

ORION GN&C SEQUENCING FOR OFF-NOMINAL RENDEZVOUS, PROXIMITY OPERATIONS, AND DOCKING

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This paper discusses the Concept of Operations of the nine contingency strategies available for off-nominal Rendezvous, Proximity Operations, and Docking of Orion with the Gateway in a Near-Rectilinear Halo Orbit around the Moon. Explanations are provided for each contingency strategy, how they are initiated, when they can be initiated, and how they are designed to protect the crew. Then an overview is provided of the sequencing of the Guidance, Navigation, and Control flight software used to achieve each contingency strategy, in the form of Phases, Segments, Activities, and Modes. These off-nominal scenarios require the definition of new Segments and Activities.

INTRODUCTION

The goal of NASA’s Artemis program is to sustainably return humans to the Moon. The Orion Multi-Purpose Crew Vehicle will be the vehicle used to transport astronauts to cis-lunar space and to the Gateway for the Artemis program. Orion is responsible for performing Rendezvous, Proximity Operations, and Docking (RPOD) in cis-lunar space with the Gateway in a Near-Rectilinear Halo Orbit (NRHO).¹ The first crewed lunar landing is scheduled to take place in 2024. The Gateway will not be constructed by 2024 in time for this landing, so Orion will instead rendezvous directly with the Human Landing System either in an NRHO or in another orbit nearer to the Moon. This paper focuses on RPOD with Gateway in an NRHO, though some of the concepts may be applicable to other target vehicles or orbit regimes.

In the event of an anomaly during RPOD, Orion must abort its approach to the Gateway for crew and mission safety. Orion will have the capability to abort and reattempt docking on the same crew day, abort and reattempt docking on the next crew day, and abort for early departure. Additionally, each contingency category will be available from NRHO insertion to soft capture. These three categories provide the framework for the nine contingency strategies discussed in this report. This paper is a follow on to “GN&C Sequencing for Orion Rendezvous, Proximity Operations, and Docking”.²

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NOMINAL RPOD CONCEPT OF OPERATIONS

Before understanding the off-nominal RPOD scenarios it is important to have a basic understanding of the nominal RPOD Concept of Operations (ConOps). RPOD begins after Orion has completed the NRHO Insertion burn (NRI). This point begins the Far Range section of the approach. During Far Range RPOD, Orion will complete a series of Rendezvous Burns (RB). These burns require a significant delta-V, so the Orion Main Engine (OME) or Auxiliary (Aux) thrusters will be used. The Aux thrusters are fixed to the spacecraft, and the OME is attached to Thrust Vector Control actuators with only a few degrees of freedom, so Orion must adjust its attitude to point in the direction of the burn before firing the thrusters. This maneuver is called “turn-to-burn,” and is only used for OME/Aux burns. Figure 1 shows the Far Range RPOD trajectory.

The free-drift trajectories of Orion in the Far Range portion of RPOD are passively safe. That is, if Orion were to stop all burns and continue drifting, the vehicle would not be at risk of intercepting the Gateway. However, after RB3 the free-drift trajectory intersects the Approach Sphere (AS), which is a 1 km sphere centered at the Gateway. Since the free-drift trajectory crosses into the AS after HR3, the crew must provide the Authority to Proceed (ATP) before executing RB3. The AS can be seen in Figure 2.

