for different total ΔV requirements affects the mass ratio necessary to achieve mission success. As can be seen, the mass ratio

associated with the minimum I_{sp} value for each ΔV case increases as expected, with a notable increase occurring between values of 25 m/s and 50 m/s. Regardless, these values help verify the validity of performing an RPO mission within a CubeSat architecture, given that it makes up a small fraction of the total mass of the CubeSat structure as a whole. However, based on past and current missions that seek to demonstrate RPO, the structure required to contain and manage this amount of propellant will likely take up 1U of space, which makes performing this type of mission on anything smaller than a 3U CubeSat unfeasible, as elaborated upon in Section 5.2.2.2.
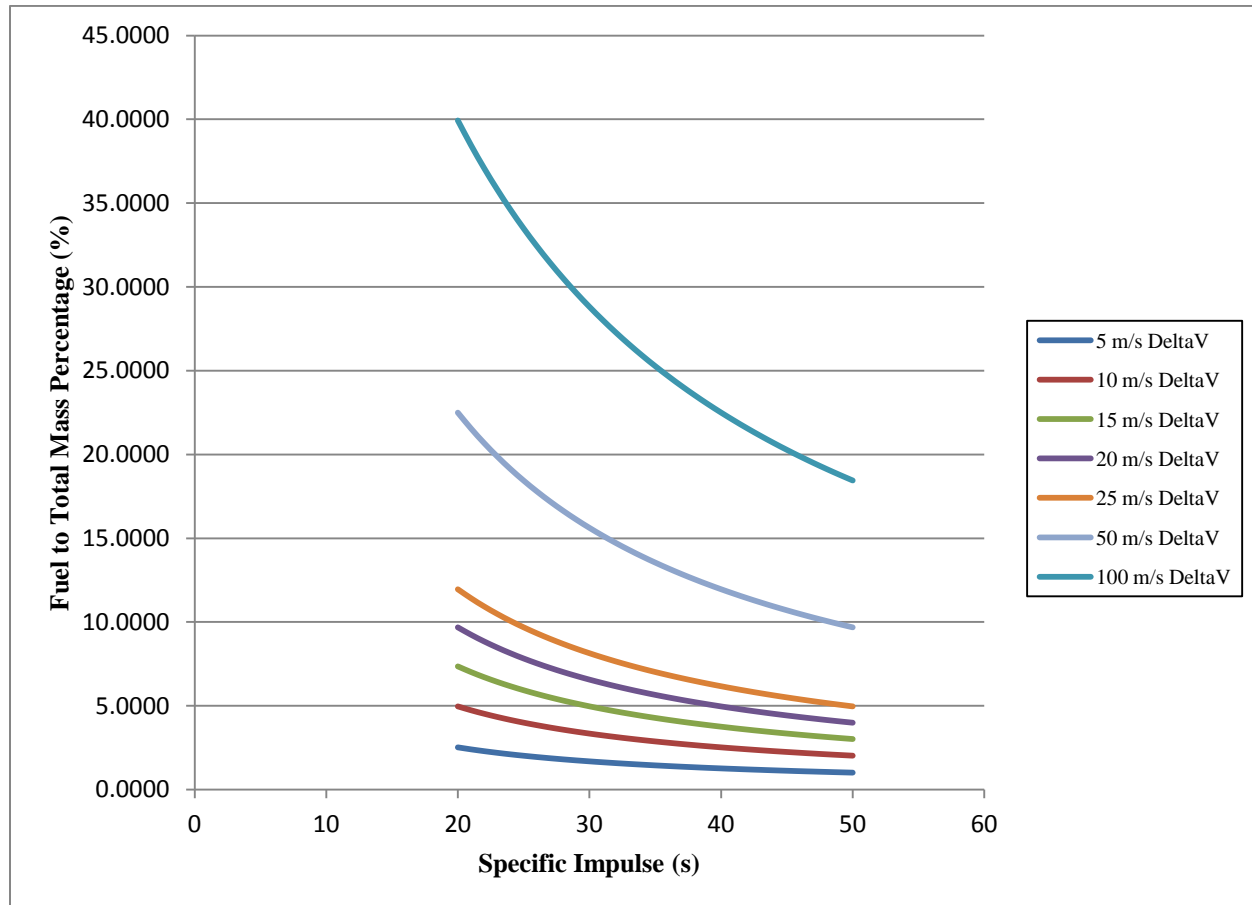
Figure 5-10. Change in Mass Ratio with Propellant I_{sp}

5.2.2.2 Previous Mission Experience

Over the past four years, SSRL has developed two previous CubeSat missions. The first, COPPER, is a 1U CubeSat that carries a small infrared imaging payload designed to document the deployment sequence of other spacecraft from the launch vehicle upper stage. COPPER was selected for launch by NASA's CubeSat Launch Initiative as part of the Educational Launch of Nanosatellites (ELaNa) in January of 2011. After 3+ years of development, COPPER was launched on November 19th, 2013 on board a Orbital Sciences Minotaur I rocket out of Wallops, Virginia.

SSRL's second spacecraft, Argus, is a 2U CubeSat that carries a radiation modeling payload designed by Vanderbilt University to analyze how the radiation environment of space affects small scale electronics in order to provide calibration data for ground based experiments. Argus was selected for launch by NASA's CubeSat Launch Initiative as part of the ELaNa program in February of 2012, and is scheduled for launch in July of 2014.

Both COPPER and Argus utilize a common component and software architecture, the SLU Core Aerospace Research and Application Bus (SCARAB), which consists of the Pumpkin motherboard with a PIC-24 processor, the Astrodev Helium radio, Clyde Space Electrical Power System (EPS), and spacecraft operating system. Altogether, SCARAB occupies approximately 1U of space and can accommodate various payloads so long as they conform to the CubeSat bus. By utilizing this common architecture of commercial off the shelf parts, spacecraft complexity and development time were significantly reduced and gives future missions utilizing SCARAB a degree of flight heritage.

