

Rascal Concept of
Operations Trade Study
Saint Louis University
Rascal



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1 Introduction

1.1. Background

This document serves to outline and compare two proposed concept of operations (CONOPS) associated with the Rascal mission. Each CONOPS would successfully demonstrate Rascal's mission statement (As discussed in Section 1.2), though each would do so in drastically different fashions, as discussed in Section 2.

1.2. Rascal Mission Statement and Overall Mission Architecture

Rascal's mission can be summed up as:

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.

Though there are many other missions attempting to demonstrate similar or greater capabilities as those outlined above (Such as Tyvak's PONSFD, Surrey's STaND-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:

- **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.
- **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.
- **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.

2 Concept(s) of Operations

2.1. General CONOPS Overview and Definitions

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

- **RPO Demonstration without Docking**
- **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).

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

- **Target Spacecraft**: spacecraft about which all RPO maneuvers would be performed.
- **Interceptor Spacecraft**: spacecraft with which all RPO maneuvers would be executed.
- **Fully Cooperative State**: target spacecraft state in which all interceptor RPO aids (such as image processing aids, differential GPS, etc) are active.
- **Semi-Cooperative State**: target spacecraft state in which some (but not all) interceptor RPO aids are active.
- **Uncooperative State**: target spacecraft state in which no interceptor RPO aids are active.
- **Stationkeeping**: keeping a set relative distance between the target and interceptor spacecraft while maintaining as small a relative velocity as possible.
- **Inspection Stationkeeping (ISK)**: stationkeeping within 10 meters of the target spacecraft.
- **Remote Stationkeeping (RSK)**: stationkeeping at least 100 meters away from the target spacecraft.
- **Rendezvous**: the act of reducing the relative distance between the target and interceptor spacecraft.
- **Separation**: the act of increasing the relative distance between the target and interceptor spacecraft.
- **Docking**: the act of conjoining the target and interceptor spacecraft after separation (only occurs during cooperative state).
- **Pause State**: mission state in which the target and interceptor spacecraft are docked due to mission timing constraints.
- **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.

2.2. CONOPS-1: RPO Demonstration without Docking

Figure 2-1 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.

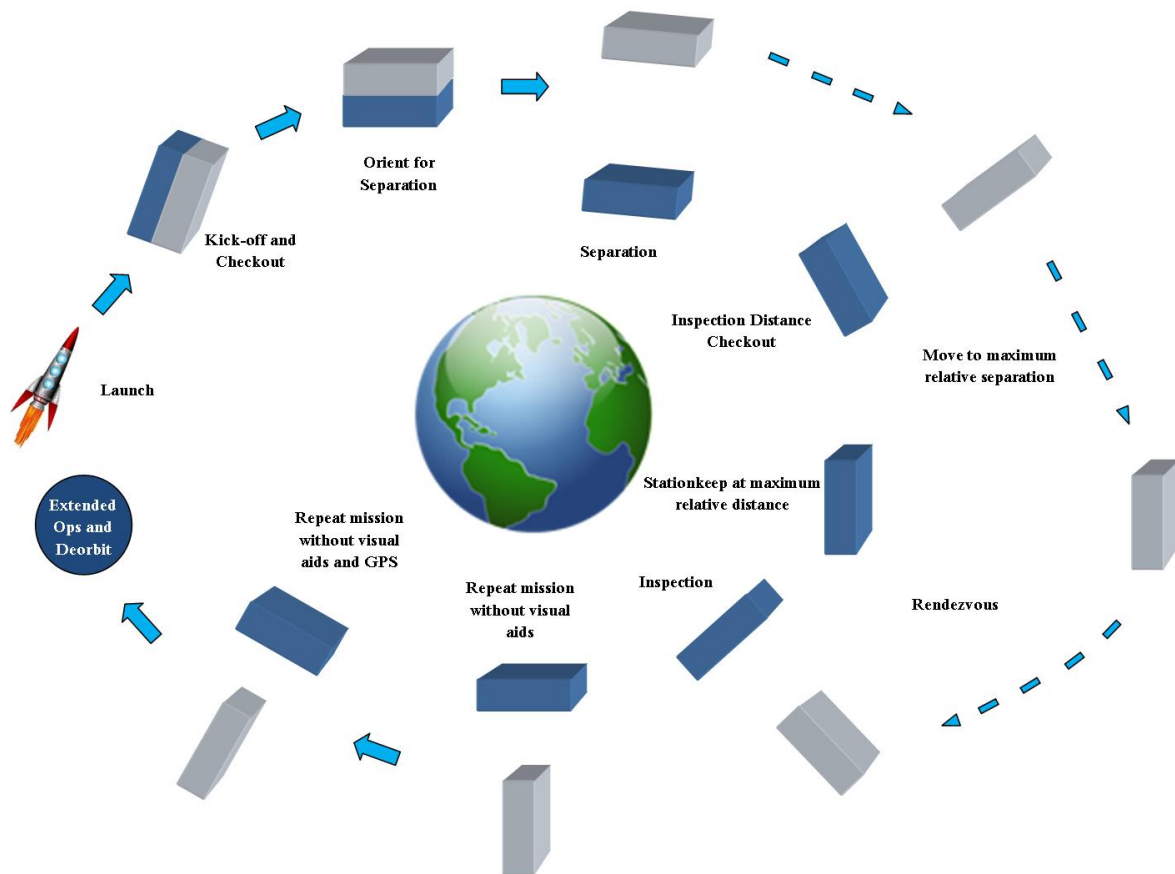


Figure 2-1 CONOPS-1 Illustration. The Concept of Operations for the Rascal mission without docking consists of several distinct phases, mainly: Initial Separation, Imaging Payload Checkout, Continued Separation, Remote Stationkeeping, Rendezvous, and Inspection Stationkeeping. It also has three overlying states: Cooperative, Pseudo-Cooperative, and Uncooperative.

