N90-13436

ACTIVE RENDEZVOUS BETWEEN A LOW-EARTH ORBIT USER SPACECRAFT AND THE SPACE TRANSPORTATION SYSTEM (STS) SHUTTLE*

H. L. Hooper and J. R. Herrnstein
Computer Sciences Corporation (CSC)

ABSTRACT

This study considers active rendezvous of an unmanned spacecraft with the Space Transportation System (STS) Shuttle. The paper first discusses the various operational constraints facing both the maneuvering spacecraft and the Shuttle during such a rendezvous sequence. Specifically, the actively rendezvousing user spacecraft must arrive in the generic Shuttle control box at a specified time after Shuttle launch. In so doing it must at no point violate Shuttle separation requirements. In addition, the spacecraft must be able to initiate the transfer sequence from any point in its orbit.

The paper then discusses the four-burn rendezvous sequence incorporating two Hohmann transfers and an intermediate phasing orbit as a low-energy solution satisfying the above requirements. The general characteristics of the four-burn sequence are discussed, with emphasis placed on phase orbit altitude and delta-velocity (ΔV) requirements. The report then considers the planning and execution of such a sequence in the operational environment. Factors crucial in maintaining the safety of both spacecraft, such as spacecraft separation and contingency analysis, are considered in detail.

*This work was supported by the National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center (GSFC), Greenbelt, Maryland, under Contract NAS 5-31500.

PRECEDING PAGE BLANK NOT FILMED

1. INTRODUCTION

This report presents the results of an investigation into analysis and mission planning techniques for unmanned user spacecraft involved in active rendezvous with the Space Transportation System (STS) Shuttle. During the investigation, a rendezvous computation program that incorporates these techniques was developed. This software was used to generate the results presented in the report.

Section 2 presents background information on Shuttle standard rendezvous policies. These requirements coupled with a desire to minimize fuel expenditures make a rendezvous sequence consisting of a series of Hohmann transfers a desirable technique. The general characteristics of such a rendezvous sequence are discussed in detail in Section 3. Special attention is given to the cost in terms of Delta-V (ΔV) of such a maneuver sequence.

Section 4 discusses several operational issues confronting unmanned spacecraft rendezvousing with the Shuttle. The issues include safety of the Shuttle during the maneuver sequences, tracking coverage, lighting coverage, and maneuver contingencies. Section 5 presents a summary of the conclusions reached in the report.

2. BACKGROUND — STS SHUTTLE RENDEZVOUS REQUIREMENTS

This section presents the requirements imposed by the Shuttle on an actively rendezvousing user spacecraft. These requirements were derived from References 1 through 5. Because many of these policies are still formulative, all the referenced reports are preliminaries.

The rendezvous sequence is initiated when the "Go for descent" declaration is issued by mission controllers at Johnson Space Center (JSC). This is done after the Shuttle has achieved orbit and a systems check has determined that the rendezvous sequence may proceed. Nominally, this occurs at 5 hours mission-elapsed time (MET), or 5 hours after launch.

Upon receiving the "Go for descent" declaration, the unmanned user spacecraft (chase spacecraft) must complete its rendezvous with the Shuttle (target spacecraft) at a predetermined time, currently given as 53 hours MET. This rendezvous completion time is referred to by JSC as the Control Box Start Time (CBST). The rendezvous is considered complete when the maneuvering spacecraft has achieved the Shuttle control box (Figure 1) and has ceased all translational maneuvering. As illustrated, the control box is a region above and ahead of the Shuttle with its origin at the Shuttle. The horizontal component measures angular separation along the Shuttle orbit, while the vertical component measures radial distance from the Shuttle.

Upon achieving the CBST at the completion of the rendezvous, the user spacecraft must satisfy a semimajor axis and eccentricity requirement limiting the difference in apogee and perigee altitudes to 14.8 kilometers (km). In addition, a maximum angular separation

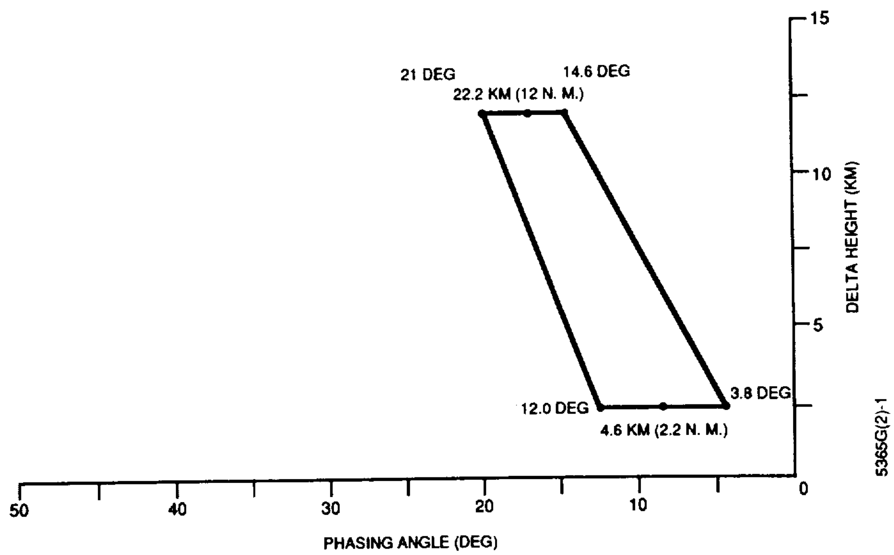

Figure 1. STS Shuttle Generic Control Box; Orbit Normal Out of Page

of 0.03 degree (deg) in the orbital planes of the spacecraft is required. The user spacecraft must be capable of absorbing up to approximately 0.1 deg of launch dispersion errors in the orbit plane of the Shuttle. Finally, the user spacecraft must be capable of handling Shuttle launch slips of up to 1 hour. This, combined with the possibility of 24-hour Shuttle launch delays, requires that the user spacecraft be capable of completing rendezvous with the Shuttle from any initial orientation (or phasing) with the Shuttle. Stated differently, the user spacecraft must possess a 360-deg phasing capability with the Shuttle.

3. USER SPACECRAFT/STS SHUTTLE RENDEZVOUS SEQUENCE

This section describes a rendezvous sequence that is well-suited to the operational environment and that satisfies all the requirements presented in the previous section while minimizing ΔV requirements. The section begins with a discussion of the characteristics of the Hohmann transfer and proceeds to describe a rendezvous sequence consisting of a series of Hohmann transfers with intermediate phasing orbits. The rendezvous technique does not require any specific initial orbital conditions. However, to simplify the current discussion, it is assumed that the user spacecraft begins in a higher orbit than the Shuttle.

3.1 THE HOHMANN TRANSFER

A Hohmann transfer is well-known as the optimum maneuver sequence for transferring between two circular coplanar orbits. The first burn of such a maneuver places the chase spacecraft in an elliptic transfer orbit with perigee at the same altitude as the target orbit. The second burn occurs 180 deg after the first and circularizes the transfer orbit, leaving the chase spacecraft in the same orbit as the target vehicle.

