Rascal Concept of Operations Trade Study

Saint Louis University

Rascal



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Copper Operational

Test Plan

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# Introduction

## 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.

## 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 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:

* **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.

# Concept(s) of Operations



## 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.

## 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.

Rascal ConOps NO Docking.tif

**Figure 2‑1CONOPS-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.

### 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.

#### 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).

#### 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).

#### 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.

#### 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.

### 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.

#### 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.

#### 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.

#### 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.

#### 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.

#### 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.

#### Phase 1-F: Verify RSK

Max Separation Distance.tif

**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.

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.

#### 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.

#### 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.

### 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.

### 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.

### 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.

## 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.

CONOPS 2 Illustration.tif

**Figure 2‑3CONOPS-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.



### 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.

### 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.

#### 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.

### 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.

### 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.

### 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.

# 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.

## 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.

### 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 **r** is the inertial position of a spacecraft, is the acceleration of said object spacecraft, **g(r)** is the influence of a general gravitational field, and Γ is the thrust acceleration vector of the spacecraft.

(1)

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

The simplest coordinate frame to utilize for linear orbit theory analysis is that utilized by Clohessy-Wilshire (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 (**rinertial**) 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 **rint** and **rtgt** are the inertial positions of the interceptor and target spacecraft respectively.

CW Coordinate Frame.tif

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

(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:

CW Coordinate Frame Target Spacecraft.tif

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

(3)

Where is defined as the 6x1 vector containing both the components of relative spacecraft position (x,y,z) and velocity ( and is the state transition matrix of relative spacecraft motion, which is defined as:

(4)

Where **M(t)**, **N(t)**, **S(t)**, and **T(t)** are each 3x3 matrices defined as:

(5)

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

(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:

(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:

(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.

### 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 (Vrel,i), relative ISK displacement (risk), and relative RSK displacement (rrsk).

#### Low Vrel,I, rrsk and risk 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 Separation, RSK, Rendezvous, and Docking). The ISK and RSK distances are each indicated by black dots.

Ideal CONOPS-1 All In-Track.tif

Ideal CONOPS-2 All In-Track.tif

**Figure 3‑3 Relative Displacement between target and interceptor for Phase 1 of each CONOPS for low Vsep,i, and risk and rrsk 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 has CONOPS-1: it requires two separation maneuvers, as opposed to just one.

**Table 3‑1 ΔV required for Each Maneuver for low Vsep,I, risk and rrsk in In Track direction**

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

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.

#### High Vsep,i,risk and r­rsk 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).

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 Vsep,i case is shown in Table 3-2.

#### Low Vsep,i, risk and rrsk Perturbed into Cross-Track and Out-of Plane Direction

**Table 3‑2 Total ΔV required for High Vsep,I, risk and rrsk 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 |