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2.2.1 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.

2.2.1.1 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).

2.2.1.2 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).

2.2.1.3 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.

2.2.1.4 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.

2.2.2 Phase 1: Fully Cooperating Mission Phase

Phase 1 of 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.

2.2.2.1 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.

2.2.2.2 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.

2.2.2.3 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

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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.

2.2.2.4 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.

2.2.2.5 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 2-2.

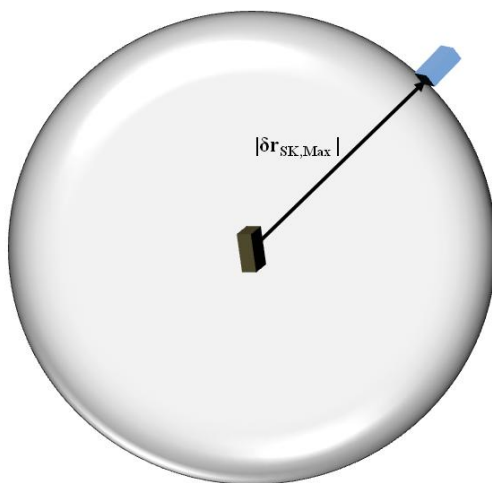


Figure 2-2 Remote Stationkeeping distance illustration. This image shows the maximum allowable separation distance between the target and interceptor. This distance is visualized as a sphere of constant radius surrounding the target spacecraft.

2.2.2.6 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 Section 2.2.2.4.

2.2.2.7 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.

2.2.2.8 Phase 1-H: Verify Rendezvous

After the interceptor has reached its ISK distance, rendezvous will be verified in the same manner discussed in Section 2.2.2.4. Once this has been done, Phase 1 will be considered complete, and preliminary mission success will be considered achieved.

2.2.3 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.

2.2.4 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.

2.2.5 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.

2.3. CONOPS-2: RPO Demonstration with Docking

Figure 2-3 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.

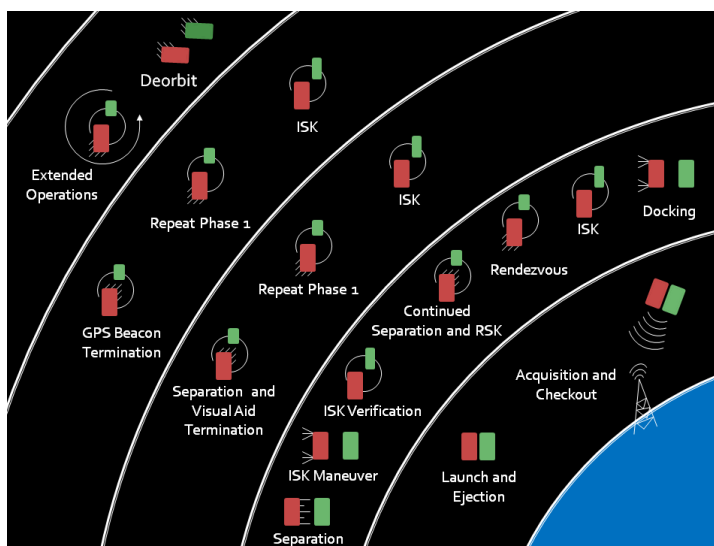


Figure 2-3 CONOPS-2 illustration. The second CONOPS for the Rascal mission is almost identical to the first, with the only difference being a docking maneuver that is performed at the end of Phase 1.

2.3.1 Phase 0: Launch to Checkout

Phase 0 for CONOPS-2 is identical to that for CONOPS-1. Thus, refer to Section 2.2.1 for more information.

2.3.2 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.

2.3.2.1 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

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Rascal's ground station network, allowing for and almost instant verification that docking occurred.

2.3.3 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.

2.3.4 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.

2.3.5 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.

3 CONOPS Trade Study

With each of these CONOPS defined, it is now necessary to compare each against the other, as to determine which one is best able to achieve the goals laid out by Rascal's mission objective. This was accomplished by comparing each CONOPS in four specific categories: ΔV requirements, Cost, Risk, and relevance. Each of these categories, and the methodology involved in their derivation, are described in the following sections.

3.1. ΔV Requirements

One of the most important parameters associated with the execution of the Rascal mission is that of the Delta-V (ΔV) required to perform each of the maneuvers associated with its mission profile, as described in each of its CONOPS. As such, the total ΔV required to perform each CONOPS was calculated. The manner in which this was accomplished is laid out in Sections 3.1.1 through 3.1.2, with the results of said calculations summarized in Section 3.2.

3.1.1. ΔV Calculation Methodology

All ΔV values calculated for the Rascal mission were done so through the use of linear orbit theory. This theory effectively takes the equation of motion for a body exposed to a general gravitational field, where \mathbf{r} is the inertial position of a spacecraft, $\ddot{\mathbf{r}}$ is the acceleration of said object spacecraft, $\mathbf{g}(\mathbf{r})$ is the influence of a general gravitational field, and Γ is the thrust acceleration vector of the spacecraft.

$$\ddot{\mathbf{r}} = \mathbf{g}(\mathbf{r}) + \Gamma \tag{1}$$

As opposed to having to analytically solving this second-order, non-linear differential equation (For

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which several methods and algorithms already exist), one can approximate a solution through the use of linearized equations that describe the motion of one spacecraft relative to each other. This process works well when the relative displacement between a target and interceptor spacecraft is small relative to the overall size of each spacecraft's orbit (As is the case for the Rascal mission). Though this technique is hindered by the assumption that each spacecraft's orbit is near-circular, it still offers a useful approximation of the expected ΔV that is to be used in a given mission.