If the chase and target orbits are not coplanar, a plane change must be done at some point in the maneuver sequence. This could be accomplished by executing all the plane change in either the initial or the final orbit, independently of the altitude change to be performed. However, the transfer ΔV is optimized by simultaneous execution of the plane-change and orbital-change maneuvers. Efficiency is further improved by distributing the plane changes between the two burns. Figure 2 shows the significant ΔV savings associated with linking plane and altitude changes by distributing the plane changes between the two burns of the Hohmann transfer.

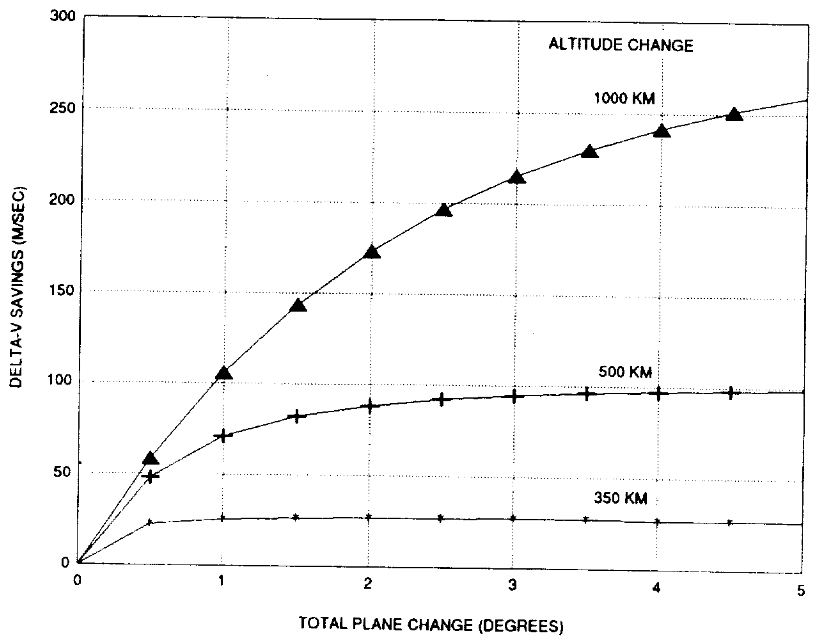

Figure 2. Delta-V Savings by Coupling Altitude and Plane Changes

3.2 MULTIPLE BURN TRANSFERS

If two spacecraft are to rendezvous using a Hohmann transfer, the correct angular separation, or phasing, must exist between the spacecraft at the initiation of the transfer. This angle is referred to as the Hohmann phase angle (HPA). The relative periods of the two orbits determine the value of the HPA.

The synodic period represents the length of time required for spacecraft in different orbits to return to the same orientation with respect to each other. This is the time between successive occurrences of the HPA. If the synodic period is greater than the amount of time allotted for a particular rendezvous scenario, the required HPA may not be achievable for all initial orientations. For a 2-day rendezvous, the synodic period is longer than the rendezvous duration if the initial user spacecraft altitude is less than 145 km above the nominal Shuttle altitude of 315 km. For a spacecraft such as the Gamma Ray Observatory (GRO), which is nominally only 35 km above the Shuttle at the start of the rendezvous sequence, additional measures must be taken.

The required 360-deg phasing capability can be achieved while maintaining the ΔV advantages inherent in the Hohmann transfer by employing a sequence consisting of a series of Hohmann transfers. Such a sequence, the four-burn rendezvous sequence, is illustrated in Figure 3. The four-burn sequence consists of two Hohmann transfers. The first transfer places the chase spacecraft in an intermediate orbit called the phase orbit. The second transfer maneuvers the chase vehicle to the target spacecraft. The phase orbit is computed such that the HPA between the phase and target orbits is achieved at the time of the final transfer. By varying the altitude of the phase orbit, the user spacecraft is capable of achieving rendezvous with the Shuttle from any initial relative orientation.

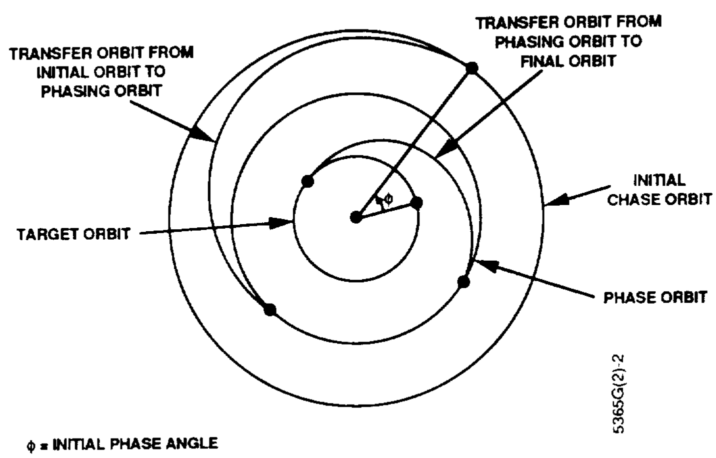

Figure 3. Four-Burn Transfer Scenario

The concept of linking in- and out-of-plane corrections to save ΔV is as applicable to the four-burn scenario as it is to the case of a direct Hohmann transfer. To combine plane changes and altitude changes, each of the four burns must occur along the relative node defined by the intersection of the user spacecraft and Shuttle orbit planes at the termination of the rendezvous sequence.

3.2.1 PHASE ORBIT ALTITUDE

To apply the four-burn sequence, it is necessary to accurately compute the semimajor axis of the phase orbit, given a set of initial conditions. This is done using the foliowing equation:

$$0 = \left[\left(\frac{\mu}{a_t^3}\right)^{1/2} - \left(\frac{\mu}{a_p^3}\right)^{1/2}\right] T - \phi - 2\pi - \frac{\pi}{\sqrt{8}}\left[\left(\frac{a_p + a_c}{a_p}\right)^{3/2} + \left(\frac{a_p + a_t}{a_p}\right)^{3/2}\right] \tag{3-1}$$

where

μ	=	Earth's gravitational constant (398600.64 (km3/sec2))
a_t	=	target spacecraft semimajor axis
a_c	=	chase spacecraft semimajor axis
a_p	=	phase orbit semimajor axis
ϕ	=	initial phase angle
T	=	total rendezvous duration

Equation (3-1) is solved iteratively until a value for a_p is found which makes the right-hand side of the equation arbitrarily close to zero.

Figure 4 shows phase orbit altitude as a function of phase angle, ϕ, for a 3-day transfer from 350 to 315 km. The figure demonstrates that two phase orbit solutions exist for each initial phase angle: one above the target spacecraft and the other below. The solid portions of the curves show the phase orbit solutions having the lower ΔV requirement for each specific initial phase angle. The crossover point from the upper to the lower solution occurs when the solutions require equivalent ΔV expenditure.