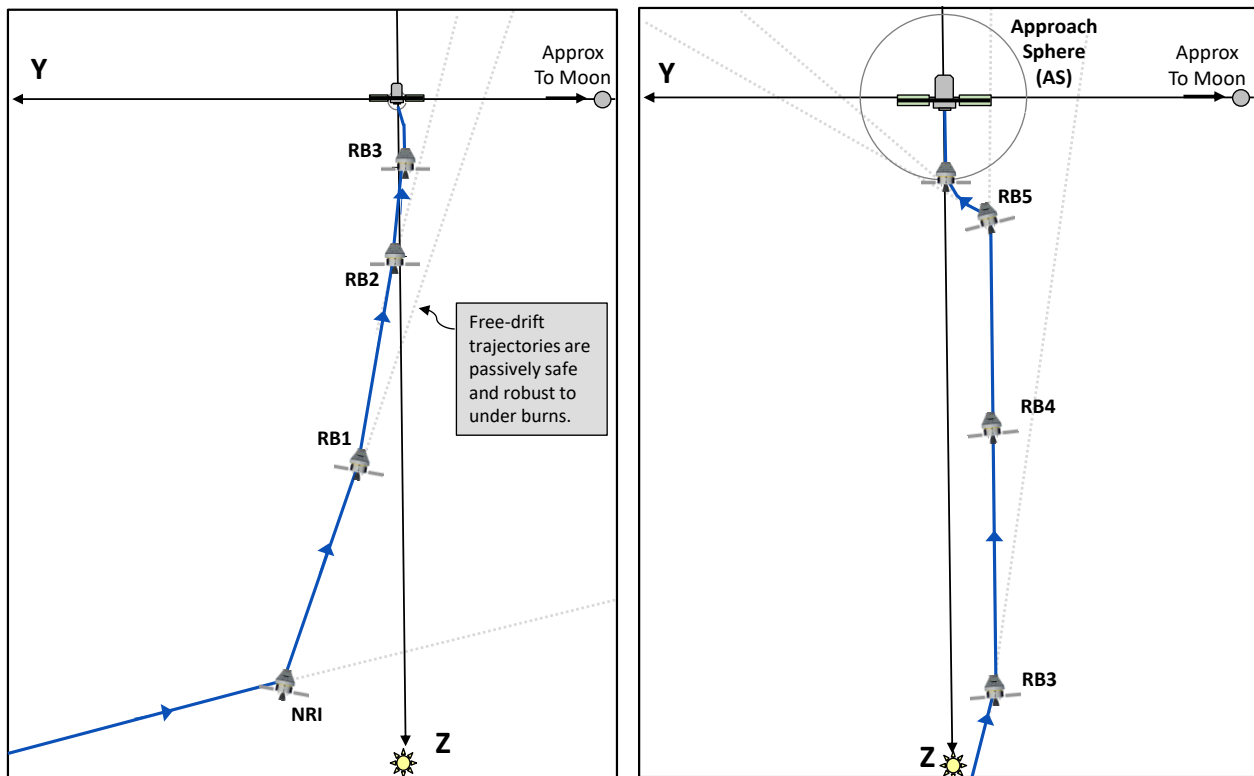


Figure 1. Far Range RPOD trajectory (not to scale).² Figure 2. Mid-Range RPOD trajectory (not to scale).²

Similar to the Approach Sphere after RB3, Orion’s free-drift trajectory crosses the Keep Out Sphere (KOS) after the RB5 burn. The KOS is a 200 m sphere centered at the Gateway. The RB5 burn requires an ATP before executing. Orion begins the Close Range portion of the RPOD trajectory after the execution of RB5. Orion will then complete the RB6 burn. After RB6, Orion begins Braking Gates to reduce its relative velocity at specified ranges as it approaches the

Gateway. When the vehicle's range from Gateway is several meters, it will perform a stationkeeping burn until the crew provides docking ATP. Then, the vehicle will approach and dock with the Gateway. Figure 3 shows the Close Range RPOD trajectory.

Orion will separate from the Gateway after the crew have completed their mission. The vehicle will reverse from the Gateway following a range and range-rate profile until it reaches the initial Departure Burn (DB1) point. From there, Orion will execute a series of Departure Burns to target the NRHO Departure (NRD) point. The departure plan will be unique to each Orion mission after DB1. Figure 4 shows an example departure trajectory.

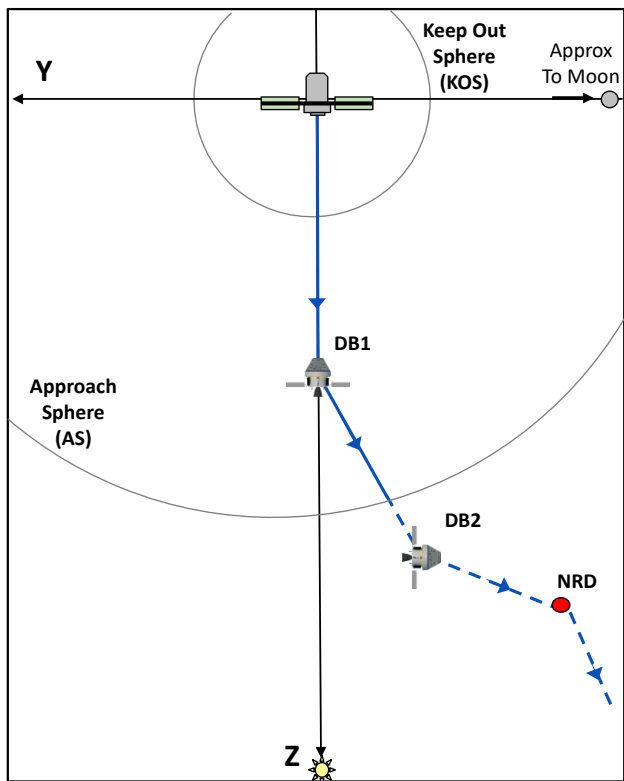
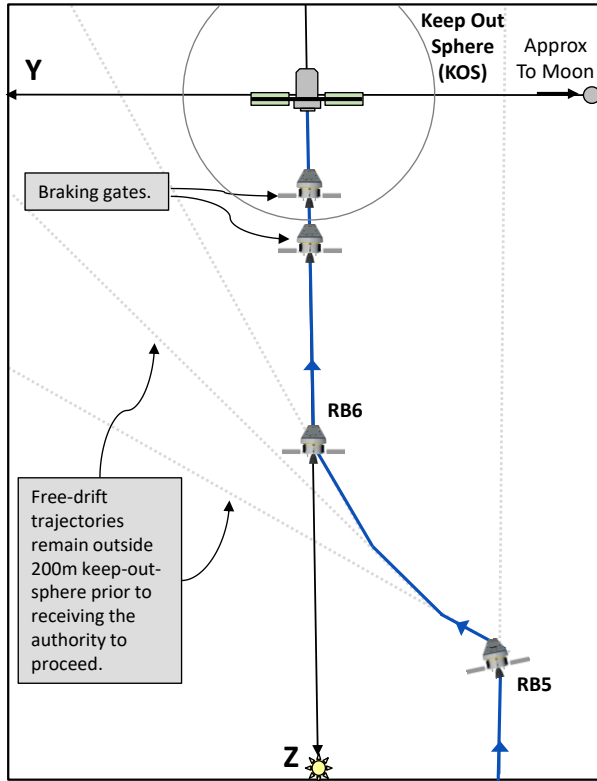


Figure 3. Close Range RPOD trajectory (not to scale).² Figure 4. RPOD Departure trajectory (not to scale).²

OFF-NOMINAL RPOD CONOPS

This section describes the Concept of Operations for each off-nominal scenario. There are three different contingency categories utilized for Orion RPOD: abort and same day docking, abort and next day docking, and abort and early departure. Orion has the ability to execute at least one contingency strategy from each category at any point along the RPOD trajectory.