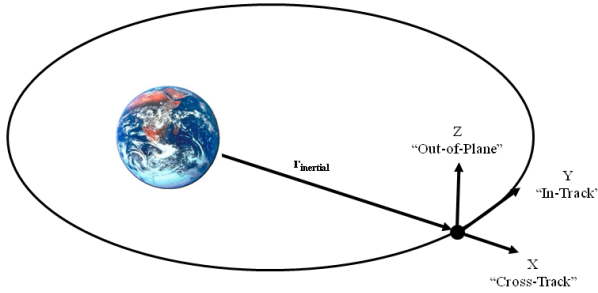


Figure 3-3-1 Illustration of the Clohessy-Wiltshire coordinate frame.

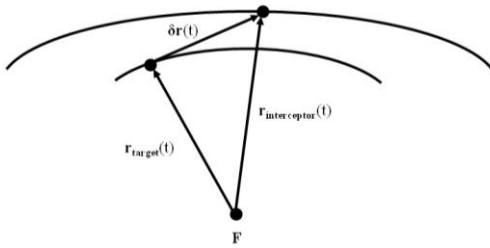


Figure 3-3-2 Relative position illustration, with target spacecraft as origin of CW-frame.

The simplest coordinate frame to utilize for linear orbit theory analysis is that utilized by Clohessy-Wiltshire (CW), as shown in Figure 3-1. This coordinate frames is spacecraft-fixed, as opposed to Earth-fixed, meaning that it rotates with the radius vector ($\mathbf{r}_{inertial}$) of a given spacecraft. In the case of Rascal, the origin of the coordinate frame is assigned to the target spacecraft. This means that all the relative velocities and positions discussed throughout this overview are defined relative to the target spacecraft's CW coordinate frame, as shown in Figure 3-2. From this, the relative position between an interceptor and target spacecraft can be defined by the following equation, where \mathbf{r}_{int} and \mathbf{r}_{tgt} are the inertial positions of the interceptor and target spacecraft respectively.

$$\delta \mathbf{r}(t) = \mathbf{r}_{int}(t) - \mathbf{r}_{tgt}(t) \quad (2)$$

This equation can then be substituted into Equation (1), which, after quite a bit of arithmetic (As fully laid out in Prussing[1]), results in a general solution

of the following form:

$$\delta \mathbf{s}(t) = \Phi(t) \delta \mathbf{s}(0) \quad (3)$$

Where $\delta \mathbf{s}(t)$ is defined as the 6x1 vector containing both the components of relative spacecraft position (x,y,z) and velocity ($\dot{x}, \dot{y}, \dot{z}$) and $\Phi(t)$ is the state transition matrix of relative spacecraft motion, which is defined as:

$$\Phi(t) = \begin{bmatrix} \mathbf{M}(t) & \mathbf{N}(t) \\ \mathbf{S}(t) & \mathbf{T}(t) \end{bmatrix} \quad (4)$$

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Where $\mathbf{M}(\mathbf{t})$, $\mathbf{N}(\mathbf{t})$, $\mathbf{S}(\mathbf{t})$, and $\mathbf{T}(\mathbf{t})$ are each 3x3 matrices defined as:

$$\begin{aligned}\mathbf{M}(\mathbf{t}) &= \begin{bmatrix} 4 - 3c & 0 & 0 \\ 6(s - nt) & 1 & 0 \\ 0 & 0 & c \end{bmatrix} & \mathbf{N}(\mathbf{t}) &= \begin{bmatrix} \frac{s}{n} & \frac{2}{n}(1 - c) & 0 \\ -\frac{2}{n}(1 - c) & \frac{4s - 3nt}{n} & 0 \\ 0 & 0 & \frac{s}{n} \end{bmatrix} \\ \mathbf{S}(\mathbf{t}) &= \begin{bmatrix} 3ns & 0 & 0 \\ -6n(1 - c) & 0 & 0 \\ 0 & 0 & -ns \end{bmatrix} & \mathbf{T}(\mathbf{t}) &= \begin{bmatrix} c & 2s & 0 \\ -2s & 4c - 3 & 0 \\ 0 & 0 & c \end{bmatrix}\end{aligned}\tag{5}$$

With c , s , and n in canonical units being:

$$\begin{aligned}n &= \sqrt{\frac{1}{r_{tgt}^3}} \\ s &= \sin nt \\ c &= \cos nt\end{aligned}\tag{6-8}$$

With these formulations in mind, one can finally form the general equations for the change in relative position and velocities between a target and interceptor spacecraft with time as:

$$\begin{aligned}\delta\mathbf{r}(\mathbf{t}) &= \mathbf{M}(\mathbf{t})\delta\mathbf{r}(\mathbf{0}) + \mathbf{N}(\mathbf{t})\delta\mathbf{v}(\mathbf{0}) \\ \delta\mathbf{v}(\mathbf{t}) &= \mathbf{S}(\mathbf{t})\delta\mathbf{r}(\mathbf{0}) + \mathbf{T}(\mathbf{t})\delta\mathbf{v}(\mathbf{0})\end{aligned}\tag{9-10}$$

From here, the total ΔV required to perform a maneuver that defines a new relative displacement between a target and interceptor spacecraft such that, when the interceptor arrives at said new position, the two spacecraft have no net relative velocity, can be defined as:

$$\begin{aligned}\Delta\mathbf{v}_0 &= \mathbf{N}(\mathbf{t}_f)^{-1}[\delta\mathbf{r}(\mathbf{t}_f) - \mathbf{M}(\mathbf{t}_f)\delta\mathbf{r}(\mathbf{0})] - \delta\mathbf{v}(\mathbf{0}) \\ \Delta\mathbf{v}_f &= -[\mathbf{S}(\mathbf{t}_f)\delta\mathbf{r}(\mathbf{0}) + \mathbf{T}(\mathbf{t}_f)(\delta\mathbf{v}(\mathbf{0}) + \Delta\mathbf{v}_0)] \\ \Delta\mathbf{v}_{tot} &= |\Delta\mathbf{v}_f + \Delta\mathbf{v}_i|\end{aligned}\tag{11-13}$$

It is this final result that was used to calculate the total ΔV required to execute each of the maneuvers laid out in the results section.

