Rascal: A Demonstration of Rendezvous and Proximity Operations within a Small Spacecraft Architecture

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The Rascal mission consists of the demonstration of rendezvous and proximity operations within small spacecraft architecture. Spacecraft RPO missions are defined as those that demonstrate the performance of orbital maneuvers near and around resident space objects (RSO), such as rocket bodies, orbital debris, or other spacecraft, while a small spacecraft architecture is defined as one that utilizes a standard satellite configuration and size that allow for rapid development and launch vehicle integration. In recent years, many RPO missions have been conducted, such as NASA's DART, DARPA's MiTEx, and Orbital Science's Orbital Express, each to varying degrees of success. Regardless of the program, each of these RPO missions consisted of large spacecraft (100 kilograms and up) that were developed with an equally large amount of capital, resources, and effort. Rascal, on the other hand, seeks to demonstrate similar RPO missions within an architecture that can be developed at a university-level while still capable of demonstrating key RPO capabilities, such as stationkeeping (maintaining a set distance between two RSO's), collision avoidance (rapidly increasing the distance between two RSO's), and rendezvous (moving two RSO's within a set distance of each other). Furthermore, these types of demonstrations have been recently highlighted by NASA as key areas of interest in the future development of intelligent spacecraft systems, meaning that the systems developed to make the Rascal mission possible can be easily transitioned to the greater aerospace community as a whole for use in future commercial or academic RPO missions. As such, the Rascal mission is critical to the further refinement and understanding of spacecraft RPO capabilities within the ever-changing small spacecraft landscape.

Nomenclature

RPO	=	Rendezvous and Proximity Operations
RSO	=	Resident Space Object
ISK	=	Inspection Stationkeeping
RSK	=	Remote Stationkeeping
CONOPS	=	Concept of Operations
P-POD	=	Poly-Picosatellite Orbital Deployer
NLAS	=	Nanosatellite Launch Adapter System
CSD	=	Canisterized Satellite Dispenser
NASA	=	National Aeronautics and Space Administration
ELaNa	=	Educational Launch of Nanosatellites
AFRL	=	Air Force Research Lab
UNP	=	University Nanosat Program
AS&IS	=	Advanced Space & Intelligence Systems
DART	=	Demonstration for Autonomous Rendezvous Technology
DARPA	=	Defense Advanced Research Projects Agency
MiTEx	=	Micro-satellite Technology Experiment

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[1] Command and Data Handling Engineer
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DOF	=	degrees of freedom
ADC	=	attitude determination and control
km	=	kilometers
km/s	=	kilometers per second
PWR	=	power
UHF	=	ultra high frequency
dB	=	decibel
MHz	=	megahertz
kbps	=	kilobits per second
GHz	=	gigahertz
Mbps	=	megabits per second
*W*hr*	=	Watt hours

I. Introduction

THE Rascal mission consists of the demonstration of rendezvous and proximity operations (RPO) within a small spacecraft architecture.

Spacecraft RPO missions are defined as those that demonstrate the performance of orbital maneuvers near and around resident space objects (RSO), such as rocket bodies, orbital debris, or other spacecraft. Examples of such orbital maneuvers consist of stationkeeping, collision avoidance, and rendezvous, with stationkeeping defined as a spacecraft remaining within a set relative distance of an RSO, collision avoidance as quickly increasing the relative distance between a spacecraft and an RSO, and rendezvous as decreasing the relative distance between a spacecraft and an RSO.

A small spacecraft architecture is one that utilizes a standard satellite configuration and size that allows for rapid launch vehicle integration, which in turn reduces the costs associated with securing a launch and increases the likelihood of a given mission to reach orbit. Examples of small spacecraft architectures that meet this definition are the CubeSat and Microsatellite-Classes of spacecraft, with the former having a more well-defined and rigorous meaning than the latter. For example, a CubeSat is defined as a spacecraft that consists of some combination of standard unit volumes, with a 1U being a 10cm x 10cm x 10cm cube, 2U being a 10cm x 10cm x 20cm rectangular prism, and so on. This, along with several other well defined specifications, has allowed for the development of standard launch vehicle adapters (such as the P-POD, NLAS, and CSD adapters), as well as the emergence of organizations that are willing to fund CubeSat launch opportunities, such as NASA's Educational Launch of Nanosatellites (ELaNa), the AFRL's University Nanosat Program (UNP), and Boeing's Advanced Space & Intelligence Systems (AS&IS) group. Microsatellites, on the other hand, have little to no standard specifications beyond the fact that they remain under 100 kilograms (though even this specification is disregarded in certain cases). This has prevented the development of standard adapter systems for Microsatellites, meaning that a microsatellite has to be designed with a particular launch vehicle in mind, whereas a CubeSat design is launch vehicle independent. This difference in ease of integration manifests itself in the launch costs for CubeSats versus those of Microsatellites, with the former costing $50 thousand and the latter $2 million on average. Thus, any mission that seeks to use microsatellite architecture, whether for increased payload capacity or extended mission lifetime, will do so at the risk of never actually reaching orbit.

With these definitions in mind, we can now go into greater detail as to what will constitute as a demonstration of an RPO mission within a small spacecraft architecture with respect to the Rascal mission, as well as the way in which Rascal will go about achieving such a demonstration.

II. Mission Overview

With the previous section in mind, as well as the lessons learned from previous RPO missions, the objective of the Rascal mission can be stated as follows: **The Rascal mission seeks to incrementally demonstrate the capability of a small-spacecraft in performing proximity operations, rendezvous, and inspection of both a cooperating and non-cooperating resident space object**. The reasons for selecting such a mission, as well as for limiting its execution to the realm of small spacecraft, relate to past missions that have attempted to demonstrate RPO missions, with varying success (and cost), as well as current areas of interest in the future of spacecraft mission development and execution, as described in the following sections.