Abort and Same Day Docking

The purpose of Abort and Same Day Docking strategies is to temporarily abort the approach towards the Gateway but maintain the ability to reattempt docking during the same crew day. These contingency strategies are intended to be used if a minor issue is detected that could prevent the vehicle from docking nominally. If the issue is not quickly resolvable and more than a few hours will be added to the nominal docking timeline, the crew will be required to initiate an Abort and Next Day Docking strategy to avoid interference with the crew's sleep schedule. The

crew day can be extended if needed, but that decision will be made by the Operations team. Same day docking contingency strategies are useful transitions to Abort and Next Day Docking strategies or Abort and Early Departure strategies. It is always preferable to perform a same day docking abort first, if possible, for minimal impact on the crew and mission.

Same Day Strategy #1: Stationkeep. The first contingency strategy is stationkeeping. In this strategy the vehicle executes a Rendezvous (RNDZ) Null burn to null its velocity relative to the Gateway. Then, it uses SM RCS thrusters to execute a series of Stationkeep (SK) burns to maintain a zero relative velocity. When the crew is ready to resume the RPOD approach, they will provide Restart ATP. Orion will then resume along the nominal trajectory from its current position. This contingency strategy can be initiated anywhere along the trajectory, from NRI until Soft Capture. However, if the abort is initiated before the RB3 burn, the vehicle will continue along the nominal trajectory until RB3 and will stationkeep at that point. Figure 5 shows an example of the Stationkeeping strategy.

Same Day Strategy #2: Retreat to Hold Point. The second contingency strategy is retreat to the hold point and stationkeep. When this contingency strategy is initiated, the vehicle will execute a Null/Retreat burn. Then, the vehicle will retreat from the Gateway following the reverse Braking Gate range-range rate profile. Once the vehicle has retreated to the Hold Point, it will perform another null burn and begin actively stationkeeping. Similarly, the crew will provide a Restart ATP when they are ready to dock. This strategy can only be executed after passing the Hold Point and before Soft Capture. Figure 6 illustrates an example of the Retreat to Hold Point strategy.

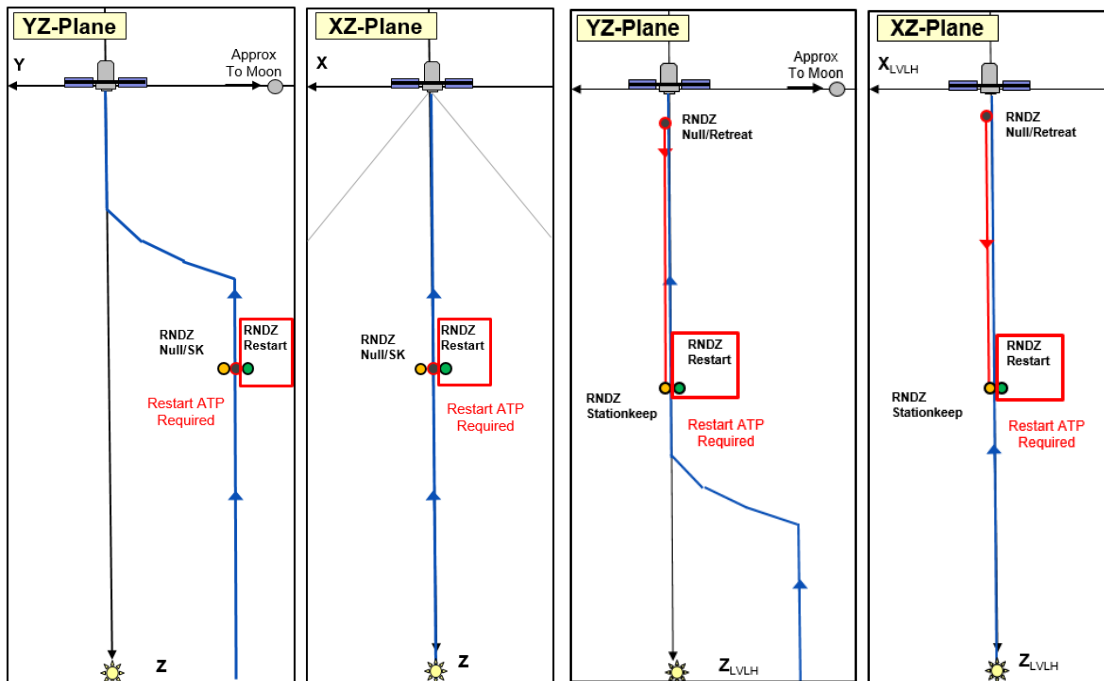


Figure 5. Same Day Strategy 1: Stationkeep (not to scale).

Figure 6. Same Day Strategy 2: Retreat to Hold Point (not to scale).