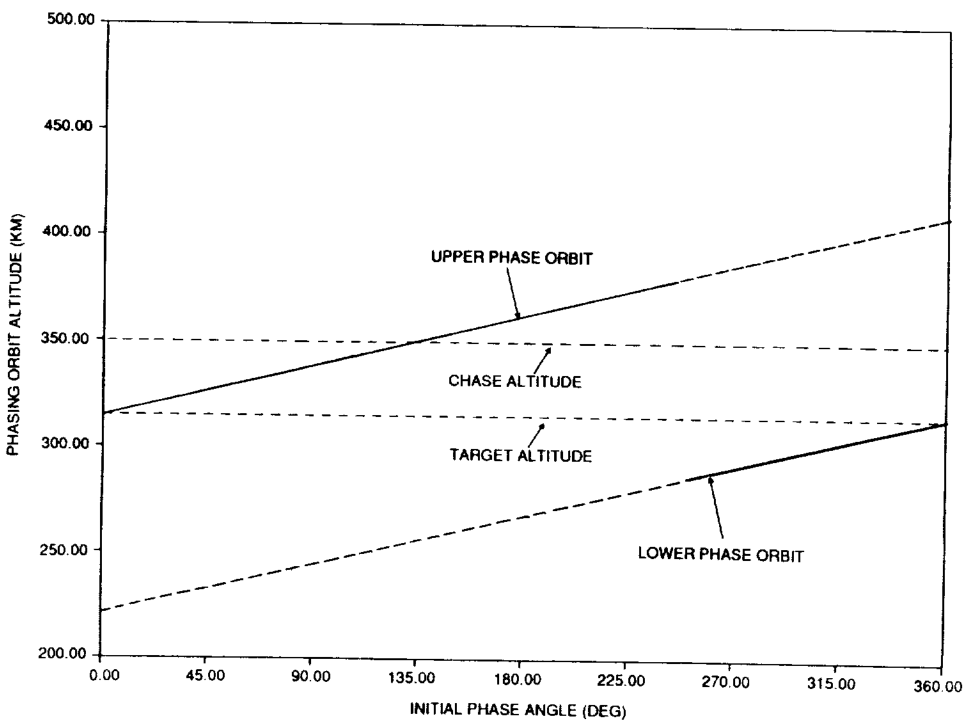

Figure 4. Phase Orbit Altitude as a Function of Initial Spacecraft Phase Angle for a 3-Day, 350- to 315-km Scenario

Further examination of variations in phase orbit altitude with rendezvous time and initial spacecraft altitudes suggests several noteworthy trends. The phase orbit semimajor axis is essentially a linear function of phase angle, with the upper and lower solutions being nearly parallel. Furthermore, the y-intercept of the upper phase orbit altitude/phase angle function is the target spacecraft semimajor axis and its slope varies inversely with T, the rendezvous duration. With these relationships in mind, it is possible to write three analytical equations that accurately predict the phase orbit altitudes and the crossover point over the ranges of Shuttle altitudes (300 to 350 km), user spacecraft altitudes (300 to 500 km), and rendezvous durations (2 to 5 days) under consideration:

$$a_{pu}(\phi) = \frac{k_u}{T}\phi + a_t \tag{3-2}$$

$$a_{p\ell}(\phi) = \frac{k_\ell}{T}\phi + \left[a_t - 2\pi\frac{k_\ell}{T}\right] \tag{3-3}$$

$$\phi_c = \frac{T}{k_\ell + k_u}\left[a_c - a_t + \frac{2\pi k_\ell}{T}\right] \tag{3-4}$$

where

a_{pu} = semimajor axis of the upper phase orbit
$a_{p\ell}$ = semimajor axis of the lower phase orbit
ϕ_c = phase angle at which crossover occurs

and

$$k_\ell = \frac{2}{3}\left[\frac{\mu}{\left[\sqrt{\frac{\mu}{a_t^3}} + \frac{\pi}{T}\right]^5}\right]^{1/3} \tag{3-5}$$

$$k_u = \frac{2}{3}\left[\frac{\mu}{\left[\sqrt{\frac{\mu}{a_t^3}} - \frac{\pi}{T}\right]^5}\right]^{1/3} \tag{3-6}$$

The expressions for k_u and k_ℓ were derived by taking a Taylor series expansion of an expression for phase orbit altitude based on spacecraft angular rates and assuming only the linear terms to be significant. Numerical analysis can be performed to demonstrate that, in agreement with the initial simplifying assumption of a linear relationship between phase orbit altitude and ϕ, k_u and k_ℓ do remain essentially constant over the ranges under consideration. The derivation of k_ℓ and k_u and the associated numerical analysis can be found in Reference 6.

Equations (3-2) through (3-6) predict phase orbit altitudes to within several kilometers of the more accurate solutions computed iteratively by Equation (3-1). They can, therefore, be used to compute quick approximations to the phase orbit altitude.

3.2.2 DELTA-V CONSIDERATIONS

Figure 5 shows the ΔV associated with the upper and lower phase orbit solutions for a 3-day, coplanar transfer from 350 to 315 km. Figure 6 presents the cost of the less expensive phase orbit solutions for the same transfer with rendezvous durations of 2, 3, and 4 days. The ΔV saved by crossing over from the upper to the lower phase orbit solution for phase angles approaching 360 deg is clear. As expected, the maximum ΔV occurs at the crossover point. This maximum ΔV value is critical in rendezvous scenarios with the Shuttle since a 360-deg phasing capability is required. This means that it is necessary to budget enough fuel to be able to handle the maximum possible ΔV.

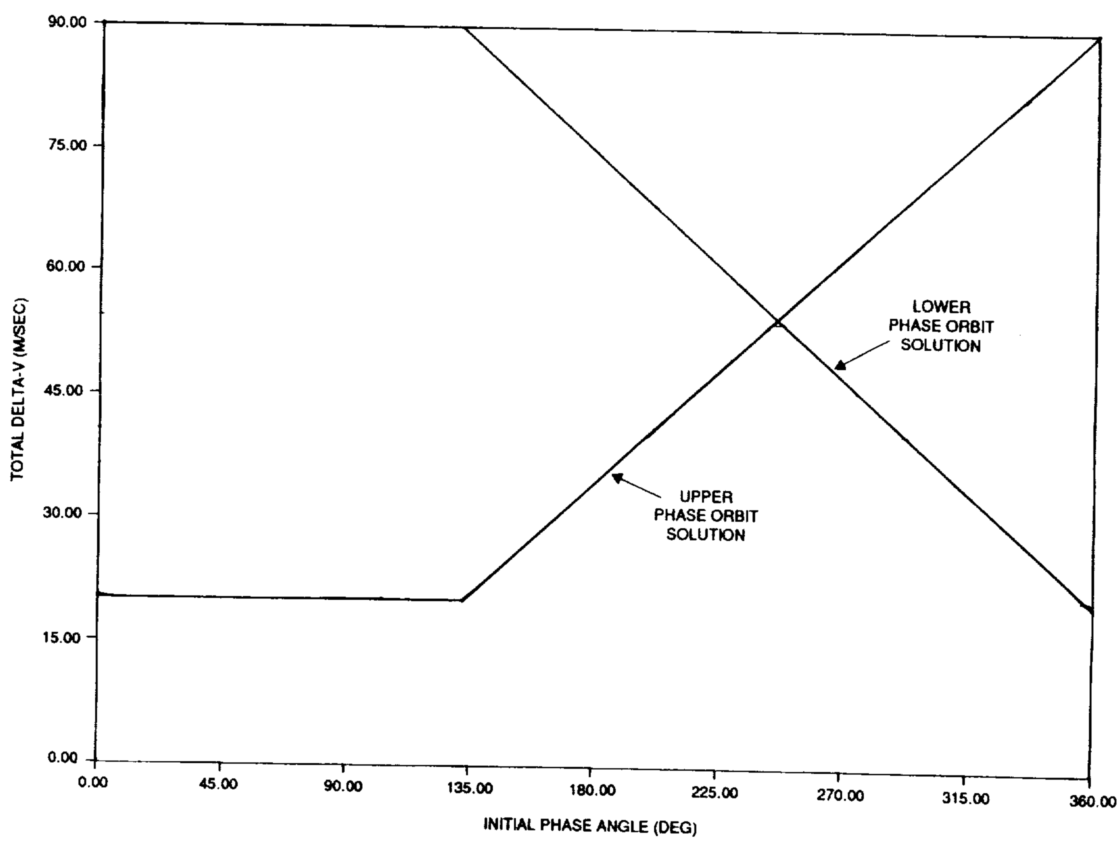

Figure 5. Delta-V Versus Phase Angle for 3-Day Rendezvous; Upper and Lower Phase Orbit Solutions