A. RPO Mission History

RPO missions have a long history in human spaceflight, dating back to the first Gemini missions. It was not until the previous decade that interest arose in approaching RPO missions with purely autonomous 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. 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, developed by the Orbital Sciences Corporation for NASA in 2005, with the mission goal consisting of the demonstration of autonomous navigation and rendezvous capabilities on a microsatellite platform, specifically related to an attempt to dock with an experimental communication satellite. The primary objectives of the mission were to navigate autonomously using GPS and to rendezvous using an Advanced Video Guidance Sensor. Within a few hours of launch, it was able to reach its target, but it experienced a malfunction as it began its approach, resulting in a soft collision between it and the target vehicle, resulting in NASA's termination of the mission. Though not publically released, this 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 second of these is *Orbital Express*, which was developed by Boeing and Ball Aerospace and managed by the Defense Advanced Research Projects Agency *(*DARPA*)* and the Marshall Spaceflight Center. The Orbital Express sought 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 at a cost of $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.

The final of these is 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, were designed 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.

From these examples, as well as those of numerous other RPO missions that have previously flown, missions of this nature are difficult or next to impossible for universities to successfully develop, so knowing how to limit the scope of university-level RPO missions is important in determining their ultimate success. The requirement that Rascal consist of a demonstration of RPO between two *small* spacecraft stems from this fact. But why do we care about RPO missions at all?

B. Mission Relevance

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 RPO mission seeking to demonstrate operations that have not been performed on a system of equal scale, the Racal mission meets both the requirements of a mission that demonstrates critical technologies, while doing so through the use of an affordable spacecraft system. As such, missions such as Rascal's are highly desirable from a NASA development perspective, the reason for this resting 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.

C. Concepts of Operation

1. Introduction

Though there are many other missions attempting to demonstrate similar or greater capabilities as those outlined in the Introduction (Such as Tyvak's PONSFD, Surrey's STraND-2, and Embry-Riddle's ARAPAIMA), Rascal is the only mission that has taken seriously the challenges associated with conducting rendezvous and proximity operation (RPO) missions of any scale and actually integrated a realistic assessment of program capability directly into its mission design.

It is from this assessment where the "incremental" part of the mission statement comes in. As opposed to seeking out another spacecraft on the same launch or going after a decommissioned spacecraft that is already in orbit, hoping that spacecraft acquisition and checkout occurs fast enough for the mission to actually be performed, Rascal will bring with it the target it seeks to perform its mission relative to. This alleviates the many risks associated with the "initial conditions" problem of orbital analysis and planning. Instead of attempting to account for the impact of perturbation forces (mainly, aerodynamic drag, third-body influences, solar-radiation pressure) on two spacecraft released at slightly different times in slightly different locations, and hoping that these initial conditions match up in a way that allow for the mission to be quickly executed, one can eliminate all the uncertainty and not start the mission until contact has been confirmed between each mission spacecraft and the ground. This allows for a more precise understanding of both where and when the mission is actually starting, which greatly increases the odds of its ultimate success.

As such, regardless of the way in which the mission will be executed, several components of the overall mission architecture will be fixed, mainly:

1) **The Target spacecraft will be brought with the Interceptor**: this removes the risk of securing permission to go and inspect either another organization's spacecraft or a company's rocket body (as has been done in the past), as well as that of finding an object to perform inspection of.
2) **The Target and Interceptor will be conjoined up until mission commencement**: this removes the problem of "initial conditions", giving the mission operators greater control over the mission as a whole.
3) **The mission will be conducted "incrementally"**: this attests to the difficulties that past RPO missions have encountered over the course of their mission life, as well as realistically assesses the risks associated with RPO missions of any scale. An example of this would be performing the mission in steps, first inspecting a cooperating resident space object (with image processing visual aids, differential GPS, etc), and then incrementally removing the cooperating portions of the mission until enough confidence could be put into demonstrating inspection on a non-cooperating resident space object.

With the discussion in the previous section in mind, two general CONOPS can be drafted that are capable of demonstrating mission success:

1) **RPO Demonstration without Docking**
2) **RPO Demonstration with Docking**

The former would still demonstrate key RPO maneuvers, such as the ability to stationkeep at various distances from a resident space object, to rendezvous with said object, and to inspect said object through the use of image processing, thus warranting its launch. The latter would demonstrate all of the same maneuvers, with the added complexity of integrating a reusable docking system and the more complicated orbital mechanics related therein. Though this would allow for the ability to "pause" the mission (for example, if midterms are coming up for student operators, the target and interceptor spacecraft can be docked until some date, at which point separation can be initiated and the mission can recommence), it also adds developmental risk (greater focus being put on developing a docking mechanism, as opposed to payload or mission design), as well as mission risk (colliding at too great a speed, missing the target, damaging the imaging payload, etc). The pros and cons of each of these CONOPS will be discussed in greater detail in Section D.

Regardless, each mission CONOPS will rely on similar terminology and mission phases, as described below:

1) **Target Spacecraft:** spacecraft about which all RPO maneuvers would be performed.
2) **Interceptor Spacecraft**: spacecraft with which all RPO maneuvers would be executed.
3) **Fully Cooperative State**: target spacecraft state in which all interceptor RPO aids (such as image processing aids, differential GPS, etc) are active.
4) **Semi-Cooperative State**: target spacecraft state in which some (but not all) interceptor RPO aids are active.
5) **Uncooperative State**: target spacecraft state in which no interceptor RPO aids are active.
6) **Stationkeeping**: keeping a set relative distance between the target and interceptor spacecraft while maintaining as small a relative velocity as possible.
7) **Inspection Stationkeeping (ISK)**: stationkeeping within 10 meters of the target spacecraft.
8) **Remote Stationkeeping (RSK)**: stationkeeping at least 100 meters away from the target spacecraft.
9) **Rendezvous**: the act of reducing the relative distance between the target and interceptor spacecraft.
10) **Separation**: the act of increasing the relative distance between the target and interceptor spacecraft.