Same Day Strategy #3: Retreat Along Docking Axis. In this contingency strategy, the vehicle will execute a Null/Retreat burn and follow the reverse Braking Gate range-range rate profile. Once the vehicle has retreated past all Braking Gates, it will passively coast along the docking

axis away from Gateway. The Retreat Along Docking Axis strategy is only viable after RB6 until Soft Capture. Once the crew is prepared to recover the vehicle, they must select between two recovery methods: Recovery Method A and Recovery Method B. These methods are discussed in more detail below. After the crew has provided Recovery ATP the vehicle executes the Recovery burn at the calculated location, which is dependent on the Recovery Method selected by the crew. It is worth noting that if the crew never provides the Recovery ATP, Orion will continue to drift backwards until commanded otherwise. Figure 7 depicts the Retreat Along Docking Axis strategy with both Recovery methods. For Recovery Method A, Orion will recover along the docking axis until it reaches the Restart point at the nominal RB6 point. At RB6, the vehicle will execute a Restart burn and resume the nominal approach. For Recovery Method B, Orion executes a Recovery burn targeting the trajectory parallel to the docking axis in the nominal approach. The Restart Point is selected to be the next closest nominal burn point along the parallel trajectory. When the vehicle reaches the parallel trajectory it will execute a Restart burn and resume the nominal approach from this point.

Same Day Strategy #4: Retreat Along Parallel to the Docking Axis. The final Abort and Same Day Docking strategy is to Retreat Along Parallel to the Docking Axis. In this strategy, the vehicle will perform a Null/Retreat burn and coast backwards along the parallel trajectory. When the crew provides Recovery ATP, the vehicle will perform a Pre-Recovery burn targeting the Recovery point. When the vehicle reaches the Recovery point, it will perform a Recovery burn targeting the Restart point. At the Restart point, Orion will execute the Restart burn and continue along the nominal trajectory. If the crew does not provide Recovery ATP, the vehicle will continue to drift backwards along the parallel trajectory. This contingency strategy can be initiated only after the RB3 burn and before the RB5 burn. Figure 8 shows the Retreat Along Parallel to the Docking Axis contingency strategy.

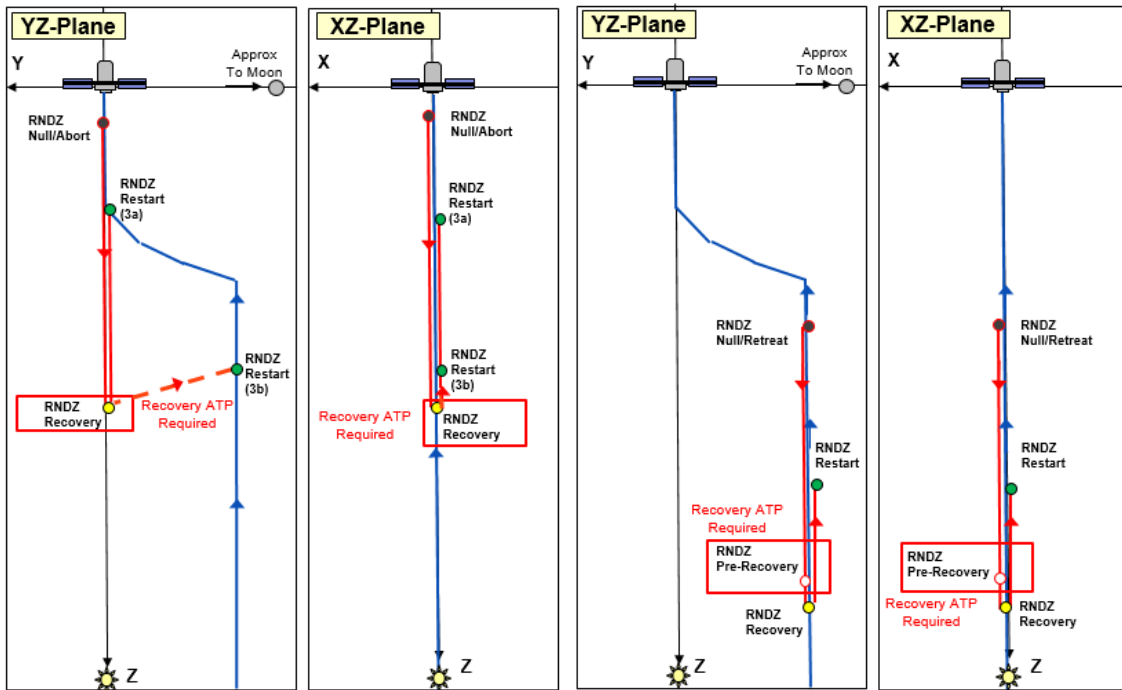


Figure 7. Same Day Strategy 3: Retreat Along the Docking Axis (not to scale).

Figure 8. Same Day Strategy 4: Retreat Along Parallel to the Docking Axis (not to scale).

Abort and Next Day Docking

The second category of contingency strategies is Abort and Next Day Docking. These strategies will abort the approach trajectory of Orion and provide the crew the ability to sleep before reattempting docking. These strategies are intended to be used for anomalies that cannot be solved within the same crew day but do not necessitate the early departure of the spacecraft and the premature ending of the mission. These strategies create an impact on mission timelines and are therefore less desirable than the Abort and Same Day Docking strategies. The three strategies in this category share a common Recovery point and a common Restart point. The Recovery point is several km from Gateway along the Z-axis and a few km out-of-plane on the X-axis. The Restart point is located at RB3.