The magnitude of the maximum ΔV can be determined without solving the rendezvous problem by computing the orbit with which the target orbit has a synodic period equal to the rendezvous duration. This orbit can be called the synodic orbit. The cost of a direct Hohmann transfer from this orbit to the target orbit is equal to the maximum four-burn

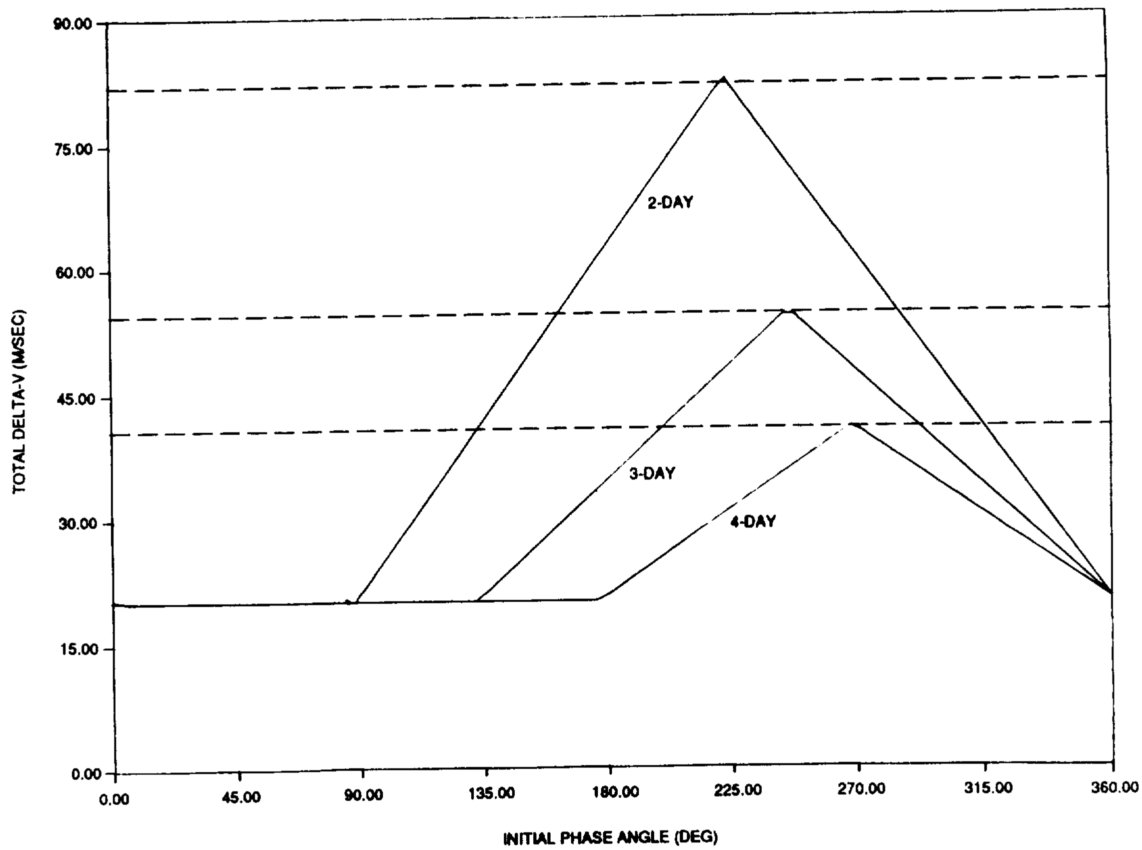

Figure 6. Delta-V Versus Phase Angle for 2-, 3-, and 4-Day Rendezvous; Low-Energy Solutions

solution ΔV. These synodic orbit ΔVs are represented in Figure 6 as dashed horizontal lines. As anticipated, each of the lines is tangent to the peak of the appropriate four-burn sequence ΔV curve.

Figure 6 leads to the intuitive result that as the rendezvous time goes down, the cost of the most expensive solution goes up. A corollary of this is the conclusion that increasing the initial altitude of the chase spacecraft has no effect on the maximum ΔV until the altitude of the synodic orbit is passed. This is graphically shown in Figure 7. The ΔV is shown as a function of phase angle for five different user spacecraft initial altitudes for a 2-day rendezvous sequence. When the initial altitude is equal to the synodic altitude of 459 km, the ΔV becomes constant at the maximum ΔV value. Raising the initial altitude beyond this increases the ΔV to a still higher value.

Figure 8 demonstrates another important characteristic of ΔV costs in the four-burn sequence. The figure illustrates the standard ΔV versus ϕ curve for a 3-day rendezvous from 350 to 315 km. In addition, Figure 8 includes the ΔV when an initial coast period of 12 hours is executed before the initiation of the rendezvous sequence while maintaining the time of rendezvous completion. Figure 8 indicates that the strategy of coasting to a

