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Spacecraft Rendezvous Operational Considerations Affecting Vehicle Systems Design and Configuration

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Introduction

One lesson learned from OMV program experience is that Design Reference Missions must include an appropriate balance of operations and performance inputs to effectively drive vehicle systems design and configuration. Rendezvous trajectory design is based on vehicle characteristics (e.g., mass, propellant tank size, mission duration capability) and operational requirements, which have evolved through the Gemini, Apollo, and STS programs. This presentation summarizes operational constraints affecting the rendezvous final approach.

The two major objectives of operational rendezvous design are vehicle/crew safety and mission success. Operational requirements on the final approach which support these objectives include:

- tracking/targeting/communications
- trajectory dispersion and navigation uncertainty handling
- contingency protection
- favorable sunlight conditions
- acceptable relative state for proximity operations handover
- compliance with target vehicle constraints

A discussion of the ways each of these requirements may constrain the rendezvous trajectory follows. Although the constraints discussed apply to all rendezvous, the trajectory presented in "Cargo Transfer Vehicle Preliminary Reference Definition" (MSFC, May 1991) was used as the basis for the comments below.

Discussion

Figure 1 is a target-centered relative motion plot of the ground-up rendezvous trajectory. Operational constraints to be considered in design of the final approach are illustrated on the figure.

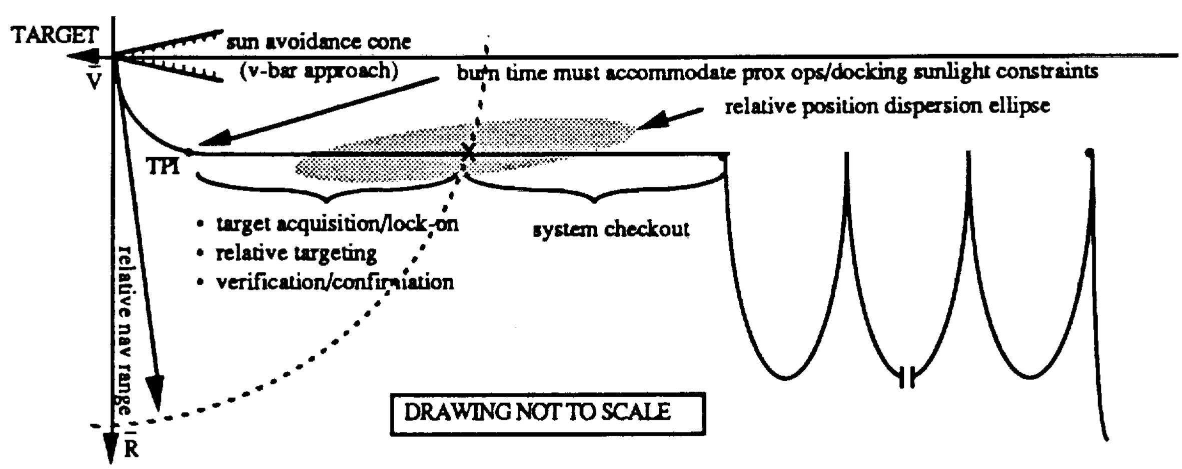

FIGURE 1. Rendezvous Operational Constraints

Tracking / Targeting / Communications

Adequate time for tracking, targeting, and necessary communications must be allotted prior to terminal phase initiation (TPI) and midcourse burns. As shown on Figure 1, the TPI burn may not take place until the chaser has been within relative navigation range for sufficient time to acquire and lock-on to the target vehicle, and for TPI burn targeting to be completed and verified. For example, the terminal phase trajectory shown in the CTV Preliminary Reference Document (300° transfer initiated from 20 nmi below the SSF) requires a radar range of ~100 nmi, assuming 15 minutes for target acquisition, lock-on, and confirmation. Alternatives to reduce the radar range requirement include inserting higher to reduce the target/chaser Δh at TPI, or initiation of TPI at a "stable orbit point" on the target v-bar.

Additionally, the final approach (pre-TPI through TPF) trajectory must provide favorable conditions for accurate target tracking. This includes advantageous relative motion, target background, and sunlight conditions, if required.

Tracking, targeting, and communications requirements all extend the rendezvous timeline. Target tracking needs also influence navigation sensor selection and insertion altitude specification (which affects onorbit fuel requirements).

Trajectory Dispersion and Navigation Uncertainty Handling

The final approach design must provide a satisfactory trajectory for the expected range of dispersions (an example relative position dispersion ellipse is illustrated on Figure 1). To preclude premature contact between the chaser and target vehicles, the chaser/target relative position must remain safely outside the envelope of predicted dispersions during the entire final approach. Additionally, the chaser-to-target range must remain greater than the navigation range uncertainty.