11) **Docking**: the act of conjoining the target and interceptor spacecraft after separation (only occurs during cooperative state).
12) **Pause State**: mission state in which the target and interceptor spacecraft are docked due to mission timing constraints.
13) **Uncooperative Mission Timer**: timer that is set prior to the uncooperative portions of the mission that, upon running down, forces the target spacecraft into its cooperative state.

2. CONOPS-1: RPO Demonstration without Docking

Figure 1 shows a general overview of CONOPS-1. The defining feature of this CONOPS is that it is done in a very incremental fashion, allowing at various points for payload performance assessment, as well as for mission alteration (such as the ability to update RPO algorithms based on in-orbit observation, as opposed to relying solely on ground testing and predictions).

Thus, after initial launch, launch vehicle ejection, and checkout, the mission can be broken down into three primary phases, each of which repeat the same mission with different amounts of aid from the target spacecraft. Mission success would be defined by meeting the first phase of the mission (RPO and Inspection Performance relative to a Cooperating Target Spacecraft), with the completion of the remaining two mission phases being contributing to secondary mission success.

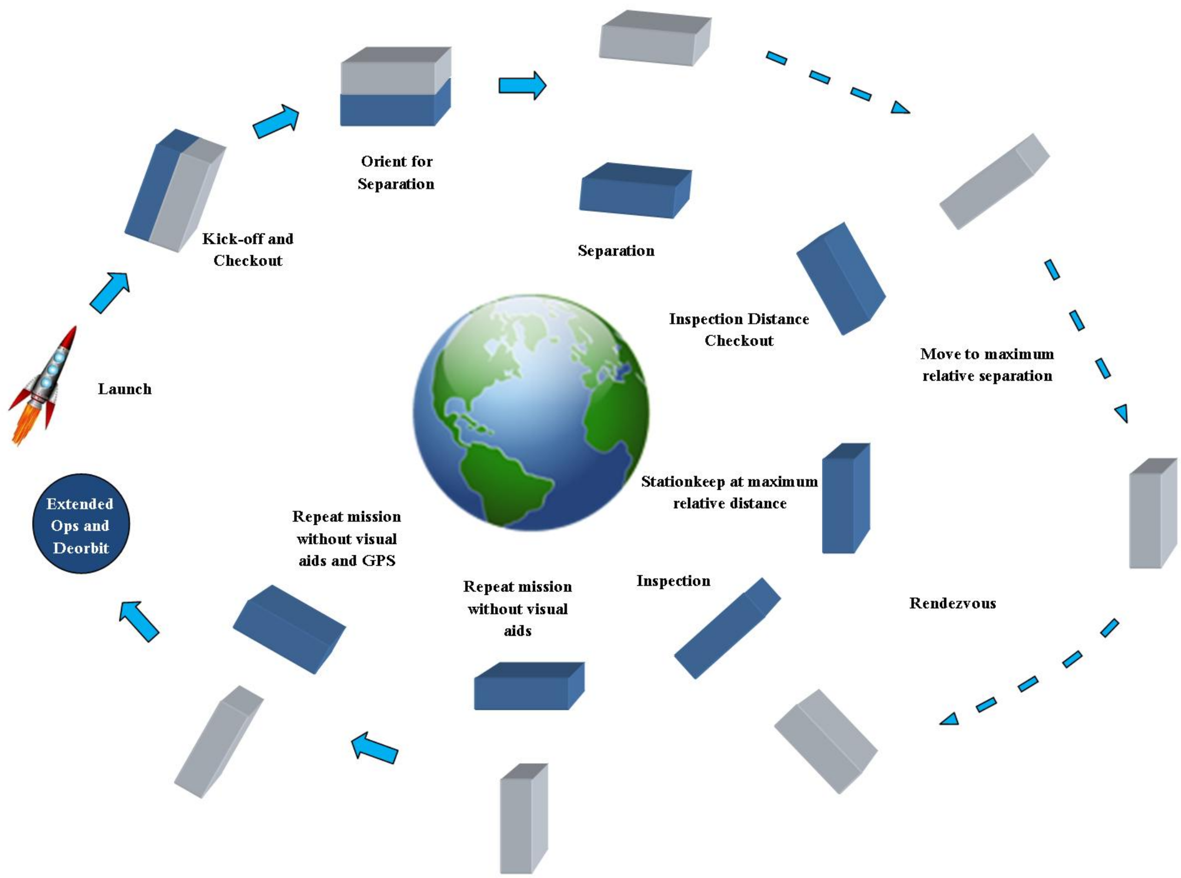


***Figure 1- CONOPS-1 Illustration*.** The Concept of Operations for the Rascal mission without docking consists of several distinct phases, mainly: Initial Separation, Imaging Payload Checkout, Continued Separation, Remote Stationkeeping, Rendezvous, and Inspection Stationkeeping. It also has three overlying states: Cooperative, Pseudo-Cooperative, and Uncooperative.

1) **Phase 0: Launch to Checkout**

Phase 0 of the mission consists of all of the standard processes that define the beginning of any spacecraft mission: Launch, Launch Vehicle Ejection, Spacecraft Power-On, Ground Acquisition, and Checkout. Each of these stages is laid out in detail in the following sections.

2) **Phase 0-A: Flight Vehicle Integration and Launch**

This phase begins with Rascal's integration into the flight vehicle and ends upon the flight vehicle reaching its target orbit. The main requirements associated with this phase would be ensuring that Rascal can survive the launch vehicle environment (Random Vibration Testing), as well as actually integrate into the launch vehicle (Following CubeSat deployer interface control document).

3) **Phase 0-B: Ejection**

This phase begins with the opening of Rascal's CubeSat deployer and ends with Rascal's exit from its launch vehicle. The only requirement during this stage is that no deployables (such as solar panels, antennas, etc) are released for a specified period of time (as dictated by the launch provider).

4) **Phase 0-C: Power-On**

This phase begins the moment that Rascal is ejected from its CubeSat deployer. It consists of the powering on of both the target and interceptor spacecraft, which would include initiating satellite beaconing, inter-satellite communication, and attitude determination and control (ADC) systems.