5.2.3 Mission Lifetime

A critical component for any proximity operations mission is mission lifetime; specifically the maximum elapsed time during which the mission can be accomplished. Historical data shows that rendezvous missions are typically short or fail, with the best example being Surrey Satellite Technology Ltd's microsat SNAP-1. SNAP-1 was intended to rendezvous with the Tisinghua-1 microsatellite after deployment from the launch vehicle's upper stage. Though SNAP-1 carried 600 m/s in delta-V, it was not able to neutralize its velocity relative to Tisinghua-1 before the spacecraft were too far away to rendezvous. Their closest proximity was slightly less than 2000 km roughly 1.5 years after launch.

Orbital analysis corroborates the conclusion that relative velocities must be neutralized quickly after separation for rendezvous to be possible (As Discussed in Section 5.2.2.1). Separation velocities of 5cm/s, 10 cm/s, and 50 cm/s were considered, as well as factors from the low Earth orbit environment such as atmospheric drag and solar radiation pressure. The analysis concluded that a separation velocity greeter than 5 cm/s would result in the two Rascal spacecraft being greater than 1 km apart after just one orbit, meaning that mission timing is crucial in ultimate mission success.

Based on the historical data, the preliminary orbital analysis of the separating spacecraft, and the time that may be required to contact and checkout the spacecraft after deployment form the launch vehicle, a mission lifetime of six months was selected.

5.2.4 Mission Success Verification

Another crucial constraint imposed upon any spacecraft mission involves actual verification that mission success was met. This can be accomplished through the transmission of relevant science data to the ground over radio, laser communications, or through physical delivery (As Was Done with Film Canisters for Surveillance Satellites back in the 1960's). In the case of CubeSat missions, radio has been the one and only way of relaying mission data to the ground, meaning that Rascal will likely utilize the same.

Once a means of relaying information to the ground has been established, it is equally important to determine what kind of information is necessary to determine mission success. In the case of Rascal, all that has to be verified is that Jade or Nephrite remains set distances apart or near each other for set periods of time. This implies that each spacecraft must implement a means of collecting and storing relative distance data for downlink upon closing a link with a terrestrial communications station.

5.2.5 Risk Mitigation

The final constraint to consider in the development of the Rascal mission is that of risk mitigation. As discussed in Section 3.2 and elaborated upon in Section 5.2.2.1, it is very easy for the target and chaser satellites in RPO missions to end up being vast distances apart. This risk is especially pernicious when attempting said missions within a CubeSat architecture, as any mistake involved in planning out the performance of each orbital maneuver, a failure in the operation of the propulsion system, or a glitch in the algorithms used to accomplish all of the mission's autonomous operations can quickly lead to the

development of large separations between the target and the chaser, and ultimately the failure of the mission as a whole.

Thus, it is important to identify risks associated with the development of the Rascal mission early on, as to implement design decisions that ultimately help mitigate their development. A few of these key risks are listed below, as well as the manner in which the Rascal mission will go about addressing them.

A summary of these risks, including each risk's likelihood and consequence, can be found in Section 5.2.5.6.

5.2.5.1 Chaser Spacecraft Unable to Locate Target Object

As discussed in Section 3.2 and Section 5.2.2.1, vast relative distances can develop between chaser and target objects in very short periods of time. This problem is compounded even more if one decides to go after an object that is already in orbit as opposed to one that is released from the same vehicle.

Thus, one way of alleviating this risk that has been attempted consists of launching both the target and chaser objects form the same spacecraft. However, as discussed in Section 3.2, this has not proven very successful. This is most likely due to the relatively long wait times associated with making first contact with and checking out any given spacecraft, which can take days or weeks. Hence, by the time said checkout is complete, and the mission is ready to begin, the target and chaser objects are already 2,000 km apart and incapable of ever achieving rendezvous ever again.

This problem can be alleviated by kicking both the target and chaser satellite out as a single unit, as opposed to two separate entities. This in turn allows for ground operators to make contact with and check out each satellite at the same time, and upon completing said process, initiate separation and begin the mission from a common starting point, thus reducing the risk associated with the two objects moving too far apart.

Hence, for the Rascal mission, it has been determined that it will consist of two separate spacecraft (Jade and Nephrite) that initially begin the mission attached to each other, as to alleviate the risk of losing the target object to the greatest extent possible (Though this does add the risk of spacecraft separation failure, as discussed in Section 5.2.5.1.1)

5.2.5.1.1 Spacecraft Separation Failure

If the Jade and Nephrite do not separate properly this upon being commanded, the entire Rascal mission is at risk of failure, as it would be extremely limited in its capabilities in such a state. To mitigate this risk, ground testing will be done to make sure the spacecraft separation mechanism is working properly. Such testing would include 2-axis low friction environment testing and potentially a weightless flight on a parabolic aircraft flight (AKA, the "vomit comet").

5.2.5.2 Propulsion System Failure

Though many RPO missions have been developed before, only one has been demonstrated within CubeSat architecture (SNaP-1). This means that not much flight data exists on the reliability and implementation of CubeSat propulsion systems, which in turn implies that any design work that goes into such a system will have to be rigorously scrutinized and tested. However, due to this lack of historical data, the best practices and margins of safety associated with a "good" CubeSat propulsion system will not be in place, leading to the development of uncertainty in the design and manufacturing of any system that is selected

Since the only means of achieving mission success are through the successful on-orbit operation of the propulsion system that is chosen, it is critical that this risk is accounted for by any means possible. The main method of accomplishing this, beyond conducting thermal, static thrust, vibration, shock, and bake-out testing on any design that is reached, would involve giving said propulsion design two chances to succeed by having each spacecraft utilize said design.