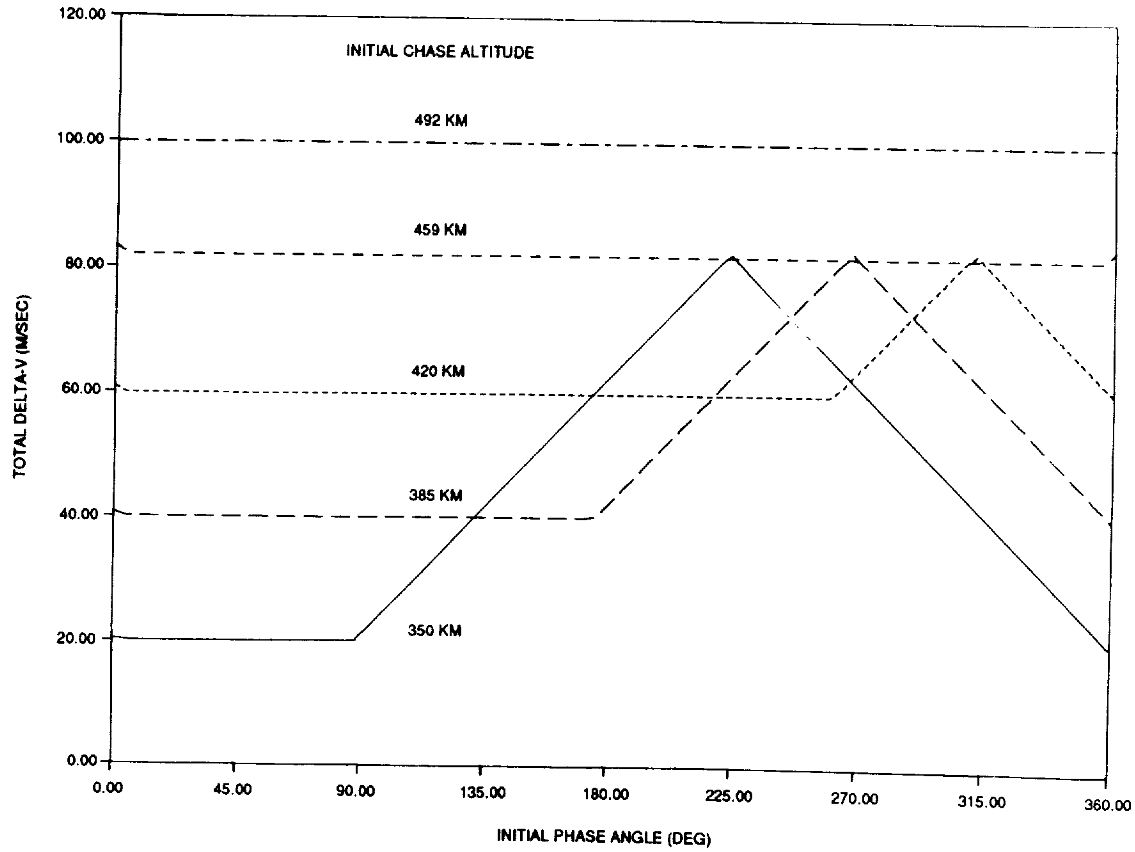

Figure 7. Delta-V Versus Phase Angle for a 2-Day Rendezvous From Five Initial Altitudes

more optimal phasing before initiating the rendezvous sequence never saves any ΔV and, in fact, raises the maximum ΔV value. The explanation for this occurrence is that the benefits of the more optimal phasing are more than countered by the increased cost associated with a shorter rendezvous duration.

The effect of plane changes on ΔV is demonstrated in Figure 9. A transfer from 350 to 315 km in 2 days for a coplanar case and for plane changes of 0.1 and 0.2 deg is shown. As previously described, the four-burn solution minimizes the impact of plane changes by combining in- and out-of-plane corrections. Because of this, the effect of plane changes on ΔV diminishes as the amount of altitude change required increases. Specifically, Figure 9 shows that the increase in the maximum ΔV is approximately 3 meters/second (m/sec) for the 0.1-deg plane change. If plane changes were not combined with the orbit maneuvers, the increase would be about 14 m/sec.

Each of the curves in Figure 9 possesses a discontinuity at a phase angle of 180 deg, which results from the requirement that each of the burns occurs at the appropriate relative node. In generating the curves shown in Figure 9, the phase angle was varied by moving the initial location of the chase spacecraft around its orbit while keeping the target position fixed. For each solution, the chase spacecraft coasts forward to the nearest

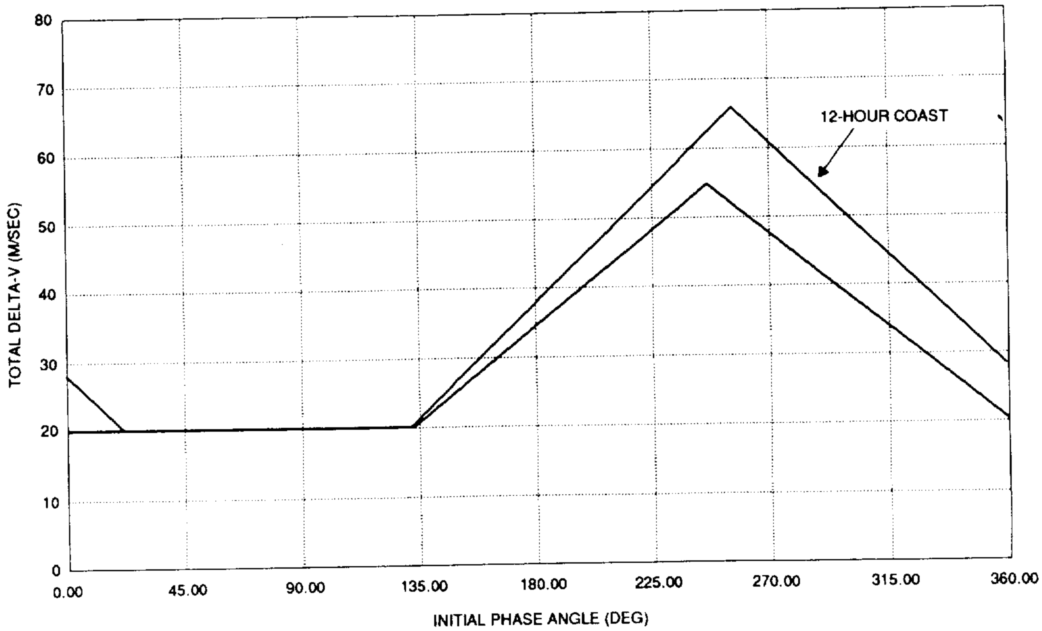

Figure 8. Total Delta-V Versus Initial Phase Angle for a 3-Day Rendezvous With a 12-Hour Initial Coast

relative node before executing the first transfer and a portion of the plane change. This coast distance monotonically decreases until the initial position of the chase spacecraft reaches the first node at a phase angle of 180 deg. At this point, no coast time is required. The change in coast time is gradual until this point and is thus not discernible. However, for the next solution, the chase spacecraft starts beyond the first relative node and must coast a full 180 deg to achieve the next node. This jump in the initial coast distance from 0 to 180 deg noticeably changes the remaining rendezvous sequence and is, therefore, discernible in the ΔV curves as a discontinuity.

4. OPERATIONAL CONSIDERATIONS

This section discusses the actual application of the four-burn sequence to user spacecraft/Shuttle rendezvous scenarios. The section describes several important considerations relevant to both the premission analysis phase and the actual maneuver-planning phase in which specific maneuvers are computed.

4.1 PREMISSION ANALYSIS

The maneuver-planning phase of rendezvous with the Shuttle requires the capability to compute exact solutions that satisfy Shuttle tolerances. To achieve adequate accuracy, it is necessary to use an integrator that includes detailed perturbation models. This process can be time consuming since the rendezvous solutions are developed through an iterative scheme. This lengthy computation time may not be acceptable during the premission analysis phase of rendezvous with the Shuttle, during which many cases must be considered and large numbers of solutions computed.