Next Day Strategy #1: Retreat to Rendezvous Recovery Point. The first Abort and Next Day Docking strategy is used after the start of the Braking Gates and before Soft Capture. When this strategy is initiated, the vehicle will perform a Null/Retreat burn to back away from the Gateway to an Abort Point. As the vehicle retreats, it will follow the reverse Braking Gate range and range-rate profile along the docking axis. At the Abort Point, the vehicle will perform an abort burn targeting the Recovery point. The spacecraft will passively drift towards the Recovery point until the crew's pre-sleep period is about to begin. Immediately before the pre-sleep period, there will be a Midcourse burn. This burn will correct any errors in the trajectory and should nominally be zero. The vehicle will continue drifting towards the Recovery point while the crew sleeps. The vehicle will reach the Recovery point soon after the crew wakes up, allowing for a post-sleep period. Then, the vehicle will perform a Recovery burn to target the RB3 Restart point. Once the Restart point is reached and a Restart burn is executed, the vehicle will resume the nominal trajectory approach to dock with the Gateway. Figure 9 shows the Retreat to Rendezvous Recovery Point abort strategy.

Next Day Strategy #2: Abort to Rendezvous Recovery Point. The next contingency strategy is very similar to the Retreat to Rendezvous Recovery Point strategy except for the location that it is initiated. This strategy can only be initiated between RB2 and the start of Braking Gates. In this strategy, the vehicle performs a Null burn at its current location. If the vehicle is between RB2 and RB3 when an abort is declared, it will continue to the RB3 point before executing the Null burn. After the Null burn, the spacecraft executes an Abort burn targeting the Recovery point. This strategy and the Retreat to Rendezvous Recovery Point strategy are functionally identical after the Abort burns. Refer to the Retreat to Rendezvous Recovery Point subsection above for the details. Figure 10 shows the Abort to Rendezvous Recovery Point strategy.

Next Day Strategy #3: RB2 and Prior Abort. The RB2 and Prior Abort is also similar to the first two Abort and Next Day Docking strategies. As the name of this strategy indicates, this contingency strategy can only be triggered at or before RB2. When the vehicle reaches RB2 it will perform a Null burn and a Single Burn Stationkeep, which is designed to keep the vehicle at the RB2 point. Once the crew's pre-sleep period is about to begin, Orion will execute an Abort burn, targeting the Recovery point. The rest of this contingency strategy is identical to Next Day Strategies #1 and #2. Figure 11 shows the RB2 and Prior Abort strategy.

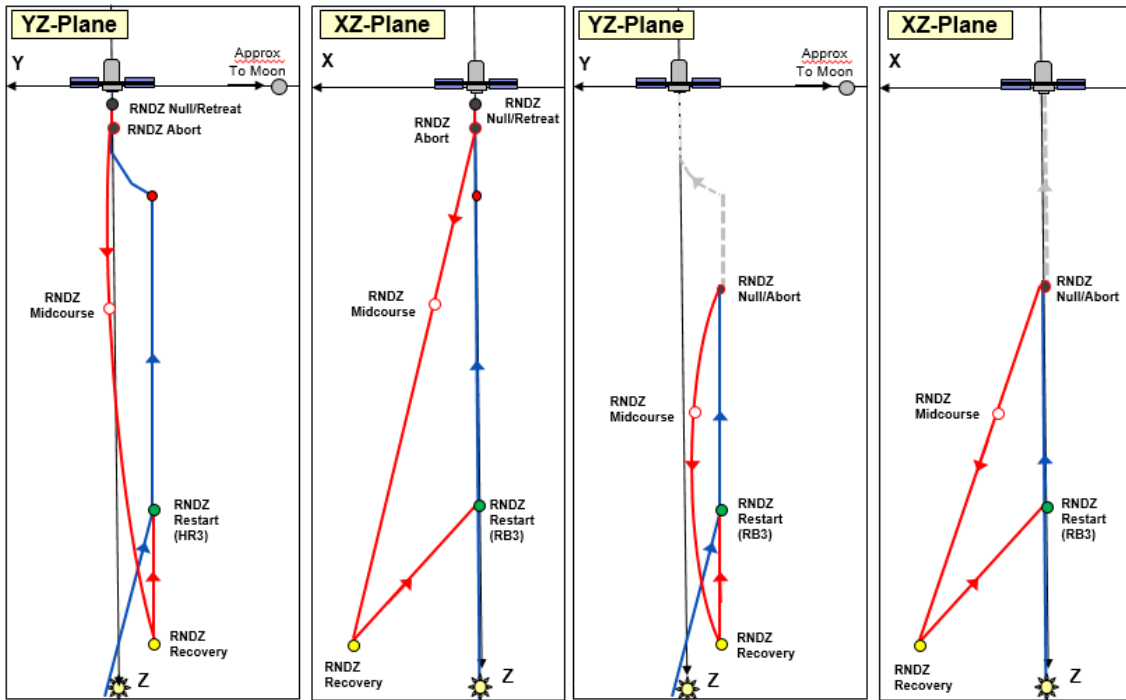


Figure 9. Next Day Strategy 1: Retreat to Rendezvous Recovery Point (not to scale).

Figure 10. Next Day Strategy 2: Abort to Rendezvous Recovery Point (not to scale).