Hence, for the Rascal mission, both Jade and Nephrite will utilize the same propulsion system, as to increase the chances of meeting mission success by giving each satellite the opportunity to conduct the mission.

5.2.5.3 Collision between Target and Chaser

As documented by the NASA DART mission, it is possible for the target and chaser objects in RPO mission to collide, though unlikely. This risk can be mitigated through the rigorous testing of the navigation algorithms used to situate the target and chaser relative to each other, as well as through the use of differential GPS data (if possible) and inter-satellite communication to further refine this position data.

5.2.5.4 Run Out of Propellant before Mission Completion

As discussed in Section 5.2.2.1, timing is key in executing each of the orbital maneuvers involved with the Rascal mission. Thus, there is a certain risk involved with using too much propellant to execute one or more of the maneuvers listed in Section 3.2, resulting in the loss of propellant before mission completion. This risk has already been somewhat mitigated through the inclusion of two spacecraft with propulsion systems. It can be further mitigated through the simulation of all orbital scenarios through the use of mission planning software on the ground (Preliminary software for just such testing has already been made available by Dr. Swartwout through his work on the Bandit mission at Washington University in St. Louis).

5.2.5.5 Standard CubeSat Mission Risks

Though more specific risks to the Rascal mission (both developmental and mission related) exist, the ones listed in Sections 5.2.5.1 through 5.2.5.4 are the largest in both likelihood and consequence. Beyond those risks, however, there are inherent risks in the development on any CubeSat mission, as discussed in the following sections.

5.2.5.5.1 Loss of Communication

Upon reaching orbit, if communication were to be lost with the Rascal spacecraft, neither mission success verification nor initial separation of Jade and Nephrite could be achieved, resulting in mission failure. Mitigation of this risk would involve ground testing, such as vibration testing, as well as radio signal strength and ground station capability testing.

5.2.5.5.2 Spacecraft Unable to Generate Enough Power

If the Rascal power system browns out or does not have enough power to transmit data down to the ground, there would be no means of verifying mission success from the ground, the resulting in mission failure. Testing can be performed on solar panels by using a lighting system consisting of numerous full spectrum light bulbs that can replicate the suns conditions in space. Additional testing can be performed in the full function flight test with a completely integrated spacecraft with the same method. This will confirm correct power draw and use. The main means of alleviating this risk, however, would involve the

creation of an accurate power budget that reflects the amount of power necessary to run the satellite and the amount that can be generated by Rascal's solar arrays.

5.2.5.5.3 Deorbit Occurs Before Six Months Has Passed

As discussed in Section 5.2.3, the mission lifetime for the Rascal mission has been set at 6 months. Thus, before any launch is accepted, the orbit that can potentially be reached by the launch vehicle through he use of orbit prediction software (Such as STK or GMAT) as to ensure that said orbit will result in at least a 6 month lifetime.

5.2.5.5.4 Launch Vehicle Causes Component Failure

The main point of failure for any spacecraft is due to the vibrations and forces associated with its launch vehicle environment causing wire harness detachment or component failure. The best way to mitigate this risk is to subject Rascal to vibration testing specified by the launch vehicle that it is set to launch on. If such data is not available and testing needs to be conducted on component boards to determined the rigidity of their design, the NASA GEVS Standard Vibration Profile (As Shown in Figure 5-11) would be used in said testing's place. This standard was developed by NASA to cover the loads and vibrations associated with any currently available launch vehicle. Thus, the results obtained from it would translate directly to any testing expected of any launch service provider.

Frequency (Hz)	ASD Level (g^2/Hz)	
	Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

The acceleration spectral density level may be reduced for components weighing more than 22.7-kg (50 lb) according to:

	Weight in kg	Weight in lb	
dB reduction	$= 10 \log(W/22.7)$	$10 \log(W/50)$	
$ASD_{(50-800 \, Hz)}$	$= 0.16 \cdot (22.7/W)$	$0.16 \cdot (50/W)$	for protoflight
$ASD_{(50-800 \, Hz)}$	$= 0.08 \cdot (22.7/W)$	$0.08 \cdot (50/W)$	for acceptance

Where W = component weight.

The slopes shall be maintained at + and - 6dB/oct for components weighing up to 59-kg (130-lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 g^2/Hz at 20 and 2000 Hz.

For components weighing over 182-kg (400-lb), the test specification will be maintained at the level for 182-kg (400 pounds).
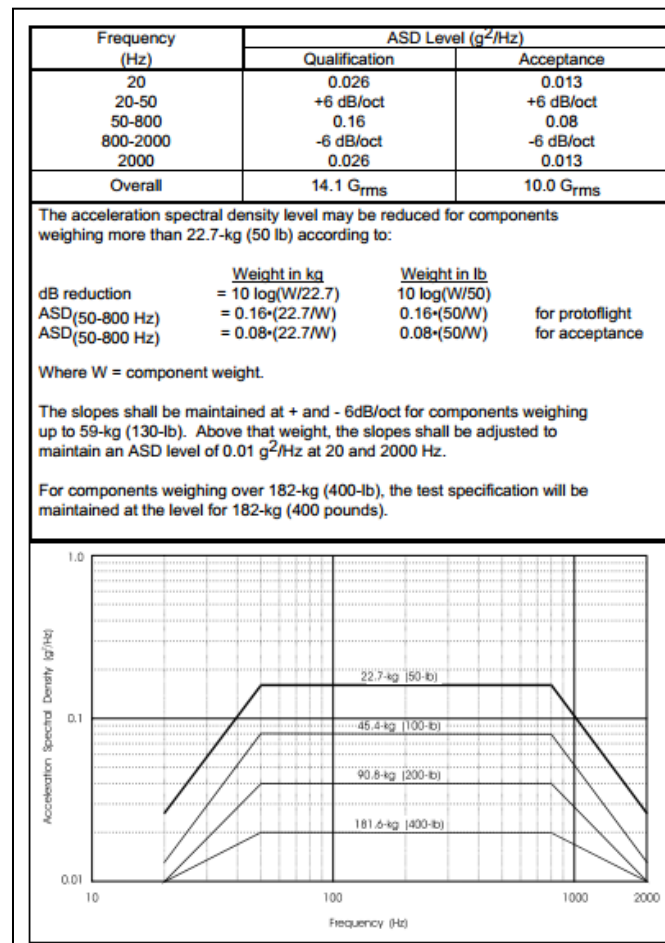
Figure 5-11. NASA GEVS Standard Vibration Profile