3.1.2. Rascal Mission Test Cases

In order to better assess the ΔV expected to be used for the execution of the Rascal mission, several different orbit path cases were considered for various initial and final conditions, as perform a trend analysis on the affects of altering different mission parameters. The main parameters that were selected for variation were: initial relative velocity ($V_{rel,i}$), relative ISK displacement (r_{isk}), and relative RSK displacement (r_{rsk}). Regardless of the case, it is assumed that each maneuver is performed impulsively at the moment that a previous maneuver is just being completed (implying that the initial relative velocity for each maneuver is zero) and that each maneuver takes the same amount of time to complete (in this case, 90 minutes, which is roughly the time it takes to complete one orbit).

3.1.2.1. Low $V_{rel,ib}$, r_{rsk} and r_{isk} Both Solely in In-Track Direction

In order to assess the bare minimum ΔV required to meet the Rascal mission, a minimal ΔV test case was created. For this test case, it was assumed that the initial relative velocity between the target and interceptor during separation was minimal, and that the ISK and RSK displacements were each only in the In-Track direction relative to the target spacecraft. The results of the analysis for this case is shown in Figure 3-3, with the path of the interceptor being plotted relative to the target, where each maneuver is marked by a different color (In ascending order from blue to orange: Initial Separation, ISK, Continued

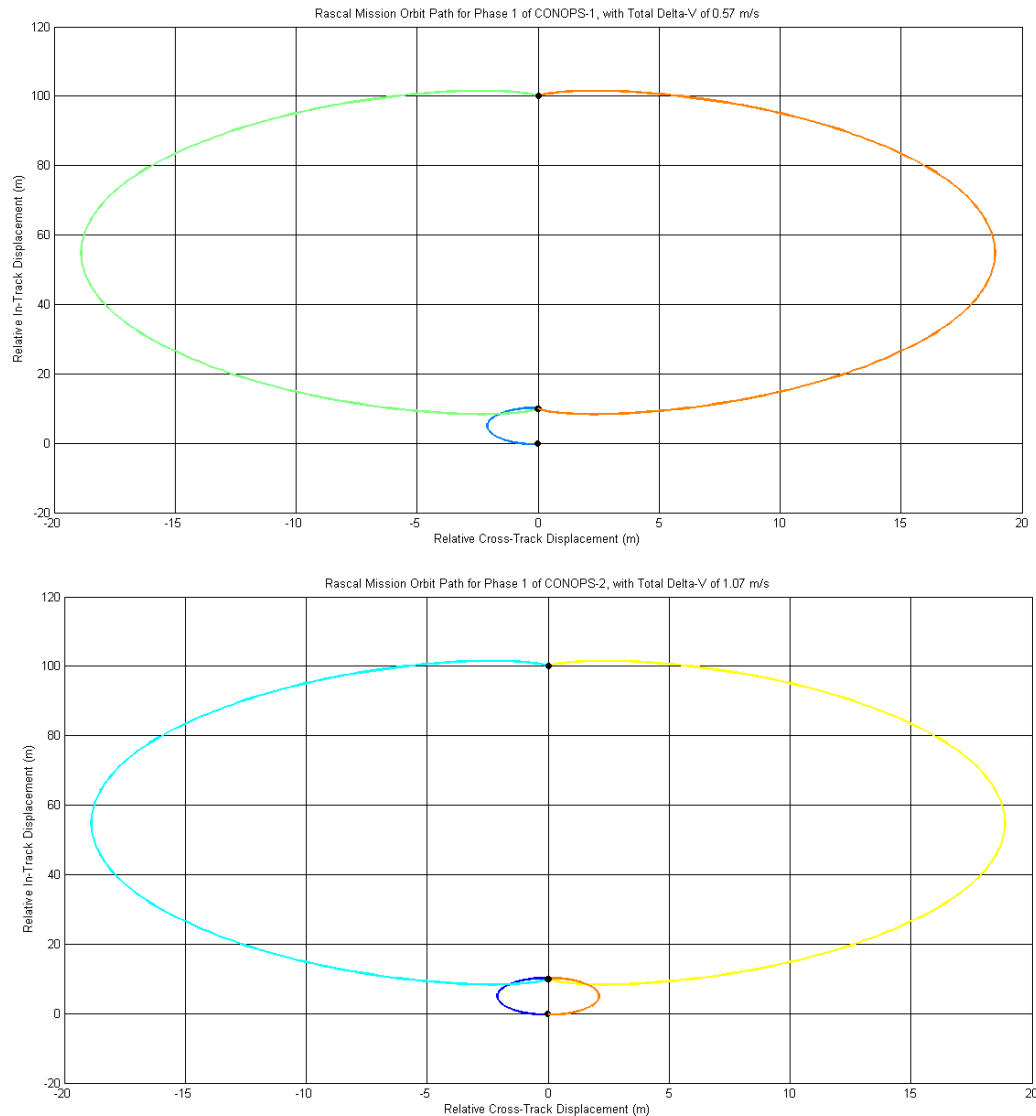


Figure 3-3 Relative Displacement between target and interceptor for Phase 1 of each CONOPS for low $V_{sep,ib}$ and r_{isk} and r_{rsk} in-track. For this case, the ΔV required to perform stationkeeping is effectively zero, with the majority of the ΔV cost being a result of mitigating the initial separation velocity between the target and interceptor (Which was 0.0005 km/s in this case). It is for this reason that CONOPS-2 utilizes twice as much ΔV as CONOPS-1: it requires two separation maneuvers, as opposed to just one.