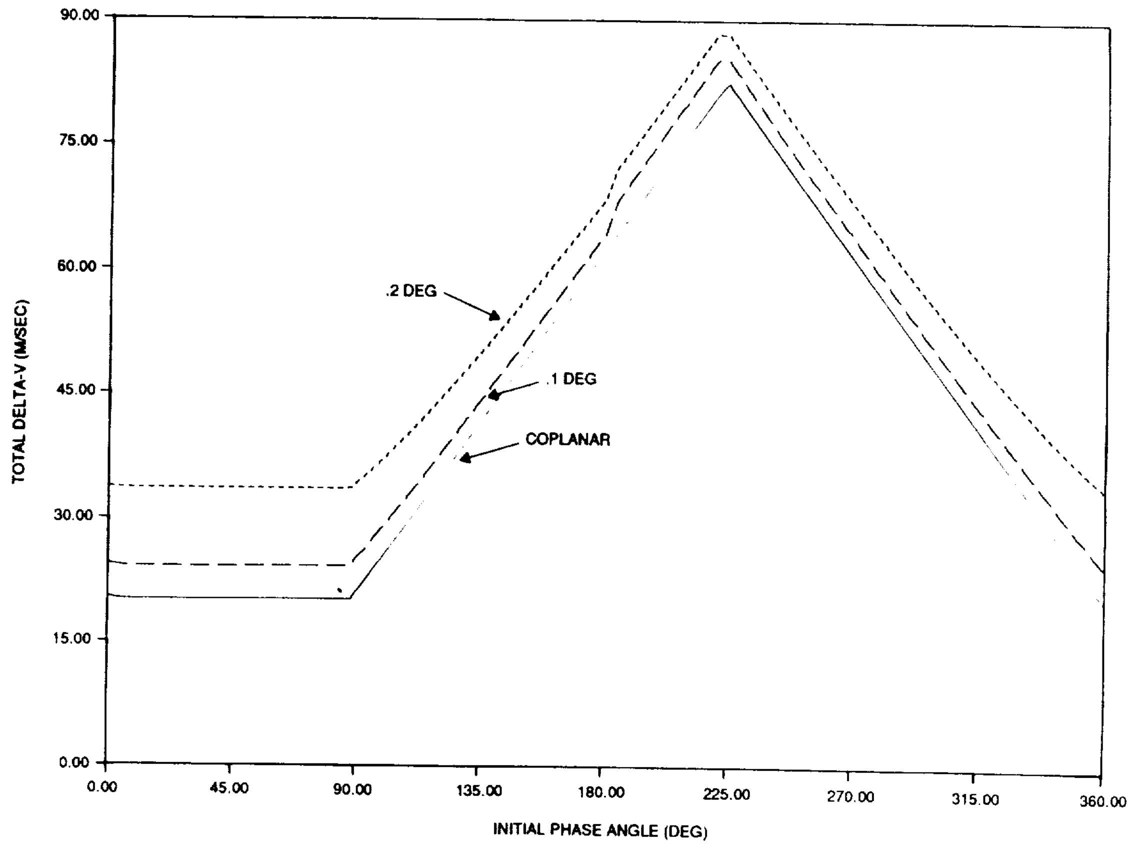

Figure 9. Delta-V Versus Phase Angle for Coplanar and Non-Coplanar Transfers

Thus, to expedite the analysis process, it is necessary to be able to quickly compute large numbers of acceptably accurate analytic solutions. However, the computation of analytic results is complicated by the various perturbations confronting spacecraft. Figure 10 illustrates the types of along-track, radial, and out-of-plane errors encountered in the final positions of the user spacecraft and Shuttle when analytic rendezvous solutions that neglect the nonspherical shape of the Earth and the effects of drag are input into an integrator that includes these perturbations. Figure 10 demonstrates that along-track errors of up to 13 deg, semimajor axis errors of 4.5 km, and ascending node errors of as much as 0.6 deg are generated when these perturbations are ignored.

These errors are dramatically reduced by incorporating into the rendezvous computation scheme analytic models describing the perturbative forces. Drag is modeled by assuming a linear relationship between altitude and density, and by employing a series of Harris-Priester atmospheric density tables that describe density conditions for a range of solar-flux values. Approximating the effects of the nonspherical shape of the Earth requires considering both the short period and secular terms of the spherical harmonic expansion describing the Earth's geopotential field. Specifically, the short-period terms affect semimajor axis, inclination, and eccentricity, while the secular terms affect ascending node, argument of perigee, and mean motion.

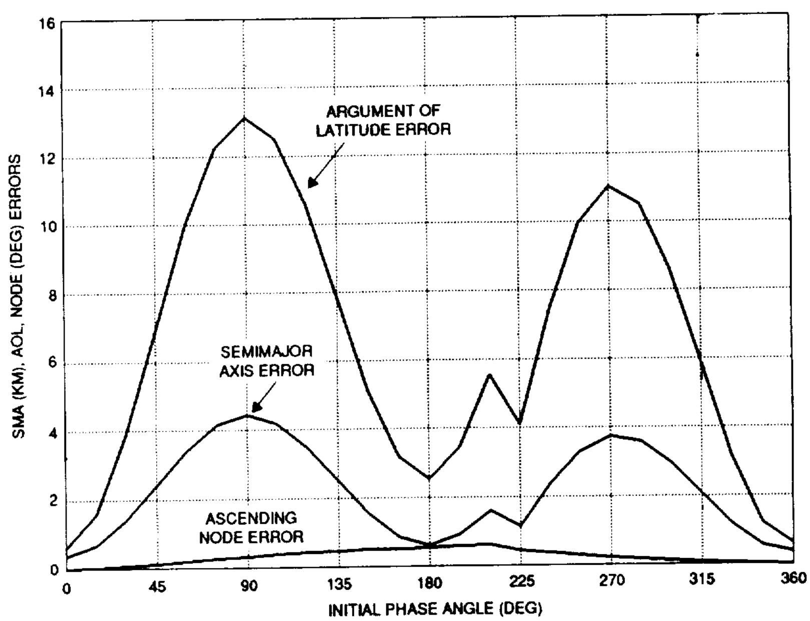

Figure 10. Errors in Analytic Solutions When No Perturbations Are Included

Figure 11 shows along-track, radial, and out-of-plane errors when these perturbation models are included in the analytic rendezvous computations. Comparison of Figure 11 with Figure 10 illustrates the significant improvement in result accuracy. The improved analytic results are accurate enough for most analysis applications and can be computed approximately 100 times faster than the integrated solutions. In addition, by using these high-quality analytic results as first-guess solutions, the speed with which exact integrated solutions can be computed for maneuver-planning purposes is greatly increased.

4.2 SPACECRAFT SEPARATION

Ensuring that the user spacecraft maintains adequate separation from the Shuttle during the entire rendezvous sequence is a crucial element of the rendezvous sequence. Any initial phase angles that could cause difficulties in this regard must be determined before the mission and handled appropriately. Of particular concern are phase angles that result in phase orbits below the Shuttle because for these cases the user spacecraft passes through the Shuttle altitude twice during the rendezvous sequence. This discussion considers separation issues relevant to both transfer orbits.

It is possible for the user spacecraft and the Shuttle to collide during the first transfer down to the phase orbit if the final rendezvous point is in the Shuttle control box and the initial phase angle is sufficiently small. For example, a phase angle of approximately 0.7 deg (chase leading target) for a 350 to 315 km, 3-day rendezvous to the center of the control box results in the two spacecraft passing within a few hundred meters of each other. This situation is shown schematically in Figure 12.