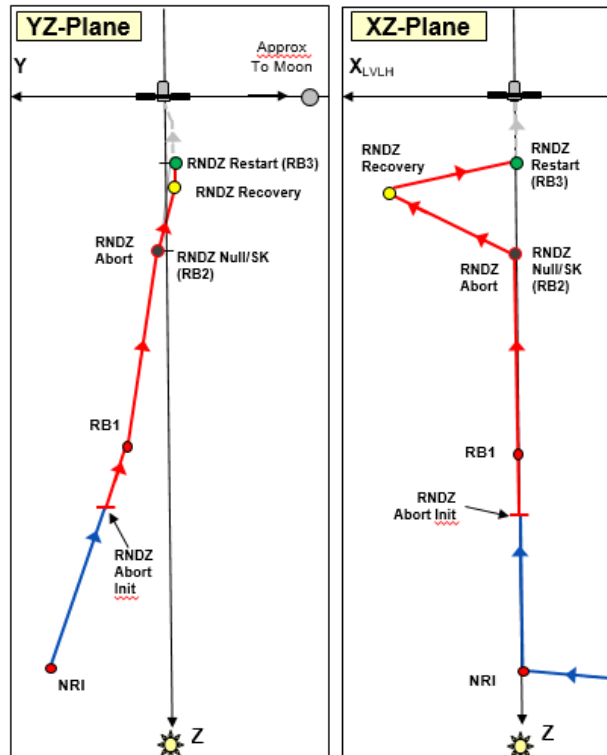


Figure 11. Next Day Strategy 3: RB2 and Prior Abort (not to scale).

Abort and Early Departure

The final category of contingency strategies is Abort and Early Departure. These strategies are designed for significant anomalies that will prevent the crew from executing their mission safely. Abort and Early Departure is a last-case option to prematurely cancel the mission for the health and safety of the crew.

Early Departure Strategy #1: Retreat, Departure Burn, and Target NRD. The first Early Departure strategy is Retreat, Departure Burn, and Target NRD. This strategy is used between ADA and Soft Capture. When initiated by the crew, the vehicle will perform a Null/Retreat burn and back away from the Gateway according to the reverse Braking Gate range and range-rate profile. Then, the vehicle will execute the nominal departure plan. The departure burn plan will be mission specific, so the details of this burn will be different for every mission. Figure 12 depicts an example of the Retreat, Departure Burn, and Target NRD strategy.

Early Departure Strategy #2: Free-Drift and Target NRD. The final contingency strategy is Free-Drift and Target NRD. The free-drift trajectories are designed to be passively safe to allow for this abort option. This strategy can be initiated at any time between NRI and RB6, except for during the RB5 burn (in which the trajectory is crossing through the KOS). When initiated, the vehicle will cancel all planned burns and passively drift past the Gateway. The Ground will be required to upload a new departure burn plan to recover the spacecraft. The vehicle will target the NRD point to return the crew safely to Earth. As mentioned above, the departure plan and Departure point will be mission specific. Figure 13 shows the Free-Drift and Target NRD strategy.

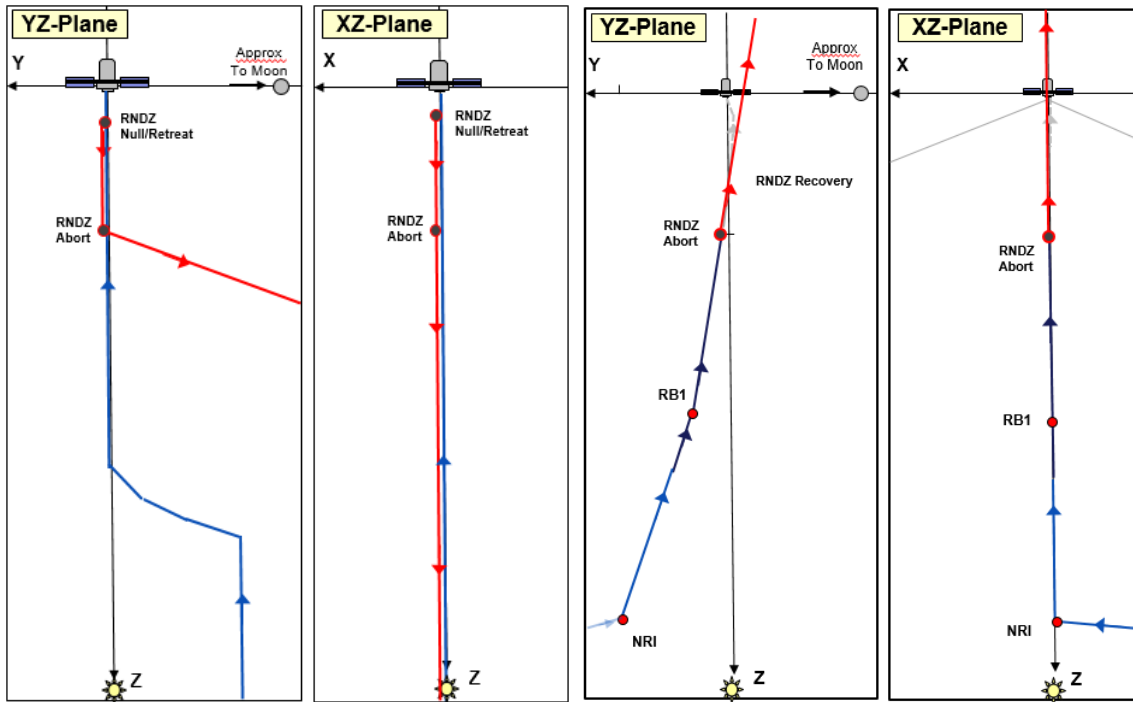


Figure 12. Early Departure Strategy 1: Retreat, Departure Burn, and Target NRD (not to scale).

Figure 13. Early Departure Strategy 2: Free-Drift and Target NRD (not to scale).