5.2.5.5.5 Damage from Radiation

Inherent in any spacecraft mission is the chance that a random burst of high energy radiation from the sun happens upon a spacecraft in orbit, causing immediate failure with no proper means of recovery. Beyond incorporating radiation-hardened components whenever possible, little can be done to fully mitigate this risk.

5.2.5.6 Risk Mitigation Summary

Table 5-2 and Figure 5-12 summarize each of the risks discussed above, as well as the likelihood and consequence of each of their occurrence.

Table 5-2. Rascal Mission Risk Summary

| Risk Number	Risk Description	Likelihood	Consequence
1	Loss of communication	2	5
2	Collision between spacecraft	3	3
3	Separation failure	3	2
4	Chaser spacecraft unable to locate target object	3	4
5	Spacecraft unable to generate enough power	2	3
6	Run out of propellant before mission completion	1	5
7	Deorbits before six months	1	5
8	Component failure during launch	2	4
9	Radiation damage	1	4
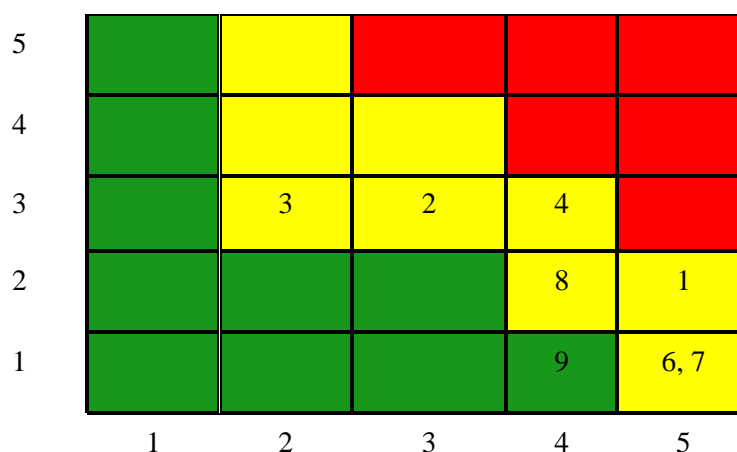
Figure 5-12. Table of Risk Consequence vs Likelihood

5.3 Requirements Verification Matrix

Requirement	Verification Method(s)				Rationale	Requirement Designation
	Test	**Analysis**	**Demo**	**Examine**		
Primary Requirements						
The Rascal mission will be executed by a spacecraft			x		RFP Requirement	RCL-RFP1
The mission must be capable of demonstrating station keeping within a 50 meter sphere of a resident space object for at least 5 orbits	x	x	x		RFP Requirement	RCL-RFP2
The mission must be capable of demonstrating a Collision Avoidance maneuver by intentionally increasing the relative distance between it and a relative space object to at least 100 meters within one orbit	x	x	x		RFP Requirement	RCL-RFP3
The mission shall be capable of demonstrating rendezvous by intentionally reducing the distance between it and a resident space object to at most 50 meters for at least 5 orbits	x	x	x		RFP Requirement	RCL-RFP4
A method of verifying the successful completion of each mission requirement shall be incorporated into the mission design and mission operations procedures	x	x	x		Mission Operations Requirement	RCL-MOP1
The mission shall be completed within 6 months of launch	x	x	x		Mission Operations Requirement	RCL-MOP2
Primary Sub-Requirements						
The spacecraft must be capable of determining relative distance between it and a resident space object	x	x	x		RCL-MOP1	RCL-MOP1-1
The spacecraft must be capable of recording relative distance between it and a resident space object	x	x	x		RCL-MOP1	RCL-MOP1-2
The spacecraft must be capable of relaying relative distance between it and a resident space object to the ground	x	x	x		RCL-MOP1	RCL-MOP1-3

Requirement	Verification Method(s)				Rationale	Requirement Designation
	Test	Analysis	Demo	Examine		
The spacecraft will utilize a Structures Subsystem	x	x	x	x	RCL-RFP1	RCL-RFP1-STR
The spacecraft will utilize a Propulsion Subsystem	x	x	x	x	RCL-RFP(2-4)	RCL-RFP-PRP
The spacecraft will utilize a Power Subsystem	x	x	x	x	RCL-MOP2	RCL-MOP2-PWR
The spacecraft will utilize an Attitude Determination and Control Subsystem	x	x	x	x	RCL-MOP1	RCL-MOP1-ADC
The spacecraft will utilize a Command and Data Handling Subsystem	x	x	x	x	RCL-MOP1	RCL-MOP1-CDH
The spacecraft will utilize a Communications Subsystem	x	x	x	x	RCL-MOP1	RCL-MOP1-COM
Structures Requirements						
The spacecraft will utilize the CubeSat standard architecture				x	Cost Constraint	RCL-STR-1
The mission will consist of two 3U spacecraft				x	Launch Vehicle Integration Constraint	RCL-STR-2
The two spacecraft must be able to integrate into the same dispenser			x		Risk Reduction	RCL-STR-3
The two spacecraft will be conjoined for integration into dispenser	x		x	x	Risk Reduction	RCL-STR-4
The two spacecraft will be capable of separating in orbit	x		x		RCL-RFP(2-4)	RCL-STR-5
Power Requirements						
The power subsystem will utilize an Electrical Power System to manager power distribution to each subsystem of the spacecraft				x	RCL-MOP2	RCL-MOP2-PWR1
The power subsystem will utilize a battery capable of powering each subsystem for the duration of the mission	x	x	x		RCL-MOP2	RCL-MOP2-PWR2
Attitude Determination and Control Requirements						
The ADC subsystem will be capable of autonomously commanding the propulsion system to perform the orbital maneuvers associated with the RFP requirements	x	x	x		RCL-MOP1	RCL-MOP1-ADC1
Propulsion Requirements						