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Separation, RSK, Rendezvous, and Docking). The ISK and RSK distances are each indicated by black dots.

As discussed in the caption for Figure 3-3, CONOPS-2 requires more ΔV for its execution than CONOPS-1. This is mainly due to the fact that CONOPS-2 requires the performance of two separation maneuvers, one to initially separate, and one to separate after docking. Since this maneuver is the most costly in terms of ΔV , and the ΔV for RSK is essentially zero, CONOPS-2 ends up requiring twice as much ΔV . Regardless, neither mission requires a high amount of ΔV , with CONOPS-2's total coming in at a meager 1.07 m/s (Roughly 1% of the total ΔV that would be available for a 100 m/s propulsion tank).

The total ΔV required for each maneuver is shown in Table 3-1.

3.1.2.2. High $V_{sep,i}$, r_{isk} and r_{rsk} Both Solely in In-Track Direction

The next case that was analyzed was the same as that in the previous section, but with variations in the initial separation velocity. For each case CONOPS, linearly varying the initial separation velocity in the In-Track direction effectively increased the total ΔV for the mission in a linear fashion, with CONOPS-2 being twice as affected as CONOPS-1 (once again due to the necessity of separating twice).

Table 3-2 Total ΔV required for High $V_{sep,i}$, r_{isk} and r_{rsk} in In-Track direction

Initial Separation Velocity (m/s)			Total ΔV (m/s)	
X	Y	Z	CONOPS-1	CONOPS-2
0	0.5	0	0.57	1.07
0	1.0	0	1.07	2.07
0	2.0	0	2.07	4.07
0	3.0	0	3.07	6.07
0.5	0.5	0	1.18	0.77
1.0	0.5	0	1.18	2.31
2.0	0.5	0	2.13	4.19
0	0.5	0.5	0.77	1.48
0	0.5	1.0	1.18	2.31
0	0.5	2.0	2.13	4.19

Table 3-1 ΔV required for Each Maneuver for low $V_{sep,i}$, r_{isk} and r_{rsk} in In-Track direction

Maneuver	ΔV (m/s)
Initial Separation	0.5011
ISK	0.0000
Continued Separation	0.0110
RSK	0.0000
Rendezvous	0.0110
Docking	0.0012
CONOPS-1	0.668
CONOPS-2	1.0704

If the initial In-Track relative velocity is held constant while the Out-of-Plane or Cross-Track relative velocities are varied, the total ΔV increases yet again, but at a slightly slower rate than in the previous case.

The results of this analysis for each $V_{sep,i}$ case is shown in Table 3-2.

3.1.2.3. Low $V_{sep,i}$, r_{isk} and r_{rsk} Perturbed into Cross-Track and Out-of Plane Direction

For this case, the initial separation velocity between each spacecraft was limited to the in-track direction, while the RSK and ISK distances were perturbed just outside of the in-line direction into both the out-of-plane and cross-track directions. Figure 3-4 shows an example of the orbital path that

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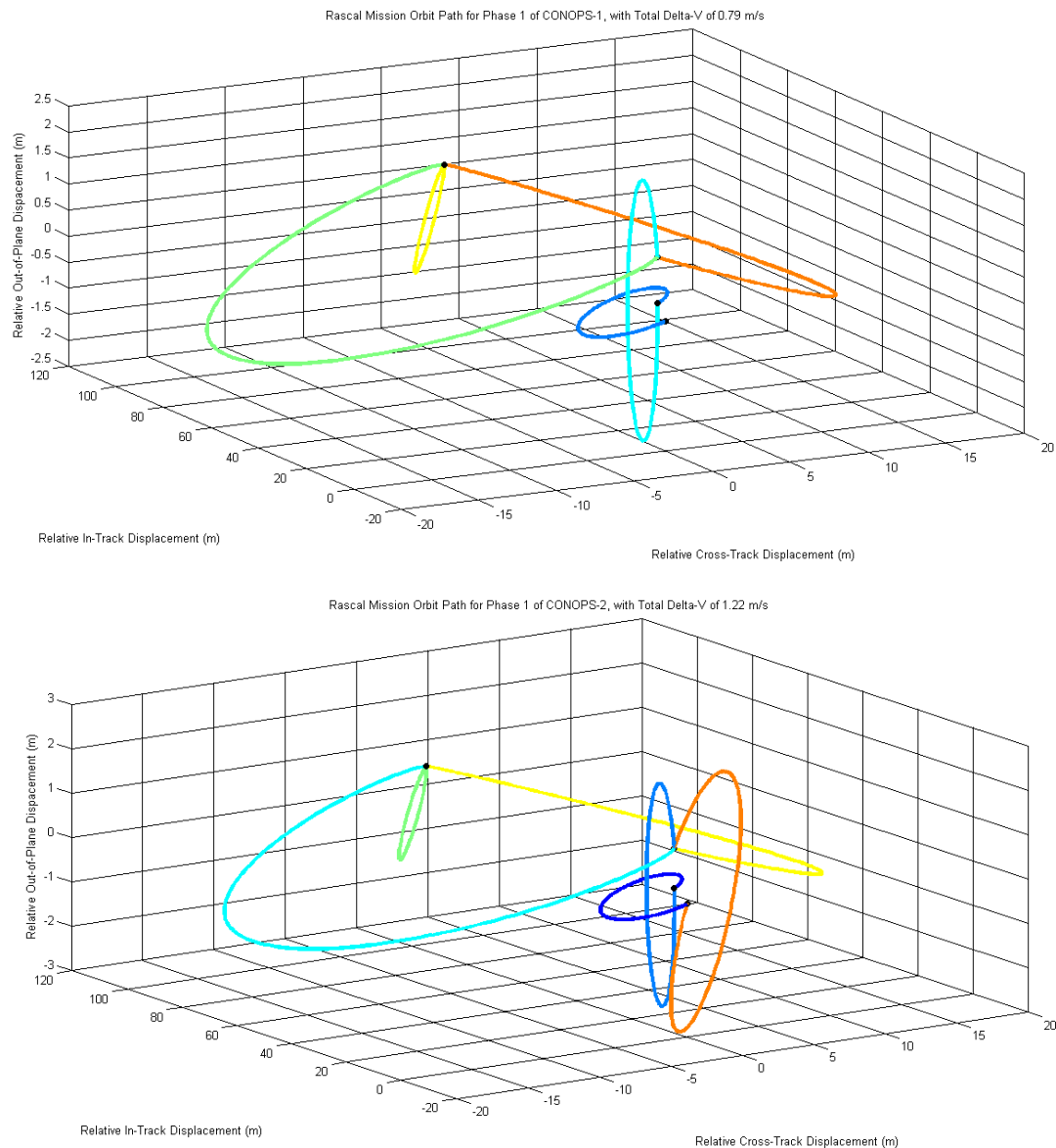