OFF-NOMINAL SEQUENCING

This section briefly discusses the implementation of each off-nominal scenario using Phases, Segments, Activities, and Modes (PSAM) sequencing. PSAM sequencing is used to configure GN&C software during RPOD, including during off-nominal scenarios.^{2,3} All of RPOD (nominal and off-nominal) occurs in the RPODOperations Phase. The off-nominal sequencing is contained in new segments that have been added to the RPODOperations Phase. An overview of the RPODOperations Phase is shown in Figure 14.

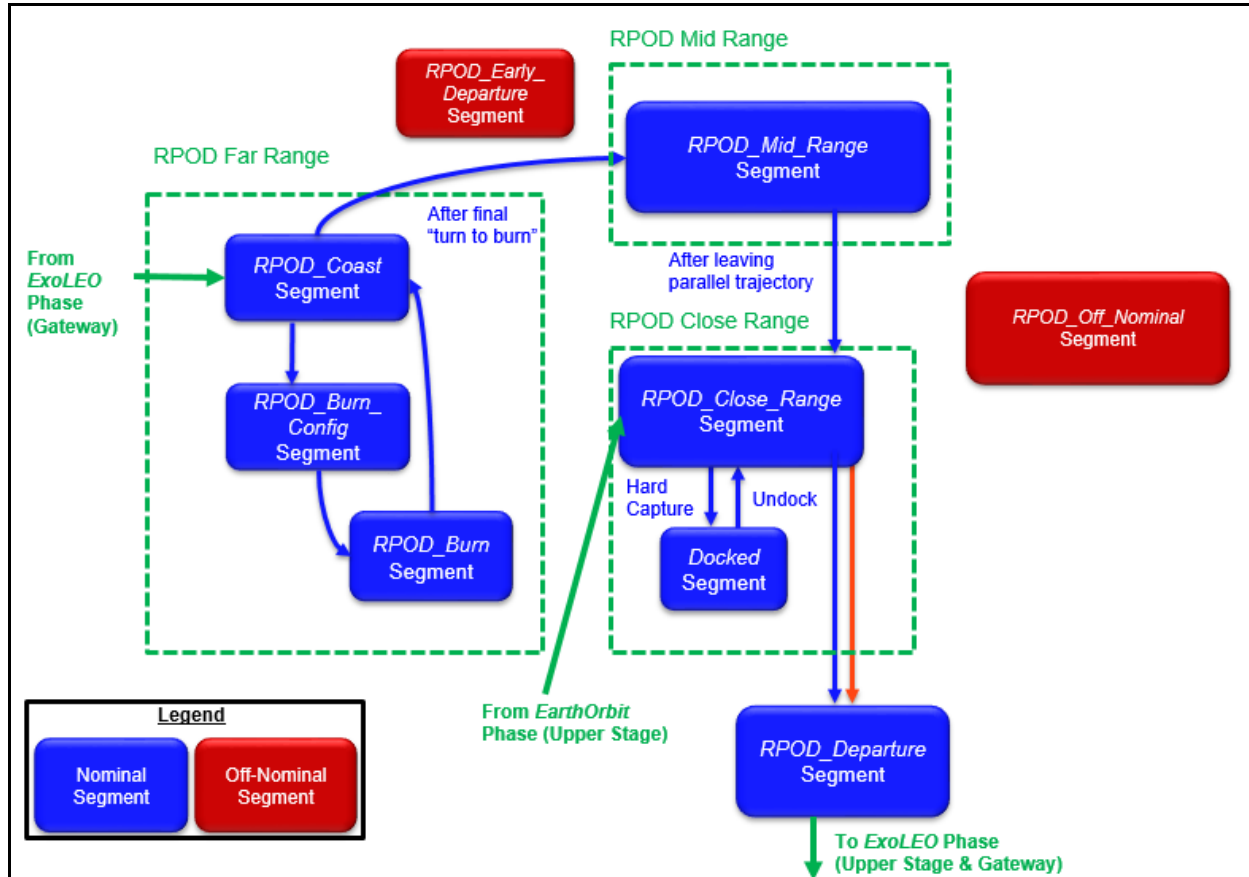


Figure 14. Orion RPODOperations Segments.

RPOD Burn Plan Interaction

The current PSAM design requires that certain data be provided from the RPOD Burn Plan, which is a construct similar to the Burn Plan used for non-RPOD burns.⁴ The RPOD burn plan manager will stop using data for nominal burns and begin using data for off-nominal burns when an abort is declared. The RPOD Burn Plan Manager is also responsible for populating the burn data fields for each planned off-nominal burn, based on the contingency strategy selected by the crew and current state data from the vehicle. Some of the data that may be provided by the RPOD Burn Plan manager includes information about when or where a burn should take place, which course of action to take based on the contingency strategy selected, or how and where to resume the nominal RPOD trajectory. Storing this information in the RPOD burn plan allows for a modular design of the RPOD_Off_Nominal segment rather than designing unique sequencing for each contingency strategy.

Sequencing Segments

RPOD_Off_Nominal can be transitioned into from *RPOD_Coast*, *RPOD_Burn_Config*, *RPOD_Mid_Range*, or *RPOD_Close_Range*. This transition is triggered when the crew or ground initiates a Same Day or Next Day contingency strategy. Additionally, if the crew fails to provide RB3 ATP at least 31 minutes before the RB3 burn, the vehicle will transition into *RPOD_Off_Nominal* and execute the Stationkeep strategy at RB3. Also, if the vehicle reaches RB5 and the crew has not provided RB5 ATP, the vehicle will automatically transition into *RPOD_Off_Nominal* to Stationkeep at RB5.