Requirement	Verification Method(s)				Rationale	Requirement Designation
	Test	Analysis	Demo	Examine		
The propulsion subsystem will be capable of executing orbital maneuvers issued to it from the ADC subsystem	x	x	x		RCL-RFP(2-4)	RCL-RFP-PRP1
Communications Requirements						
The communication subsystem will utilize a radio for transmitting data to the ground	x	x	x		RCL-MOP1	RCL-MOP1-COM1
A link budget will be created that ensures that the power level, frequency, and altitudes over which the spacecraft transmits data are sufficient to produce a signal to noise ratio on the ground that is greater than one		x			RCL-MOP1	RCL-MOP1-COM2
Command and Data Handling Requirements						
The Command and Data Handling subsystem will be capable of managing the operation of each subsystem of the spacecraft, as well as the communication of data between said subsystems	x	x	x		RCL-MOP1	RCL-MOP1-CDH

5.4 Requirements Verification Matrix Run-Down

5.4.1 Primary Requirements

The primary requirements consist of those that, if any one of them is not met, the Rascal mission as a whole is considered a failure. As such, these requirements are the starting point for all design decisions made with respect to meeting the Rascal mission criteria and help determine all of the requirements that fall under them.

5.4.1.1 RCL-RFP1: *"The Rascal mission will be executed by a spacecraft"*

This requirement stems from both the Team Bravo RFP, which dictates that its proposed mission shall demonstrate proximity operations, which can only be demonstrated in space, and the need for said mission to prove relevance to NASA's strategic objectives, as discussed in Section 3.1. Regardless, it is not possible for proximity operations to be demonstrated outside of the space environment, making it absolutely necessary that the mission is performed through the use of a spacecraft.

This requirement will be verified through demonstration that the mission is capable of flying in space.

5.4.1.2 RCL-RFP2: *"The mission must be capable of demonstrating station keeping within a 50 meter sphere of a resident space object for at least 5 orbits"*

This requirement is specifically defined in the Team Bravo RFP and restated in Section 4.2. It is an essential demonstration of mission success and will be verified through analysis, testing, and demonstrations.

5.4.1.3 RCL-RFP3: *"The mission must be capable of demonstrating a collision avoidance maneuver by deliberately increasing the relative distance between it and a resident space object to at least 100 meters within one orbit"*

This requirement also stems directly from the Team Bravo RFP and is restated in Section 4.2. It is an essential demonstration of mission success and will be verified through analysis, testing, and demonstrations.

5.4.1.4 RCL-RFP4: *"The mission must be capable of demonstrating rendezvous by intentionally reducing the relative distance between it and a resident space object to at least 50 meters for at least 5 orbits"*

This requirement also stems directly from the Team Bravo RFP and is restated in Section 4.2. It is an essential demonstration of mission success and will be verified through analysis, testing, and demonstrations.

5.4.1.5 RCL-MOP1: *"A method of verifying the successful completion of each mission requirement shall be incorporated into mission design and mission operations procedures"*

This requirement finds its origin in Section 5.2.4, which states that without mission success verification, there is no reason in flying the mission at all. This requirement will be verified through analysis, testing, and demonstrations.

5.4.1.6 RCL-MOP2: *"The mission will be completed within 6 months of launch"*

This requirement stems from the need to limit the risk associated with RPO missions, as discussed in Section 5.2.2.1 and studied in Section 3.2. This requirement will be verified through analysis, testing, demonstration, and examination.

5.4.2 Primary Sub-Requirements

These requirements consist of those that stem directly from the primary requirements listed in the previous sections. It is here that the subsystems necessary for the design of the Rascal mission are determined, as well as the methods of mission success validation are defined.

5.4.2.1 RCL-MOP1-1: *"The spacecraft must be capable of determining the relative distance between it and a resident space object"*

This requirement stems off of requirement RCL-MOP1, in that it is the first step in determining the success of the Rascal mission as a whole. This requirement helps determine the type of systems required to execute the Rascal mission (Such as GPS tracking, visual imaging, or some combination of the two) , as well as offers a simple, concrete guideline for approaching the determination of mission success. It will

be verified through analysis (Determining the type of system capable of finding such information), testing (making sure it can survive launch) and demonstration (showing that it works).

5.4.2.2   RCL-MOP1-2: *"The spacecraft must be capable of recording relative distance data between it and a resident space object"*

This requirement also finds its origin in requirement RCL-MOP1, in that it is the second step in determining the success of the Rascal mission as a whole. Without the ability to conduct the entire mission within one 15 minute pass, while simultaneously transmitting the data discussed in the previous section to the ground in real time, it is absolutely necessary that the relative distance data calculated by the spacecraft is stored for later use. Otherwise, there would be no way of verifying that the mission ever took place. Thus, this requirement will be verified in the same manner as the previous one, through testing, analysis, and demonstration.