5) **Phase 0-D: Acquisition and Checkout**

This phase is initiated on the ground and begins during the first pass of the Rascal spacecraft over any of its ground based radio stations. Once satellite acquisition has been achieved, a checkout of the systems on both the target and interceptor spacecraft would be performed. This would consist of verifying battery telemetry data, solar panel, ADC, payload, and communications functionality prior to full mission commencement. Once this has been completed, Phase-0 would be considered complete and the mission would then enter Phase 1.

6) **Phase 1: Fully Cooperating Mission Phase**

Phase 1of the mission consists of the main portion of the mission, such as the separation of the target and interceptor spacecraft, the first testing of the image processing payload, and the performance of key RPO and inspection maneuvers. Mission success is defined by the ability to perform each of sub-sections of this mission phase, which are described in detail in the following sections.

7) **Phase 1-A: Orient for Separation**

This phase begins with a command from the ground for the interceptor-target spacecraft combination to orient itself such that separation can occur with the optimal initial conditions determined before launch. This would help alleviate the risk associated with expending too much delta-V prior to mission execution. This phase ends when the proper spacecraft orientation has been verified from the ground.

8) **Phase 1-B: Command Separation**

This phase begins with a command from the ground for the target and interceptor spacecraft to separate. This would occur near the beginning of a pass over Rascal's ground network, such that successful separation could be verified. This phase would end with this verification.

9) **Phase 1-C: Move to Inspection Stationkeeping (ISK) Distance**

This phase commences upon the initiation of separation. The interceptor spacecraft will enter its search mode, in which it orients itself in such a way that the target spacecraft enters the imaging payloads field of vision. Once the target spacecraft has been acquired, the interceptor will thrust out to its ISK distance (~10 meters) and stationkeep there until it can be verified on the ground that ISK is being performed.

10) **Phase 1-D: Verify ISK**

Once the interceptor spacecraft has reached its ISK distance, it will perform thrust maneuvers to stay at said distance until verification of ISK has been made on the ground. This will be accomplished by either decoding beacon data that is being emitted by the interceptor at all times or by specifically querying for imaging/relative distance data during a pass over the Rascal ground station. This step helps alleviate the risks associated with rapidly separating the target and interceptor spacecraft, which could result in a rapid divergence in the relative displacement between each of them, making it impossible for each to rendezvous later in the mission.

11) **Phase 1-E: Command Continued Separation**

After ISK has been verified, the interceptor spacecraft will be commanded to increase the relative distance between it and the target spacecraft from ~10 meters to ~100 meters, its remote stationkeeping (RSK) distance. This RSK distance constitutes a sphere of constant radius surrounding the target spacecraft, as shown in Figure 2.

12) **Phase 1-F: Verify RSK**

Once the interceptor has reached its RSK distance, it will stationkeep until said separation has been verified, which will take place in a manner similar to that for verifying the ISK distance in Step 10.

13) **Phase 1-G: Command Rendezvous**

After RSK has been verified, a ground operator will command the interceptor to perform a rendezvous relative to the target spacecraft. This will constitute reducing the relative distance between the target and interceptor from the

RSK to the ISK distance. Upon reaching its ISK distance, the interceptor will stationkeep until rendezvous verification can be made.

14) **Phase 1-H: Verify Rendezvous**

After the interceptor has reached its ISK distance, rendezvous will be verified in the same manner discussed in Step 10. Once this has been done, Phase 1 will be considered complete, and preliminary mission success will be considered achieved.

15) **Phase 2: Semi-Cooperating Mission Phase**

Phase 2 of the Rascal mission consists of repeating the first phase of the mission without the visual aids that were used to help identify the target spacecraft to the image processing payload on the interceptor. This effectively constitutes repeating steps C-H of Phase 1, with the added step of commanding the target spacecraft to power off its visual aids. This phase will be set to take place over a set period of time. If the phase takes longer than that to complete, the visual aids will automatically power back on, as to allow for the interceptor to return to its starting position and for an assessment of its flight algorithms.

16) **Phase 3: Noncooperating Mission Phase**

Phase 3 of the Rascal mission is a continuation of Phase 2: as opposed to only powering off the target spacecraft's visual aids for the interceptor's imaging payload, the target spacecraft's GPS beacon will also be powered off, thus transforming the target into a noncooperating space object, as would be the case in an applied inspection mission. As such, Phase 3 will consist of the same maneuvers as those described in Phase 2, with the same mission timer in play as in that phase. Full mission success is defined as being able to complete Phase 3.

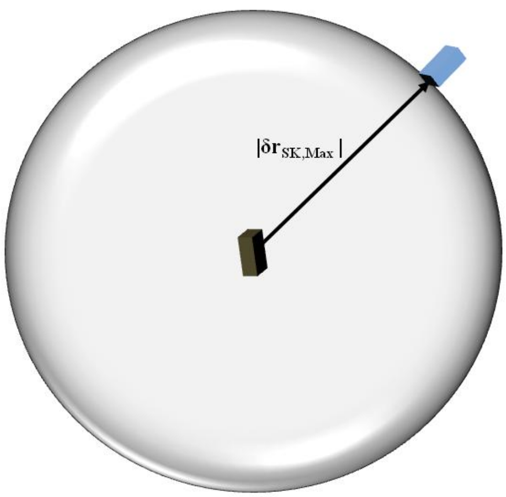


***Figure II- Remote Stationkeeping distance illustration*.** This image shows the maximum allowable separation distance between the target and interceptor. This distance is visualized as a sphere of constant radius surrounding the target spacecraft.

17) **Phase 4: Extended Operations Phase**

Phase 4 of the Rascal mission consists of extended operations, which can include performing Phases 1-3 until the propellant in the interceptor is depleted, using the interceptor's imaging payload for Earth observation, or for studying the relative drift between two different spacecraft when provided with initial velocity and position information. The extended operations phase would end when both spacecraft deorbit within 1-3 years of launch.