After the off-nominal sequencing is complete, the vehicle will transition to either *RPOD_Mid_Range* or *RPOD_Close_Range* depending on whether the restart point is before TDA or after TDA.

RPOD_Early_Departure can be transitioned into from the *RPOD_Coast*, *RPOD_Burn_Config*, *RPOD_Mid_Range*, and *RPOD_Close_Range* segments. Abort and Early Departure strategy #1: Retreat, Departure Burn, and Target NRD is implemented by adding a new transition between *RPOD_Close_Range* and *RPOD_Departure*. Abort and Early Departure strategy #2: Early Departure and Target NRD is implemented in the *RPOD_Early_Departure* segment. Each of the Abort and Same Day Docking strategies and the Abort and Next Day Strategies have been consolidated into a single *RPOD_Off_Nominal* segment. This modularization is made possible by the RPOD Burn Plan Manager that is used to identify and plan the selected contingency strategy.

Sequencing Activities

RPOD_Off_Nominal can support both SM RCS burns and Aux burns, depending on the magnitude of the Delta-V of each burn. In the nominal sequencing, most burns are executed using a Time of Ignition (TIG). Off-Nominal burns can be executed based on a TIG or based on the spacecraft's range to target. Data from the RPOD Burn Plan is used to determine whether a burn should be triggered using time or relative state. Although currently no off-nominal burns are planned to execute based on TIG, this provides flexibility to use the same sequencing for future strategies with other target vehicles or orbit regimes. After a burn has been executed, the option to execute a trim burn is available if necessary.

After the trim burn, the sequencing will have the option to transition to Coast, Stationkeep, Reverse Braking Gates, or Burn Prep activities. This transition is determined by data in the RPOD Burn Plan. During the Reverse Braking Gates activity, if the vehicle exits the Braking Gates range, it will transition to the Coast activity until the next burn.

To transition from any of these post-burn activities back to the Burn Prep activity, the sequencing looks at the data fields of the next burn in the burn sequence. The sequencing evaluates different information in the RPOD Burn Plan depending on whether the next burn is time triggered or position triggered. This information tells the sequencing how far in advance of the next burn point (temporally or spatially) it should transition back to the Burn Prep activity. From the Stationkeep activity, preparation for the next burn will not begin until the Restart ATP is provided. If the final burn in the off-nominal sequence has been reached, the sequencing will transition to the Return activity and then transition out of the *RPOD_Off_Nominal* segment and back to a nominal segment. A representative flow diagram of the *RPOD_Off_Nominal* activities is shown in Figure 15.

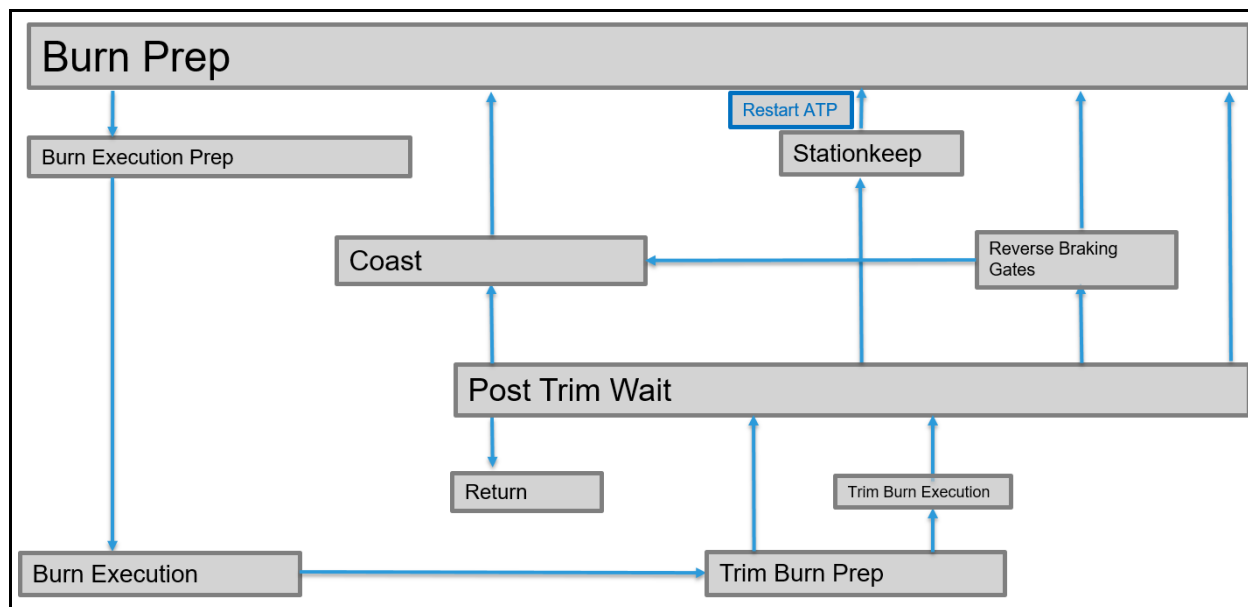


Figure 15. Representative *RPOD_Off_Nominal* Activities.

CONCLUSION

This paper presented the Orion GN&C Concept of Operations for off-nominal RPOD. It also gave an overview of the PSAM Sequencing. The contingency strategies discussed here will provide the women and men aboard Orion security and safety in the event of an anomaly during Rendezvous, Proximity Operations, and Docking. These strategies also provide flexibility to the crew for guaranteed safety for a sustainable return to the Moon.

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