5.4.2.3   RCL-MOP1-3: *"The spacecraft must be capable of relaying relative distance data between it and resident space object to the ground*

This requirement is the final step in determining the success of the Rascal mission as a whole, and thusly stems from Requirement RCL-MOP1. Even if the spacecraft is capable of calculating and recording relative distance data, if it has no means of transmitting said information to a user on the ground, there is no way that mission success would ever be able to be verified. This requirement will be verified in the same manner as the previous requirement, through testing, analysis, and demonstration.

5.4.2.4   RCL-RFP1-STR: *"The spacecraft will utilize a Structures subsystem"*

This requirement stems from Requirement RCL-RFP1, in that it is a necessary part of any spacecraft mission. The type of structure that a spacecraft uses determines the type of adapter that it can utilize (As Discussed in Section 5.2.2.1), as well as the manner in which each other subsystem of the spacecraft interacts with each other. This requirement will be verified though all four available verification methods, as it will involve vibration testing to assess its integrity, dimensions checks to verify its launch vehicle integration capabilities, analyses to determine its center of mass and moments of inertia, and demonstrations to show its compliance to spacecraft standards.

5.4.2.5   RCL-RFP-PRP: *"The spacecraft will utilize a Propulsion subsystem"*

This requirement stems from the fact that in order to perform orbital maneuvers, it is necessary to utilize a propulsion system. This requirement will be verified though the same methods as described in the previous section.

5.4.2.6   RCL-MOP2-PWR: *"The spacecraft will utilize a Power subsystem"*

This requirement comes from the need to survive in orbit for at least 6 months, as defined by Requirement RCL-MOP2. Without a power system, each other subsystem on the spacecraft would have no means of operating, thus preventing full mission success from being achieved. This requirement will be verified in the same manner discussed in the previous section.

5.4.2.7 RCL-MOP1-ADC: *"The spacecraft will utilize an Attitude and Determination System"*

This requirement stems from the need to verify mission success and is the heart of providing the relative distance values discussed in sections 5.4.2.1-5.4.2.3. It will be verified in the same manner discussed in those sections.

5.4.2.8 RCL-MOP1-CDH: *"The spacecraft will utilize a Command and Data Handling subsystem"*

This requirement stems from the need to handle the information necessary to both operate the spacecraft and determine mission success. It will be verified in the same manner as discussed in the previous section.

5.4.2.9 RCL-MOP1-COM: *The spacecraft will utilize a Communications subsystem"*

This requirement derives itself from the need to transmit data related to mission success to the ground. It will be verified in the same manner discussed in the previous section.

5.4.3 Structures Requirements

Structures requirements relates to those that define the constraints and goals of the structures system as a whole. These include the need to be integrated into a launch vehicle, to utilize two spacecraft to accomplish mission success, etc.

5.4.3.1 RCL-RFP1-STR1: *"The spacecraft will utilize a CubeSat architecture"*

This requirement stems from the discussion of spacecraft architecture that took place in Sections 5.2.1.1-5.2.1.4. The ultimate decision reached at the conclusion of these discussions was that a CubeSat mission would better facilitate launch opportunities for the Rascal mission, making it much more likely to reach orbit than it would otherwise. This requirement will be verified through examination (to ensure that its dimensions fall under those dictated for CubeSat design) and demonstration (verifying that said design can successfully integrate into an available deployer).

5.4.3.2 RCL-RFP1-STR2 "*The mission will consist of two identical 3U spacecraft"*

This requirement stems for the risk mitigation discussion of Section 5.2.5.1, as well as the volume constraint discussion listed in Section 5.2.3. Verification of this constraint will involve examination (visual inspection to ensure components between each CubeSat are identical).

5.4.3.3 RCL-RFP1-STR3: *"The two spacecraft must be able to integrate into the same dispenser"*

This requirement stems from the risk mitigation discussion of Section 5.2.5.1, which listed discussed the relative ease with which previous RPO missions had drifted apart before even being able to begin their primary missions. This requirement will be verified through demonstration that each spacecraft can integrate into the same dispenser.

5.4.3.4 RCL-RFP1-STR4: *"The two spacecraft must be conjoined prior to dispenser integrations"*

This requirement stems from the same discussion listed in the previous section and will be verified in the same way.

5.4.3.5 RCL-RFP1-STR5: *"The two spacecraft will be capable of separating in orbit"*

This requirement stems from the need to execute to mission upon actually reaching orbit. It will be verified through testing on the ground, as well as through analysis and demonstration.

5.5 Power Requirements

Power requirements consist of those that contribute to the definition of the components that will constitute the Rascal power system, as well as the manner in which power will be dissipated to each subsystem of the spacecraft.

5.5.1.1 RCL-MOP2-PWR1: *"The power subsystem will utilize and electrical power system to manage power distribution to each subsystem of the spacecraft"*

This requirement stems from to need for an energy storage device to serve as the spacecraft's primary power provider and manage the allotment of charge to each subsystem of the spacecraft. This requirement will be verified through inspection, as it only refers to the use of such a system, not its capabilities.

5.5.1.2 RCL-MOP2-PWR2: *"The power subsystem will utilize a battery capable of providing power to each subsystem for the duration of the mission"*

This requirement derives itself from the need for the Rascal mission to occur over a period of six months. As such, no currently available COTS battery system is capable of maintaining a charge for such a long period of time, meaning that a means of recharging said battery system must also be incorporated into the spacecraft's power subsystem. Based on previous mission experience and previous mission data, the best and simplest way to meet this goal is through the use of body mounted or deployable solar panels. Regardless, this requirement will be verified through analysis (As determined by a power system budget), testing (Ensuring that the system, when operating in each of its functional states, has a net positive power margin) and demonstration.