3. CONOPS-2: RPO Demonstration with Docking

Figure 3 shows a general overview of CONOPS-2. This CONOPS is almost identical to CONOPS-1, with the exception that it will end Phase 1 (As discussed in the previous section) with docking, as opposed to just stationkeeping. This CONOPS also offers points over the course of the mission where mission operations can be "paused", allowing for mission operators ample time to plan out each phase of the mission, as well as for a reduction in the amount of risk associated with relative spacecraft separation distances becoming too large to overcome as the mission goes on.

Thus the general mission operations of this CONOPS are quite similar to CONOPS-1, with beginning with initial launch, launch vehicle ejection, and checkout, and ending with the 4 phases discussed in the previous section.

1) **Phase 0: Launch to Checkout**

Phase 0 for CONOPS-2 is identical to that for CONOPS-1. Thus, refer to Step 1 in the previous section for more information.

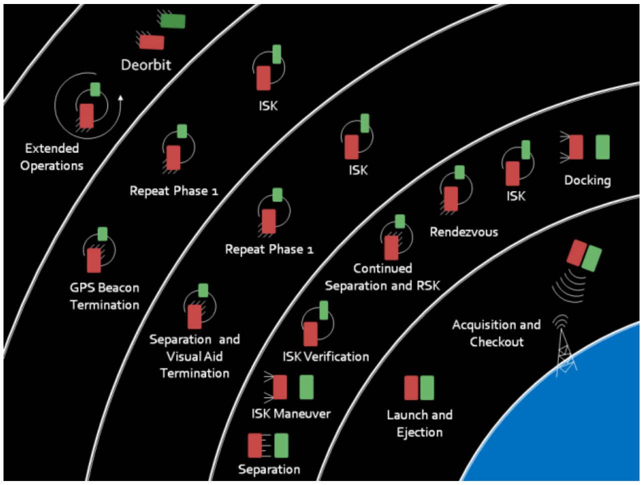


Figure 3- CONOPS-2 illustration. The second CONOPS for the Rascal mission is almost identical to the first, with the only difference being a docking maneuver that is performed at the end of Phase 1.

2) **Phase 1: Fully Cooperating Mission Phase**

Phase 1 for CONOPS-2 consists of exactly the same maneuvers as those listed in Phase 1 of CONOPS-1, a single step added after Phase 1-H, as described below.

3) **Phase 1-F: Docking**

After the verifying that ISK has been achieved, the interceptor will be commanded to commence docking. Docking would then take place within a single pass over Rascal's ground station network, allowing for and almost instant verification that docking occurred.

4) **Phase 2: Semi-Cooperating Mission Phase**

This mission phase is exactly the same as that listed in CONOPS-1, with the only difference between the two being the availability of the "pausing" option, which would entail docking after the completion of the phase's RPO demonstration, allowing more time for planning out the third phase.

5) **Phase 3: Noncooperating Mission Phase**

Once again, this mission phase is identical to that listed in CONOPS-1, with the same pausing option discussed in the previous section still being available. Thus, the primary mission would end either when the two spacecraft are docked with each other or have completed their rendezvous.

6) **Phase 4: Extended Operations**

Like its corresponding phase in CONOPS-1, this phase consists of either performing Phases 1-3 until depleting the entirety of the interceptor's propellant, performing earth observations with the interceptor's imaging payload, or studying the relative distance characteristics between the interceptor and the target. This phase would end when each spacecraft deorbits 1-3 years after launch.

D. CONOPS Comparisons

Now that each of the potential CONOPS for the Rascal mission have been described, it is necessary to compare them to each other, as to assess which one bests suits Rascal's mission goals in the most cost effective, risk free manner possible. This was done by considering the differences in the ΔV required to execute the mission, the cost of components and labor associated with each, the risks associated with each, and the relevance of each mission to RPO and Inspection demonstrations.

1. ΔV and Orbital Planning Comparison

The difference in ΔV usage for each mission was calculated through the application of linear orbit theory to the planning of each of the orbital maneuvers that would have to be performed in each mission case. This theory essentially takes the equation of motion for a body in a general gravitational field a second-order, nonlinear, differential equation, and, through the use of a few assumptions (Such as near-circular orbits & small relative distances between the target and interceptor spacecraft) and the Clohessy-Wiltshire (CW) coordinate frame (As Shown in Figure 4) produces a linear, closed form solution for the relative position and velocity between and interceptor and target spacecraft.

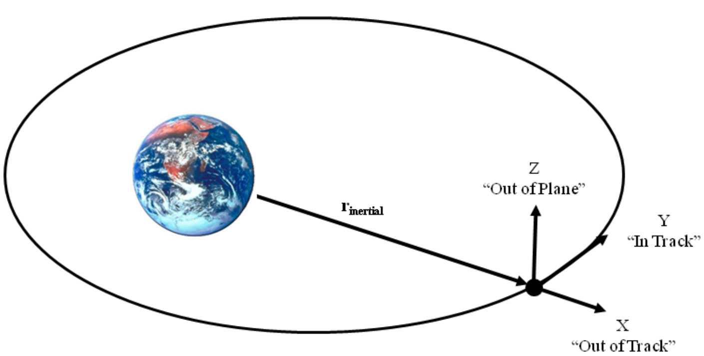
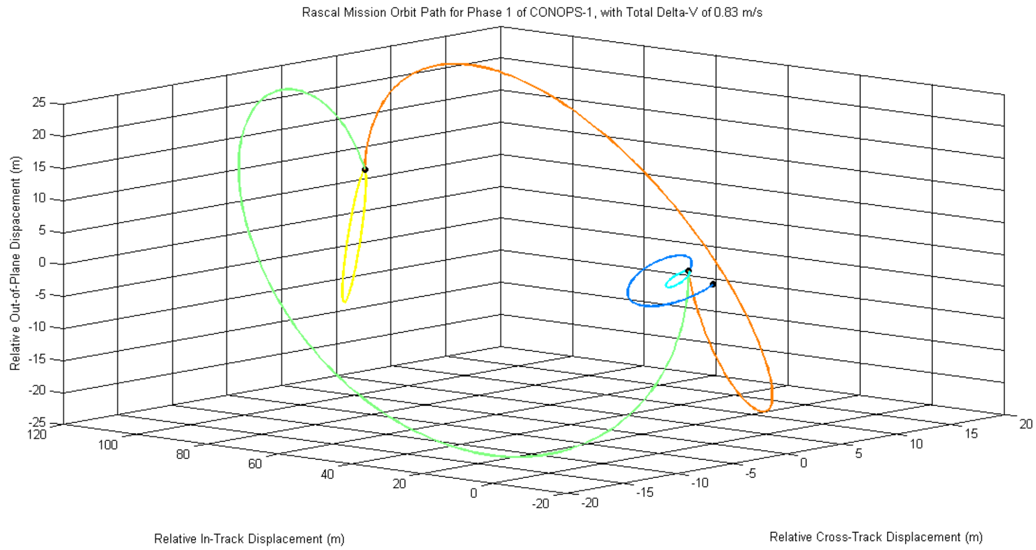