One method of avoiding the dangers associated with small initial phase angles is to coast to a larger phase angle before beginning the rendezvous sequence. As Figure 13 shows

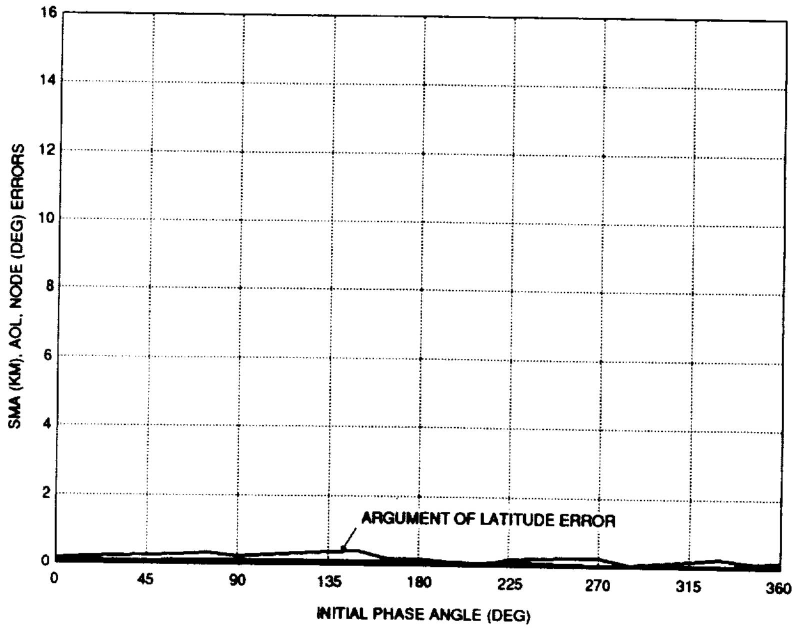

Figure 11. Errors in Analytic Solutions When Drag and J2 Are Included

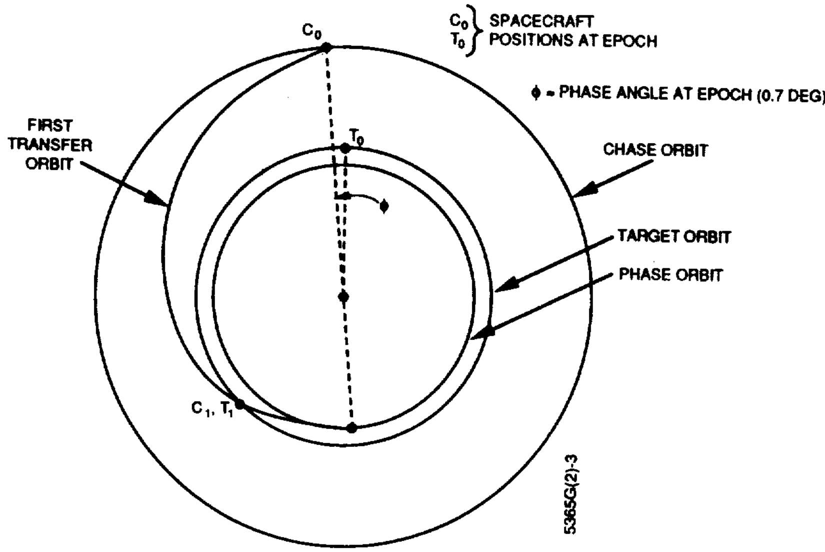

Figure 12. First Transfer Orbit for a 0.7-Deg Phasing

schematically, this initial coast increases the initial phase angle to a value that presents no danger of contact even if the second burn cannot be performed and extra revolutions are required in the transfer orbit. For the specific case involving the 0.7-deg phasing described above, a coast period of 6 hours increases the minimum separation of the spacecraft to approximately 1500 km. Such a coast would not increase the maximum ΔV of the rendezvous sequence since it would only be performed for phasings near 0 deg.

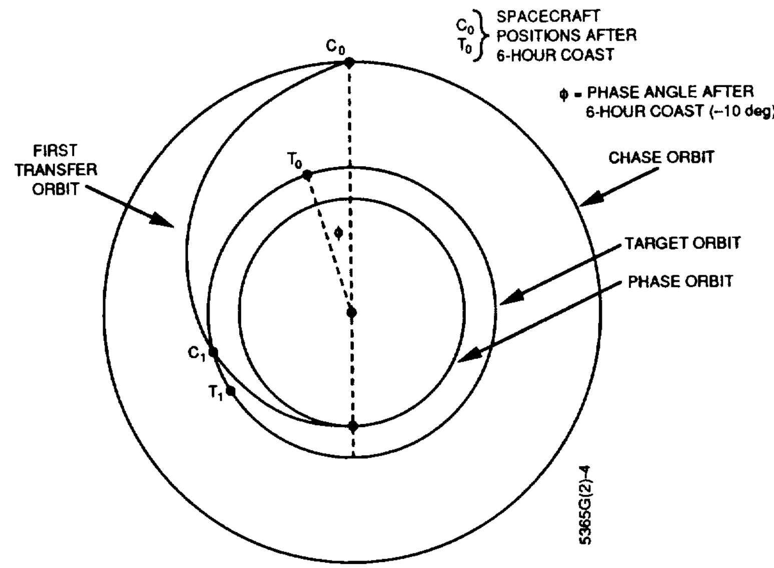

Figure 13. First Transfer Orbit After an Initial 6-Hour Coast

Separation problems are less severe for the second transfer from the phase orbit up to the Shuttle control box. It can be demonstrated that, irrespective of the altitude of the phase orbit, the angular separation when the user spacecraft passes through the Shuttle altitude will always be essentially the same as the final angular separation. This phenomena, shown schematically in Figure 14, implies that adequate separation during the final transfer can be ensured by simply adjusting the final rendezvous point in the Shuttle control box.

While the final transfer presents little difficulties under nominal conditions, under certain off-nominal circumstances, separation problems can arise. Specifically, if unplanned extra revolutions are necessary in the second transfer orbit, the user spacecraft and Shuttle may drift closer together. This will occur if the phase orbit is sufficiently close to the Shuttle orbit such that the period of the transfer orbit is greater than that of the Shuttle. This will cause the Shuttle to catch up with the user spacecraft during the unplanned extra revolutions and introduce the possibility of contact. All dangers associated with extra revolutions in the second transfer orbit are removed by positioning the phase orbit further below the Shuttle than the final rendezvous point is above. This can be achieved using the initial coast option described previously.

4.3 BIASING

J2 nodal precession due to the nonspherical shape of the Earth causes initially coplanar orbits of differing altitudes to become noncoplanar over time. For rendezvousing spacecraft, it is possible to compute an offset angle that when applied to the initial plane of one spacecraft causes the orbits to precess into the same plane by the termination of the

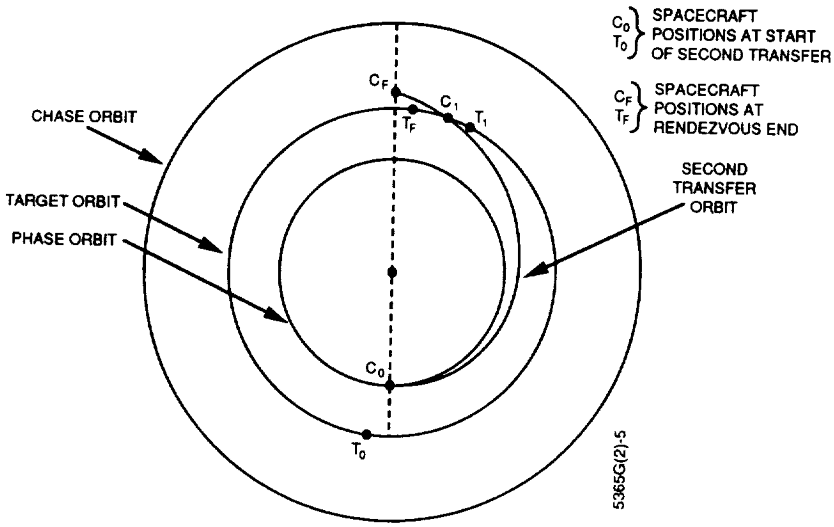

Figure 14. Final Transfer Orbit for Rendezvous to the Control Box

sequence. This bias angle can be used to avoid the plane changes that J2 would otherwise generate. Computation of this bias angle is a critical element in the interface between the user spacecraft and the Shuttle. Shuttle mission planners will use the computed bias angle to define the orbit plane into which the Shuttle is to be launched.