Figure 3-4 Relative Displacement between target and interceptor for Phase 1 of each CONOPS for low $V_{sep,i}$ and perturbation for RSK and ISK into cross-track and out-of-plane directions. For this case, the ΔV required to perform stationkeeping is no longer zero, meaning that the longer the interceptor has to stationkeep, the more ΔV it must expend. However, the majority of the ΔV cost is still a result of mitigating the initial separation velocity between the target and interceptor (Which was 0.0005 km/s in this case). This effect still results in the ΔV for CONOPS-2 being greater than that of CONOPS-1

would be followed for this case for both CONOPS-1 and CONOPS-2.

As discussed in the caption for Figure 3-4, this case still results in the ΔV usage for CONOPS-2 being greater than that of CONOPS-1. However, since not all of the motion is being concentrated in the in-track direction, ΔV now has to be expended in order to stationkeep. If this ΔV usage were to increase even a small amount, the total ΔV required for CONOPS-1 would increase substantially, as it necessitates stationkeeping for an entire day between each phase of the mission, whereas CONOPS-2 only requires

this between one phase.

Table 3-3 ΔV required for Each Maneuver for low $V_{sep,lb}$, r_{isk} and r_{rsk} perturbations

Maneuver	ΔV for Each Perturbation Case (m/s)			
	1 m	5 m	10 m	100 m
Initial Separation	0.5033	0.5134	0.5288	1.0791
ISK	0.0067	0.0216	0.0432	0.4325
Continued Separation	0.0151	0.0323	0.0538	0.4430
RSK	0.0043	0.0216	0.0432	0.4325
Rendezvous	0.0069	0.0116	0.0329	0.4220
Docking	0.0084	0.0418	0.0837	0.8369
CONOPS-1	0.7903	1.3801	2.2593	18.3775
CONOPS-2	1.2165	1.6746	2.3501	15.0760

Thus, if the RSK and ISK perturbations from the in-track direction were to increase, the ΔV for stationkeeping should increase, as is seen in Table 3-3, when the ΔV for CONOPS-1 eclipses that of CONOPS-2, even with one few separation events. As the perturbations begin to increase further, they cease to become minimal in their effects, instead dictating the ΔV usage for the entire mission, as seen in the final column of Table 3-3. Since it is unrealistic for the interceptor to maintain a distance from the target solely in the in-track direction (both from a geometric and controls perspective), it is important to

note the affects of these kind of perturbations on the ΔV required to execute the mission.

Table 3-4 Total ΔV required for High $V_{sep,lb}$, Perturbed r_{isk} and r_{rsk}

Initial Separation Velocity (m/s)			Total ΔV (m/s)	
X	Y	Z	CONOPS-1	CONOPS-2
0	0.5	0	1.38	1.67
0	1.0	0	1.88	2.67
0	2.0	0	2.88	4.67
0	3.0	0	3.88	6.67
0.5	0.5	0	1.60	2.12
1.0	0.5	0	2.02	2.95
2.0	0.5	0	2.96	4.83
0.5	0.5	0.5	1.77	2.46
1.0	0.5	1.0	2.41	3.73
2.0	0.5	2.0	3.78	6.48

However, changing the RSK and ISK distances does not have nearly as great of an affect as changing the initial relative velocity condition, as will be seen in the next case study.

3.1.2.4. High $V_{sep,lb}$, r_{isk} and r_{rsk} Perturbed into the Cross-Track and Out-of-Plane Directions

For this test case, the previous case of perturbed stationkeeping distances was kept constant, while the initial separation velocity between the target and interceptor spacecraft was varied. Just like the second test case, the ΔV

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required for CONOPS-2 was more greatly affected by this variation than that of CONOPS-1. However, the variation as a result of perturbing the RSK and ISK distances by 10 meters (as was done in this case) does not greatly affect the ΔV required for either CONOPS. This is an indication that variations in initial relative velocity are the driving factors behind the total ΔV required for the mission as a whole.