Figure 4- CW Coordinate Frame. Where the X-Axis is parallel to the radial line from the CG of the spacecraft to that of the Earth, Y-Axis is parallel to the spacecrat's velocity vector, and the Z-Axis is perpundicular to the X and Y Axes.

With this in mind, an ideal mission was defined through an optimization of the ΔV required to perform each phase of each mission, with the constraint being that each maneuver take at least



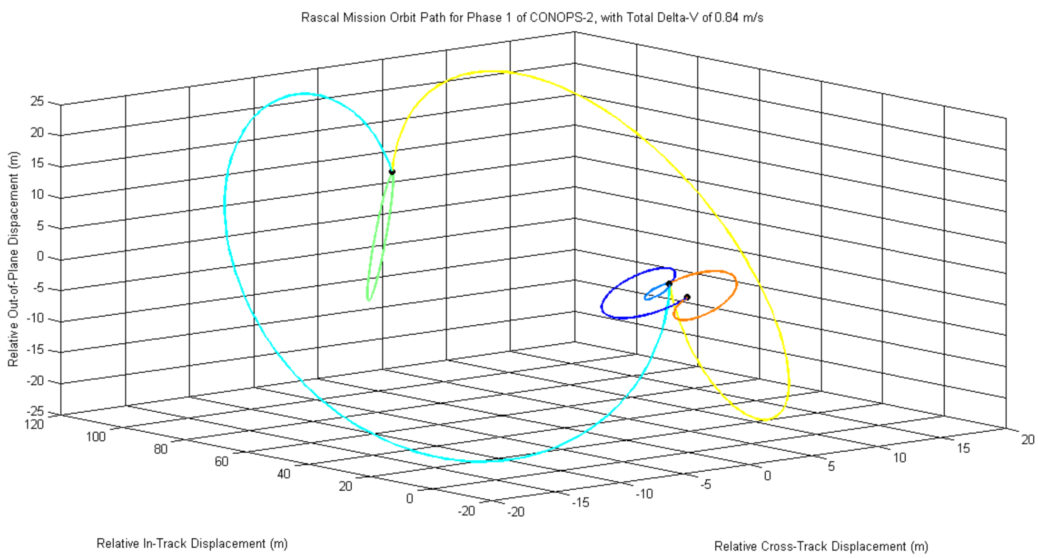


Figure 5- Relative Position Plots for Phase 1 of CONOPS-1 (Top) and CONOPS-2 (Bottom). Each color on each plot demonstrates a differnt potion of the mission, with each CONOPS starting with Initial Separation (Dark Blue), and progressing through ISK, Continued Separation, RSK, and Ending on either Rendezvous or Docking (Orange).

Table 1- Total ΔV Required for Each Maneuver and CONOPS.

Maneuver	ΔV (m/s)
Initial Separation	0.714
ISK	0.004
Continued Separation	0.053
RSK	0.004
Rendezvous	0.052
Docking	0.012
CONOPS-1	**2.482**
CONOPS-2	**2.561**

one orbit (~90 Minutes) to occur. The relative position of the interceptor spacecraft relative to the fixed target spacecraft was then plotted for each case (As shown in Figure 5). Each case utilized the same initial separation relative velocities ([0.001, 0.001, 0] km/s) and the same final positions for each maneuver that is to be performed ([0.001, 0.01, 0.001] km for ISK, Separation, and Rendezvous, [0.001, 0.1, 0.001] km for RSK). The total ΔV for each maneuver, as well as the mission ΔV for each CONOPS, is shown in Table 1.

As can be seen from Figure 5 and Table 1, there exist very few distinguishable differences between CONOPS-1 and CONOPS-2. This suggests that ΔV usage is not an important parameter in distinguishing each mission.

2. Risk Comparison

The purpose of the risk analysis is to identify each undesirable event that might affect the success of the mission and to assess the likelihood and consequence of occurrence. A Risk Reporting Matrix allows for the visualization of risk to mission success in terms of likelihood and consequence. The level of risk associated with each root cause is reported as low (green), moderate (yellow), or high (red), while the level of likelihood of each root cause and the consequences of said causes taking place are defined in Table 2 and Table 3.

Table 2- Level of Risk Likelihood Definitions.

Level	Likelihood	Probability of Occurrence
1	Not Likely	~10%
2	Low Likelihood	~30%
3	Likely	~50%
4	Highly Likely	~70%
5	Near Certainty	~90%

Table 3- Risk Consequence Level Definitions.

Level	Associated Risk
1	Minimal or no consequence to technical performance
2	Minor reduction in technical performance or supportability, can be tolerated with little to no impact on the mission
3	Modest reduction in technical performance or supportability with limited impact on mission objectives
4	Significant degradation in technical performance or major shortfall in supportability; may jeopardize mission success
5	Sever degradation in technical performance; failure to meet mission objectives; will jeopardize mission success

1) **CONOPS-1 Risk Assessment**

Figure 6 summarizes the various risks associated with CONOPS-1, each of which is discussed in greater detail below.