5.6 Attitude Determination and Control Requirements

Attitude Determination and Control Requirements (ADC) relate to defining the requirements associated with the pointing control and navigation of the spacecraft.

5.6.1.1 RCL-MOP1-ADC1: *"The ADC subsystem will be capable of autonomously commanding the propulsion subsystem to perform the orbital maneuvers associated with the RFP requirements"*

This requirement stems from the first 3 RFP requirements RCL-RFP1, RCL-RFP2, and RCL-RFP3. This will be verified with a demonstration to show that the ADC system will be capable of performing all that is required of it while on orbit. There are several systems available to use for ADC and an in depth trade study will have to be performed to determine which system or combination of systems will have to be used.

5.7   Propulsion Requirements

5.7.1.1 RCL-RFP-PRP1: *"The propulsion subsystem shall be capable of executing orbital maneuvers commanded of it by the ADC subsystem"*

This requirement derives itself directly from the need for the mission to take place when Rascal is beyond the contact of operators on the ground. This means that the propulsion system has to be capable of accepting command information from the ADC system and perform the corresponding orbital maneuvers associated with said data input. This requirement will be verified through analysis (on-ground navigation software development) and testing (Low Friction 2-D or Static Fire Thrusting).

5.8   Communication Requirements

Communications requirements relate to defining those associated with the transmission of data collected by the spacecraft to the ground. As such, it helps define the type of system that will be utilized to accomplish this, as well as the necessary power levels and data rates to achieve mission success.

5.8.1.1 RCL-MOP1-COM1: *"The communications subsystem will utilize a radio for transmitting data to the ground"*

This requirement stems from requirement RCL-MOP1, in that it is a method of verifying the successful completion of each mission requirement. This requirement will be verified through a demonstration of the subsystem's capabilities.

5.8.1.2 RCL-MOP1-COM2: *"A link budget will be created that ensures that the power level, frequency, and altitudes over which the spacecraft transmits data are sufficient to produce a signal to noise ratio great enough to maintain a continuous link with a station on the ground"*

This requirement stems from the previous subsystem requirement. It will be verified through an analysis of the budget.

5.9   Command and Data Handling Requirements

Command and Data Handling requirements relate to the handling of data collected by the spacecraft and the management of said data between each subsystem of the spacecraft as a whole.

5.9.1.1 RCL-MOP1-CDH1: *"The Command and Data Handling subsystem will be capable of managing the operation of each subsystem of the spacecraft, as well as the communication of data between said subsystems"*

The requirement comes from the RCL-MOP1, which states the need for a method for verifying mission requirements on-orbit. This requirement is verified through analysis by constructing an accurate data budget with a positive margin, and through testing by performing command and day-in-the-life tests.

6   System Overview

Three configurations were considered for the Rascal mission. The first configuration considered is one 6U spacecraft. It would carry one propulsion system and find a resident space object to perform the mission with. It was considered because this is the largest CubeSat that has a deployer available. This configuration requires a method of tracking that is not available to Saint Louis University. If space object cannot communicate with Saint Louis University it will not be able to separate itself from the other space

objects, requiring ground based radar and visual tracking. If the rocket body that carried Rascal up were to be imaged, that would require the permission of the launch service provider, which they might not be willing to provide. The system does allow for more power available and slightly more propellant storage, but tracking another spacecraft that is not from Saint Louis University puts this configuration outside of this group's capabilities.

The second configuration considered was that of one 3U with a propulsion system and another 3U without propulsion. As described in Section 3.2 and Section 5.2.2.1, it can be seen that it is easy to get separated far away from the other spacecraft, so the spacecraft would be deployed conjoined to prevent separate before the mission can start. A 3U was selected because as stated in section 5.2.2.1, the propulsion unit will take about 1U and as stated in section 5.2.2.2, the power subsystem, radio subsystem, and the CDH subsystem will take up at least another 1U of space. This leaves 1U of space left for the ADC system and essentially prohibits the use of any small CubeSat architectures.. The passive spacecraft would be a 3U as well to prevent the other spacecraft or object that would be put in the empty space left if it was not a 3U from getting caught in that space and interfering with the mission. Also this entire space would likely be made available to the Rascal mission and making the passive spacecraft a 3U would maximize the space available.

The last configuration considered was two 3U's (Jade and Nephrite) that each have their own propulsion units. As stated for the active-passive configuration, they would be conjoined prior to launch vehicle integration, as to prevent large distances from developing between the two spacecraft. They would each be 3U-sized for the same reasons discussed in the previous paragraph. Having two propulsion systems allows for increased redundancy, if one spacecraft fails there is another one available to complete the mission. It also shows the mission is reproducible, if one spacecraft does the mission and then the other spacecraft performs it as well it demonstrates the mission was not a fluke.

After analyzing the possible configurations, the active-active configuration was selected. From the Mission History it can be seen that it is easy to lose a spacecraft that is not under control. While the active passive configuration has its benefits, risk mitigation is important as well and an active-active configuration offers the chance to reduce the distances that would build up between the two spacecraft, this is discussed in greater detail in section 5.2.5.1. Two spacecraft allows the mission to be repeated again with a different spacecraft. Having two propulsion systems increases complexity, but it also increases the chance of success.

7   Subsystem Overview

7.1   *Structure*

The structure subsystem is responsible for containing the spacecraft and providing support and protection to the components as to prevent damage during use. The subsystem consists of the exoskeleton, screws, nuts, bolts, clips, rods, and any object necessary for securing the spacecraft.