3.1.2.5. Low $V_{sep,b}$ No r_{rsk} or r_{isk} Perturbation, V_{isk} Perturbation

The final test case consisted of an analysis of the affect of varying the initial relative velocity between each spacecraft at the beginning of an ISK maneuver. Varying this parameter for the ISK maneuvers was done due to it being the main distinguishing factor between CONOPS-1 and CONOPS-2. If there were some sort of mistiming in when a particular ISK maneuver is performed, either due to sensor error, non-impulsive thrusting, or other means, more ΔV would have to be expended in order to account for the non-zero relative velocity between the target and chaser spacecraft, as demonstrated in Table 3-5. Even for

Table 3-5 Total ΔV required for perturbation in initial ISK relative velocity

Initial Relative Velocity (m/s)	Total ΔV (m/s)	
	CONOPS-1	CONOPS-2
0.1	4.97	4.37
0.2	8.07	6.07
0.3	11.17	7.77
0.4	14.27	9.47
0.5	17.37	11.17
1.0	32.87	19.67
2.0	63.87	36.67
3.0	94.87	53.67

small perturbations in initial relative ISK velocity, the total ΔV for both mission increases substantially, going from 0.69 m/s to 4.97 m/s for CONOPS-1 and from 1.07 m/s to 4.37 m/s in the 0.1 m/s case. This affect only increases as the initial relative velocity value increases, affecting CONOPS-1 much more quickly than CONOPS-2, since the former requires a whole extra day of ISK compared to the latter.

Thus, this test case demonstrates the importance of timing when it comes to performing each maneuver, as well as the benefits that come along with the ability to dock between mission phases, as is possible in CONOPS-2.

3.1.3. ΔV Comparison Conclusions

With each of these test cases in mind, a few conclusions can be made from the Rascal mission ΔV analysis:

1 For an ideal mission, ΔV is a non-factor for either CONOPS.

This statement relates to being able to execute the mission entirely in the In-Track direction. This would reduce the ΔV required to perform stationkeeping (something that has to be done for a whole day between mission phases) to zero, producing extremely high margins for both missions. As a result, neither CONOPS can really be considered more desirable than the other from a ΔV perspective.

2 An ideal mission is not feasible.

This idea relates to the perturbation analysis performed in test cases three and four. For small deviations in stationkeeping displacements, large effects on the ΔV required to perform either mission are observed. If these deviations are large enough, the stationkeeping requirement between each mission phase increases to the point of making the ΔV required for CONOPS-1 greater than that of CONOPS-2. Though this does not happen until high perturbations are observed (10+ meters), it is a factor to consider when comparing each CONOPS.

With regards to the feasibility of performing an ideal mission, it is highly unlikely that stationkeeping would be precise enough to keep all motion in the In-Track direction. More than likely, both the geometry

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of a spacecraft's orbit, as well as the influences of third-bodies, solar radiation pressure, and inaccuracies within Rascal's control algorithms will lead to the perturbations that were discussed and studied in the later test cases. As such, it is those two cases that are most important in assessing the ΔV requirements of any form of the Rascal mission.

Table 3-6 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 3-7 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

3 Initial relative velocity governs all.

As can be seen from test case two and four, small variations in initial relative velocity have a large impact on the overall ΔV required to perform any kind of proximity operation. For example, varying the RSK distance by 0.5 meters has a negligible effect on the ΔV required to perform the mission. Varying the initial separation velocity, on the other hand, can increase the ΔV required for the mission by twofold. As such, one of the most important limiting parameters on any mission (but especially for one involving docking) would be that of the initial separation velocity between each spacecraft.

4 Timing is crucial.

Finally, each part of this analysis assumed that each maneuver was performed at the end of the previous maneuver, implying that the starting relative velocity between each spacecraft would be zero. As discussed in the previous point, if this were not the case, the ΔV required to perform a given maneuver would increase substantially, greatly affecting the total ΔV required to perform the mission, as shown in the final test case. As such, thruster timing and maneuvering are crucial in limiting the ΔV required for any mission.

With these lessons in mind, it can be concluded that CONOPS-2 would likely require more ΔV to be executed than CONOPS-1, but the difference between each of them is quite minimal under most circumstances.

3.2. 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 3-6 and Table 3-7.

Table 3-8 Risk Likelihood vs Consequence for CONOPS-1

Likelihood					
				IV	
		I		V, VII, VIII	II, VI, IX
			III		
	Consequence				

3.2.1 CONOPS-1 Risk

Assessment

Table 3-8 summarizes the various risks associated with CONOPS-1, each of which is discussed in greater detail below.

3.2.1.1 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.

3.2.1.2 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.

3.2.1.3 Initial Separation Velocity is too High

As discussed in the ΔV comparison section, one of the main drivers between the ΔV required to execute the Rascal mission is the initial separation velocity between the target and interceptor spacecraft. If this value is too high, it can necessitate the use of more fuel to be used to execute the mission as a whole, which can negatively impact the ability of the interceptor to perform the whole Rascal mission. However, unless this high initial separation velocity is coupled with poor thrust timing in the rest of the mission, the mission can easily be executed for initial relative velocities up to 5 m/s (Two times faster than a CubeSat is shot out of a P-POD). This risk can also be mitigated through extensive ground testing and planning. As such, it is a low likelihood, mildly consequential risk.

3.2.1.4 Primary Spacecraft Unable to Locate Secondary Spacecraft

One of the greatest risks associated with the Rascal mission, regardless of approach, is the ability of the primary spacecraft to orient in such a manner that it can identify and determine the distance between it and the target spacecraft. If it were unable to do this early on, the target spacecraft would still be in its Cooperative State, meaning that it is constantly beaconing its GPS location, as well as powering the visual aids used to help the primary spacecraft's payload identify its target. Though this risk has a higher likelihood of taking place, it would not be mission ending, as it allows for a "redo" of the mission through the use of GPS and visual aid data.

3.2.1.5 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.

3.2.1.6 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.