Spacecraft Unable to Orient for Separation. Failure of the spacecraft to properly orient themselves for separation could lead to increased ΔV requirements for inspection stationkeeping. This risk can be mitigated by testing the pointing capabilities of the conjoined spacecraft on the ground prior to launch integration.

Spacecraft Unable to Separate. A failure of the separation mechanism to push the two spacecraft apart would result in mission failure. This risk can be mitigated by extensive ground testing of the separation mechanism under the expected environmental conditions in low Earth orbit.

Collision with Target Spacecraft during ISK. A collision with the quarry spacecraft during inspection stationkeeping may result in damage to solar arrays, communication antennas, and external sensors, potentially impeding further progress.

Unable to Rendezvous with Target Spacecraft during Cooperative Rendezvous. Failure of the primary spacecraft to rendezvous with the quarry spacecraft from maximum stationkeeping distance with both GPS and visual aids active precludes any further rendezvous attempts.

Unable to Rendezvous with Target Spacecraft during Semi-Cooperative Rendezvous. Failure of the primary spacecraft to rendezvous with the quarry spacecraft from maximum stationkeeping distance with active GPS and without the benefit of visual aids precludes any further rendezvous attempts.

Unable to Rendezvous with Target Spacecraft during Noncooperative Rendezvous. Failure of the primary spacecraft to rendezvous with the quarry spacecraft from maximum stationkeeping distance without active GPS and visual aids precludes any further rendezvous attempts.

Collision with Target Spacecraft during Rendezvous from RSK Distance. A collision with the quarry spacecraft during rendezvous may result in damage to solar arrays, communication antennas, and external sensors, potentially impeding further progress.

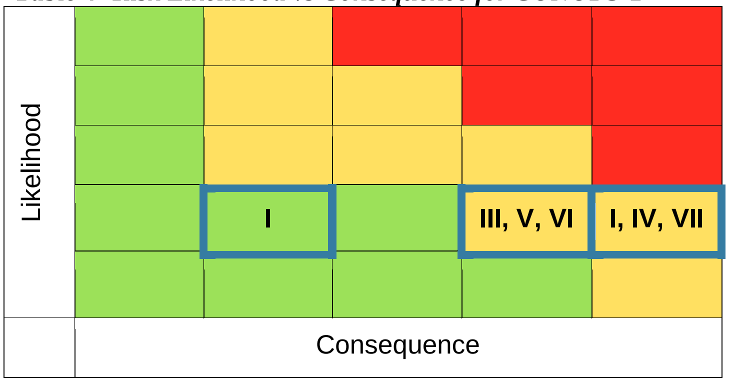
2) **CONOPS-2 Risk Assessment**

Figure 7 summarizes the risks associated with CONOPS-2, each of which is discussed in greater detail below.

Spacecraft Unable to Orient for Separation. Failure of the spacecraft to properly orient themselves for separation could lead to increased ΔV requirements for inspection stationkeeping. This risk can be mitigated by testing the pointing capabilities of the conjoined spacecraft on the ground prior to launch integration.

Spacecraft Unable to Separate. A failure of the separation mechanism to push the two spacecraft apart would result in mission failure. This risk can be mitigated by extensive ground testing of the separation mechanism under the expected environmental conditions in low Earth orbit.

Table 4- Risk Likelihood vs Consequence for CONOPS-1



Collision with Target Spacecraft during ISK. A collision with the quarry spacecraft during inspection stationkeeping may result in damage to solar arrays, communication antennas, and external sensors, potentially impeding further progress.

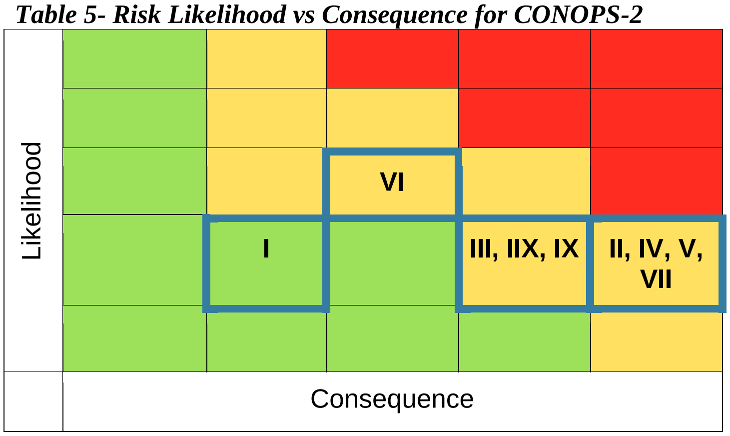
Unable to Rendezvous with Target Spacecraft during Cooperative Rendezvous. Failure of the primary spacecraft to rendezvous with the quarry spacecraft from maximum stationkeeping distance with both GPS and visual aids active precludes any further rendezvous attempts.

Collision with Target Spacecraft during Rendezvous from RSK Distance. A collision with the quarry spacecraft during rendezvous may result in damage to solar arrays, communication antennas, and external sensors, potentially impeding further progress.

Collision with Target Spacecraft during Docking Demonstration. A collision with the quarry spacecraft during docking demonstration may result in damage to solar arrays, communication antennas, and external sensors, potentially impeding further progress.

Spacecraft Unable to Separate after Docking Demonstration. Failure of the spacecraft to undock would preclude any further proximity operations. This risk is mitigated by extensive ground testing of the docking/undocking mechanisms under the expected environmental conditions of low Earth orbit.

Table 5- Risk Likelihood vs Consequence for CONOPS-2



Unable to Rendezvous with Target Spacecraft during Semi-Cooperative Rendezvous. Failure of the primary spacecraft to rendezvous with the quarry spacecraft from maximum stationkeeping distance with active GPS and without the benefit of visual aids precludes any further rendezvous attempts.