The exoskeleton is the backbone of the spacecraft and can be made of, and is in the shape of whatever is necessary to support the components of the spacecraft. There is however, a requirement of the launch provider that it fits in the deplorer and the spacecraft is no more than 12kg or 14kg depending on said deplorer. It is because of this that it is nominally standard to select the CubeSat shaped exoskeleton as defined by the CubeSat standard. The standard CubeSat can be purchased from numerous commercial vendors. The material however can still be put into question. The nominal material from commercial

vendors is Aluminum 6061-T6, which under nominal circumstances is appropriate. However, other materials are being explored. Applicable materials are stated by NASA launch requirements.

The nuts, bolts, and assembly components are nominally stainless steel, as it is lightweight and sturdy. Zinc which is also common in nuts and bolts must not be used as stated by NASA material requirements.

7.2   Power

The power subsystem is responsible for generating, storing, managing, and distributing the energy required to conduct the Rascal mission. The subsystem consists of batteries, solar arrays, and any circuitry necessary to operate the subsystem.

The spacecraft's batteries serve as the primary power source. Historically, CubeSats have used lithium-polymer batteries over more traditional nickel-cadmium batteries for energy storage because of the relative light weight and small volume combined with their high energy density of lithium-polymer. CubeSat architecture lithium-polymer batteries are available from commercial vendors at various capacities, with a standard 1U battery holding a 10 watt-hour charge. Many commercially available CubeSat batteries come integrated with an Electrical Power System board.

The Electrical Power System (EPS) serves to manage the power flowing to and from the batteries, connecting to both the spacecraft bus and the solar arrays. The EPS must provide over-current against a short circuit and under-voltage protection to prevent a complete discharge of the batteries. The EPS should also include a number of Battery Charge Regulators (BCRs) that regulate the incoming voltage and current from the solar arrays to the batteries, maximizing the efficiency of the battery charging cycle. The EPS must also be able to relay battery and solar array health data to the Command and Data Handling subsystem.

The spacecraft must be able to generate power to recharge the batteries. While there are several methods of doing this, the most practical is to mount a system of solar arrays to the spacecraft's exterior. Commercial CubeSat solar arrays can come in a variety of sizes, configurations, and generation capacities. The simplest of the 3U CubeSat-scaled arrays are static panels, though deployable arrays are also available. Though deployable arrays generate significantly more power, it comes at the cost of increased complexity, and thus, risk of failure.

Work to be done before the next review process include refining the power budget for different solar panel array configurations, selecting an EPS and battery capable of handling the voltages associated with the best solar panel configuration derived from this analysis, and then determining the manner in which such systems can be integrated into the Rascal mission as a whole.

7.3   Attitude Determination and Control

The Attitude Determination and Control (ADC) subsystem is responsible for determining the orientation and position of the spacecraft relative to the other spacecraft as well as issue commands to the Propulsion subsystem to execute orbital maneuvers.

Attitude determination can be accomplished using several methods. Sun and star trackers use external cameras to determine a spacecraft's orientation based on the observed positions of the sun and or constellations. Gyroscopes and accelerometers can be used to determine the roll rates of a spacecraft. A GPS receiver can be used to determine the relative locations of the spacecraft in their orbits. Component selection will depend heavily on the volume, cost, and power constraints.

Similar to attitude determination, control over the spacecraft's orientation can be accomplished through several methods, and which is ultimately selected depends on the volume, cost, and power constraints. Reaction wheels use the torque generated from a rotating mass to precisely align the spacecraft along the desired vector; but are mechanically complex, expensive, and power intensive to use. Magnetorquers use

current running through coils of wire to interact with the Earth's magnetic field, providing the force necessary to orient the spacecraft. However, the Earth's magnetic field is not constant across its surface and also varies due to changes in solar output, introducing a degree of uncertainty into the process.

7.4 Propulsion

The propulsion subsystem consists of the propulsion units that will be used to perform the orbital maneuvers defined in Section 4.2, as well as the controller boards that will be used to manage the data being inputted into the system from ADC. Based on the analysis discussed in Section 5.2.2.1, a preliminary idea has been made of the size necessary for each of these propulsion systems to occupy within each spacecraft of the Rascal mission.

Beyond this, work to be done over the next semester involves drafting a specific orbital maneuver plan, as to more strictly define the maneuvers associated with executing the mission. Other work includes determining the number of thrusters necessary to have full 6-Degree of Freedom control over each spacecraft, as well as the orientation methods that can be used to accomplish said goal.

7.5 Communications

The communication subsystem provides a method of verification for the completion of each mission requirement. It also provides a way to maintain communication with the spacecraft. Data that could be relayed by the communication subsystem is relative distances, relative velocities, and spacecraft health. The subsystem would consist of a radio board to generate the signals and antennas to broadcast the signals, as well as any cables need to connect the board to the antennas.

There are several requirements that go into selecting a radio. The baud rate is a major factor because if a faster baud rate is desired then a higher frequency radio would be needed. In order to have a good signal-to-noise ratio to meet requirement MOP1-COM2 the radio will have to have a high radio frequency output to overcome background noise. Altitude will also affect the signal-to-noise ratio, so that will have to be considered when selecting a radio.

7.6 Command and Data Handling

The Command and Data Handling (CDH) subsystem is responsible for making on-orbit decisions, processing health sensor data, and managing data during downlink. For CubeSats, there are several different flight computer and operating system commercial options available. Most notable is the CubeSat Kit, which includes a CubeSat standard motherboard with one of various processor daughterboards available and software tools for writing an operating system.

The spacecraft's operating system is responsible for all software tasks built on to the spacecraft. Tasks can vary in complexity, ranging from activating deployables such as antennas or solar arrays to preparing and downlinking data to the ground.

7.7 Ground Operation

The ground operations will provide support for the Rascal mission on the ground. It will provide a method of verification for the completion of each mission objective. The ground station will have radio and antennas so as to maintain link with the Rascal as it passes overhead.

8 Schedule

Listed below is the schedule that was followed for mission development this semester, as well as that will be followed over the next.