Table 3-9 Risk of Likelihood vs Consequence for CONOPS-2

Likelihood					
			VI	IV	
		I		V, X, XI	II, VI, VII, IX
			III		
Consequence					

3.2.1.7 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.

3.2.1.8 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.

3.2.1.9 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.

3.2.2 CONOPS-2 Risk Assessment

Table 3-9 summarizes the risks associated with CONOPS-2, each of which is discussed in greater detail below.

3.2.2.1 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.

3.2.2.2 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. Since CONOPS-2 involves two such separation events, it has a slightly greater risk of taking place. However, as stated, this risk can be mitigated through extensive ground testing and analysis.

3.2.2.1 Initial Separation Velocity is too High

As discussed in the risk assessment for CONOPS-1, high initial separation velocities lead to more fuel having to be expended over the course of the Rascal mission. Since CONOPS-2 involves two separation events, the odds of separating at a less than ideal velocity are slightly greater than that of CONOPS-1. The impact of such an event is also slightly greater, as shown in the ΔV comparison section. Regardless, this risk can once again be mitigated through the implementation of extensive ground testing and analysis.

3.2.2.2 Primary Spacecraft Unable to Locate Secondary Spacecraft

As stated in the CONOPS-1 risk assessment, one of the riskiest portions of the Rascal mission is whether or not the interceptor spacecraft will be capable of locating and performing maneuvers relative to its target. This risk does not change between either CONOPS, meaning that it can be mitigated in the same

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fashion discussed in the previous risk assessment.

3.2.2.3 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.

3.2.2.4 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.

3.2.2.5 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.

3.2.2.6 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.

3.2.2.7 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.

3.2.2.8 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.

3.2.2.9 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.

3.2.3 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.

3.3. Mission Relevance Comparison

As discussed in the previous sections, 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

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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.

3.4. Cost Comparison

In order to determine the costs associated with the development of the Rascal mission, it is important to

Table 3-10 Estimated Mission Cost

Secondary Spacecraft		
Subsystem	Component	Cost
COM	Radio	\$5,000.00
	Antennas	\$12.00
ADC	Hysteresis	\$125.00
	Magnets	\$2.58
	GPS	\$7,980.00
	GPS Antenna	\$1,000.00
CDH	Motherboard	\$1,200.00
	PPM	\$500.00
PLD	Visual Aids	\$50.00
STR	3U Structure	\$2,250.00
PWR	Board	\$400.00
	Batteries	\$155.88
Secondary Total Cost		\$18,675.46
Primary Spacecraft		
PLD	IR Camera	\$7,000.00
	Optical Camera	\$100.00
	Processor	\$130.00
	Interface	\$400.00
PRP	Tank	\$5,000.00
	Propellant	\$150.00
	Controller	\$400.00
STR	Mating	\$4,225.00
Primary Total Cost		\$17,405.00
Total Cost		
\$36,080.46		

first define the major subsystems necessary to make the mission possible. This was accomplished by separating each subsystem into two categories: Primary and Secondary. Primary subsystems include Payload (image sensing and processing), Propulsion (tank, valves, and control), and Attitude Determination and Control (navigation algorithms and components). Secondary subsystems include Structures (skeleton and custom parts), Power (batteries and electrical power system), Command and Data Handling (motherboard and processor), Attitude Determination and Control (magnets and hysteresis rods), and Communications (radio and antennas).

With this in mind, the cost analysis for both CONOPS was made using all of the propulsion subsystem components and tank valves were already on hand. Two possible methods for docking, docking with magnets or with Velcro, were also used in the CONOPS-2 analysis. For the secondary spacecraft, the communication subsystem, the command and data handling system, the power subsystem, and everything, but the GPS and the GPS antenna, for the attitude determination and control subsystem were estimated based on previous SSRL missions. The structure and GPS estimates came from Pumpkin Inc.'s website. The GPS antenna estimate came from Antcom. The visual aids were estimated assuming the use of LEDs. The payload cost for the primary spacecraft was estimated based off experience from COPPER and from estimates from the payload team. The propulsion cost estimated is based off of a trade performed by another SSRL group. TiNi Aerospace's ERM-250 provided the basis for the mating mechanism. The magnet method for docking was based off small neodymium magnets and an electromagnet. The Velcro docking method cost was estimated using a sheet of Velcro and a means to separate the two spacecraft. These costs are summarized in Table 3-10.

Looking at the total cost for both CONOPS, there is not much different between CONOPS-1 and 2. Most of the cost comes from the non-optional subsystem components. There is not much difference between the two docking methods

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either. These docking methods were used for cost analysis and do not reflect the final design of the mission.

4 Conclusion

Based on the discussion laid out in Section 3, it is difficult to quantize the differences between CONOPS-1 and CONOPS-2 in a meaningful way. They each share many risks in common and effectively have the same costs and ΔV requirements associated with their execution.

However, CONOPS-2 has three distinguishing characteristics that help differentiated from CONOPS-1:

- 1 It allows for the ability to “pause” the mission, eliminating the risk associated with either a) attempting to execute the mission too quickly or b) extending the mission for too long and risking losing the target.**
- 2 It helps eliminate the timing risk associated with performing ISK, limiting the necessity of performing said maneuver to a single time per phase, rather than having to do it for two entire days between each mission phase.**
- 3 It demonstrates more with less, allowing for an accelerated path for the RPO demonstrations that it is performing to be integrated into future inspection missions.**

We believe that these benefits outweigh the added risks associated with running CONOPS-2 when compared to CONOPS-1 and recommend pursuing CONOPS-2 from this point onward.

5 References

[1] Prussing, John E., and Bruce A. Conway. Orbital Mechanics. New York: Oxford UP, 1993.