Unable to Rendezvous with Target Spacecraft during Noncooperative Rendezvous. Failure of the primary spacecraft to rendezvous with the quarry spacecraft from maximum stationkeeping distance without active GPS or visual aids precludes any further rendezvous attempts.

3) **Risk Comparison Conclusions**

As can be seen from Table 5 and Table 4, CONOPS-2 has a greater number of risks than CONOPS-1. Its risks also have a higher likelihood of taking place, as well as greater consequences for if they do. This makes sense, since docking between two spacecraft is an inherently difficult and risky problem. This type of maneuver has never been demonstrated before on such a small scale, meaning that these risks are magnified even further by the greater likelihood of them to take place (Due to a lack of historical precedent and data). So, if CONOPS-2 is to be selected, there must be a justification for said selection that outweighs its greater risk.

3. Mission Relevance Comparison

As discussed in Sections A and B, the Rascal mission is worth pursuing mainly due to its demonstrations of maneuvers that have not been performed on such a small scale before. In that sense, either CONOPS is worth pursuing, since each demonstrates RPO and Inspection capabilities that have not previously been seen.

However, in terms of scaling the Rascal mission up and applying it to a real world RPO mission, CONOPS-2 would be the best selection. Think, for example, of a company that wants to assess the reasons behind the failure of multiple spacecraft, as to determine whether or not it is possible to salvage any sort of functionality from any of them. Normally, sending a large spacecraft up capable of inspecting each spacecraft this task would cost just as much replacing each of the spacecraft from scratch. If, however, a smaller host spacecraft was sent up that was capable of deploying a CubeSat, the host would be able to get within a reasonable range of the target, deploy the

CubeSat (which would perform the inspection), and then allow for the CubeSat to redock with the host, at which point it could then move on to the next spacecraft. In this case, demonstrating docking would be a huge step in demonstrating the capabilities of such an inspection mission.

E. Mission Architecture

With mission success defined, as well as the scope of the mission being limited to small spacecraft, it was determined that the Rascal mission need to be executed through the use of a CubeSat architecture. Based on CONOPS-2, it was determined that the Rascal mission could be executed through the use of two 3U CubeSats. One of these spacecraft would be designated at the interceptor, the other the target. The interceptor will be an active spacecraft that will carry a propulsion system and an active attitude determination and control system. The target spacecraft will be passive, with no propulsion or active ADC. Instead it will serve as place for the interceptor spacecraft to interact with and dock.

This mission will be developed in conjunction with Boeing, where they will be providing their Colony-II bus for the interceptor, whose specifications are defined in Table 6. The payload for the interceptor, target spacecraft, and the docking mechanism will be developed by Saint Louis University. As defined by the Colony-II constraints, the payload will be a 1U that is to provide navigation and control relative to the target spacecraft, with the mission requirements defined by Saint Louis University. With this in mind, the layout of the 1U payload allows space for an imaging capturing and processing board (for calculating the relative distance and velocity between each spacecraft), interface control board (for independent operation and handling of said image board, as well as for interfacing with the Colony-II bus), inter-satellite communication board (for the sharing the target spacecraft's location and the relaying of satellite health through either spacecraft), and a propulsion unit (that will provide 3-axis control).

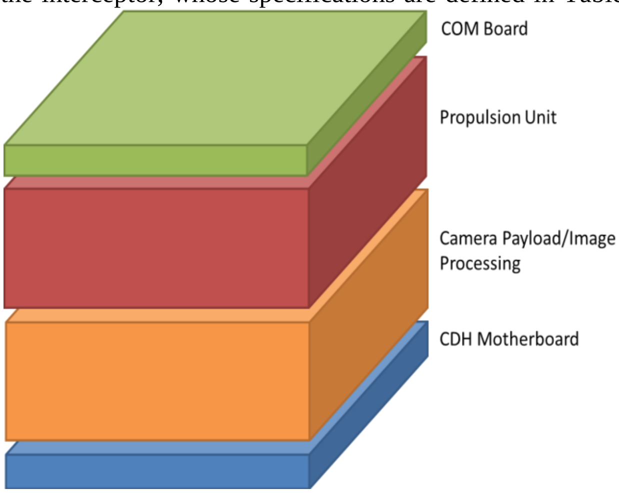


Figure 6- Example Rascal 1U payload layout

Since the target spacecraft is not as complex, it will have a component layout similar to the payload. Target spacecraft will carry a GPS receiver, so it can determine its location and broadcast it during the cooperating phase of the mission. There will be a radio to broadcast the GPS location to the interceptor spacecraft. A payload will provide visual aids for the interceptor spacecraft to image. The motherboard will be used to control all the components. In addition, it will have a power system to power the components, consisting of a power management board and enough batteries to last the duration of the mission. The target spacecraft will also have a passive ADC system to reduce that the spacecraft many experience, the interceptor spacecraft can dock.

Both spacecraft will carry components for the conjoining and docking mechanisms. The conjoining mechanism will serve to keep the two spacecraft together until mission start is initiated. The docking mechanism, which will primarily be hosted on the target spacecraft, will provide docking for interceptor spacecraft as the need arises and when the mission dictates.

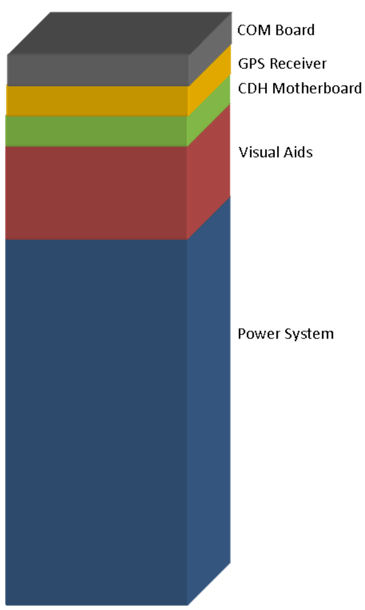


Figure 7- Example Rascal Target Spacecraft Layout