The relative trajectory is controlled by maneuver placement and target offset points. The TPI offset point should be chosen so that an acceptable trajectory can be flown for any point within the predicted dispersion ellipse. For the STS, the TPI downrange offset was chosen large enough to prevent collision with the target vehicle prior to TPI, and the radial offset was defined to ensure a positive separation rate from the target under 3σ dispersed conditions. After TPI, dispersions can be reduced by targeting midcourse burns, which correct TPI burn errors and adjust the trajectory based on current navigation data.

Dispersion and navigation uncertainty handling may influence insertion altitude and the onorbit trajectory, impacting both propellant and mission timeline requirements.

Contingency Protection

Since it is impossible to plan for every contingency, each spacecraft program must define planned contingencies and the time allotted to resolve them. Planned contingencies may include late or missed burns, navigation and communication failures, timeline delays, and other system failures.

Passive collision avoidance protects against inadvertent contact between the chaser and target in a chaser system failure scenario. Using passive collision avoidance, the trajectory is designed so the chaser trajectory won't intercept the target unless the terminal phase sequence is initiated. Coelliptic and stable orbit trajectories which use passive collision avoidance are shown in Figure 2 below. In each case, the dotted line shows the trajectory followed if the TPI burn is not executed.

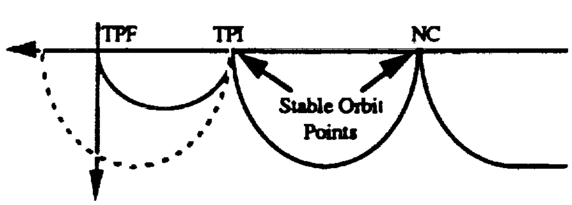

FIGURE 2a. Stable Orbit Approach

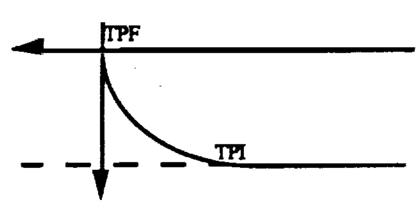

FIGURE 2b. Coelliptic Approach

The ability to halt and then restart the rendezvous increases the probability of mission success in the case of any contingency which prevents completion of the rendezvous at the nominal time (e.g., relative navigation, communication, or docking system failure). Although a contingency plan can be developed for any approach trajectory, the stable orbit approach has the advantage of one or more stopping points built into the nominal profile. After resolution of a contingency, the chaser may resume its *nominal* terminal phase trajectory with minimal fuel impact. Operational simplicity is a high priority for rendezvous, especially for automated or autonomous operations.

After TPI, the chaser and/or target must be capable of performing collision avoidance maneuvers in case of a contingency which prevents completion of the rendezvous. Again, it is desirable to maintain the ability to complete the rendezvous at a later time while minimizing fuel and time requirements, and operational complexity.

Contingency protection allowances primarily impact mission duration and fuel requirements.

Favorable Sunlight Conditions

Although sun lighting of the target during proximity operations and docking may be desirable, direct or reflected sunlight may interfere with optical sensors. An example sun avoidance cone is depicted on Figure 1. The final approach trajectory must set up correct lighting conditions for proximity operations and docking. A strategy used by the STS to achieve desirable lighting conditions is inclusion of a coelliptic phase before the final sequence of rendezvous maneuvers. This sequence is then initiated at a time such that future lighting requirements are satisfied. Sunlight concerns may affect selection of navigation sensors as well as the mission timeline.

Proximity Operations Handover

The terminal phase must provide a relative state (position and velocity) at transition from near field to proximity operations which complements proximity operations piloting capabilities. The relative state at proximity operations handover is a function of terminal phase target offset points and transfer angles. Terminal phase trajectory design influences both timeline and propellant requirements.

Target Vehicle Constraints

The final approach trajectory must comply with all target constraints, such as target orientation. For rendezvous with the SSF, command and control zone rules must be observed, as well as other station operations requirements. Target constraints may result in insertion altitude, propellant or timeline constraints, and may also influence selection of navigation sensors.

Summary

Vehicle/crew safety and mission success goals dictate many operational requirements not directly related to vehicle performance. The resulting constraints place strict limitations on the rendezvous final approach trajectory, which must be accommodated by vehicle hardware and software design. All operational requirements discussed above affect the rendezvous timeline to some extent, which dictates vehicle battery lifetime. Tracking requirements, dispersion handling, and SSF command and control zone requirements may directly influence chaser insertion altitude, and therefore onorbit propellant requirements. Trajectory modifications to accommodate contingency protection and dispersion handling capabilities may impose additional propellant requirements. Sunlight and tracking considerations, as well as target vehicle constraints, should be factors in selection of navigation sensors. It is hoped that the above discussion will enhance understanding of rendezvous issues affecting vehicle design, and that these issues will be considered in the early design stages of future rendezvous vehicles.