Since the nodal precession rate is affected by spacecraft altitude, the bias angle will be a function of the phase orbit altitude, and, therefore, a function of the initial conditions of the rendezvous. Figure 15 shows the bias angle for the upper and lower phase orbit solutions for six different sequences in which user spacecraft altitude, Shuttle altitude, and rendezvous duration were all varied. Figure 15 demonstrates that while the bias angle is a function of the initial phase angle, ϕ, it is essentially independent of spacecraft altitudes and rendezvous duration.

The following equations describing this linear relationship between bias angle, $\Delta\Omega$, and the phase angle can be derived from the analytic equations for phase orbit altitude (Equations (3-2) and (3-3)):

$$\Delta\Omega_u = -\frac{\partial \dot{\Omega}}{\partial a} k_u \phi \tag{4-1}$$

$$\Delta\Omega_\ell = -\frac{\partial \dot{\Omega}}{\partial a} k_\ell \phi + 2\pi \frac{\partial \dot{\Omega}}{\partial a} k_\ell \tag{4-2}$$

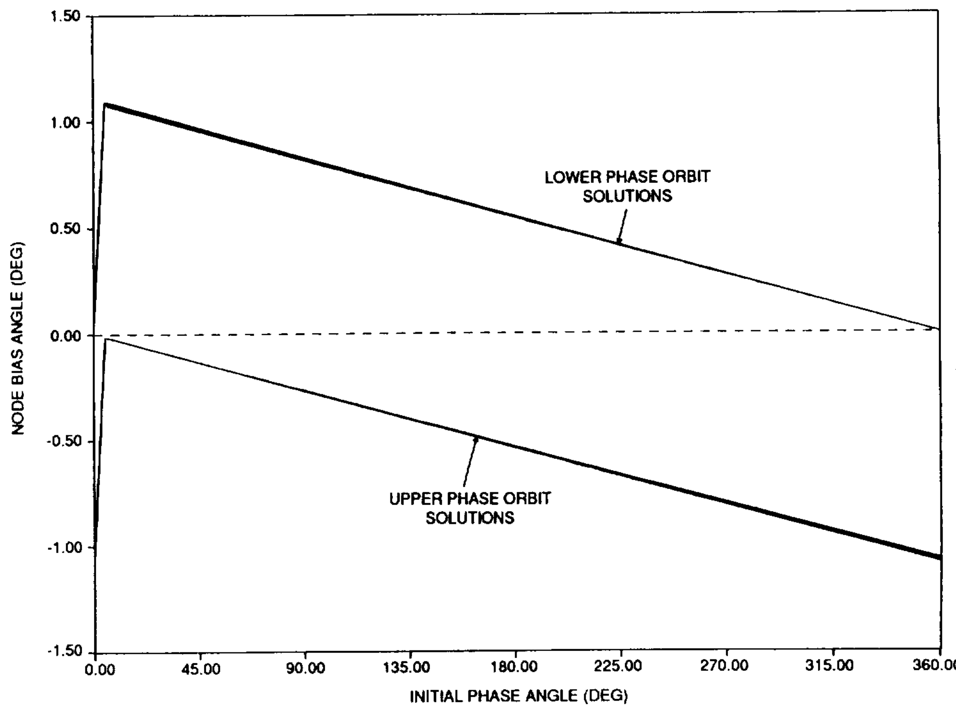

Figure 15. Bias Angle as a Function of Initial Phase Angle for Various Initial Conditions

where

$\Delta\Omega_\ell$ = bias angle corresponding to the lower phase orbit

$\Delta\Omega_u$ = bias angle corresponding to the upper phase orbit

$\dot{\Omega}$ = nodal precession rate

a = user spacecraft semimajor axis during rendezvous sequence

Numerical analysis demonstrates that the partial derivative of the nodal precession rate with respect to semimajor axis is essentially a constant over the range of altitudes under consideration (300 to 500 km). This is in agreement with the observed linearity of the bias angle/ϕ function.

Equations (4-1) and (4-2) predict the bias angle to within several hundredths of a degree and thus can be used for quick approximations.

4.4 TRACKING COVERAGE AND LIGHTING CONSTRAINTS

A probable requirement of rendezvous with the Shuttle is the capability to position each of the burns to satisfy various lighting and tracking coverage constraints. Specifically, Shuttle lighting requirements may specify that both spacecraft must be in the light at the termination of the rendezvous sequence. In addition, user spacecraft power and attitude sensor requirements may demand specific lighting conditions. Finally, Tracking Data and

Relay Satellite (TDRS) coverage will probably be necessary at each burn. Satisfying each of these requirements simultaneously can be achieved by adjusting the launch window of the Shuttle and the times of each of the burns.

It is anticipated that these constraints can be satisfied by using existing software to determine lighting and coverage characteristics during the proposed time for the rendezvous sequence. The proper conditions can be met by varying the time and therefore the location of rendezvous and by adjusting the coast period before the first burn and the time spent in the transfer orbits.

4.5 THRUSTER CALIBRATION AND CONTINGENCY PLANNING

An essential element of rendezvous between user spacecraft and the Shuttle involves contingency analysis. The sequences developed must allow for orbit determination and thruster calibration and techniques for recovering from off-nominal burns.

Thruster performance and spacecraft attitude errors in any maneuver must be compensated for in subsequent maneuvers to avoid unacceptably large errors. For example, if the first maneuver is 10 percent hot and the subsequent maneuvers are not retargeted, the resulting final along-track errors can be as large as 1300 km for a 3-day rendezvous from 350 to 315 km. Similarly, firing 10 percent hot in the final two burns of an otherwise nominal sequence can introduce final semimajor axis errors as large as 6.5 km.

Rendezvous sequences with the Shuttle must include techniques for determining and correcting for such errors. One possible technique for error determination and correction is simply to allow the first two burns to proceed, and then, upon achieving the phase orbit, to perform orbit determination and thruster calibration, and to recompute a new solution if necessary.

While straightforward, such a strategy is not desirable because it allows for the possible execution of two consecutive off-nominal burns with no thruster calibration between them. This could result in a phase orbit that is off-nominal to the extent that communications through TDRS will be jeopardized. For example, if burns 1 and 2 are both 10 percent hot, the phase orbit can be as much as 6.5 km below the nominal altitude for a 350 to 315 km scenario. Figure 16 illustrates that this altitude error will result in Doppler errors in excess of typical user spacecraft maximums (dashed horizontal lines) after only 1.5 revolutions. The maximums shown in this figure are for GRO. In addition, execution of burns 3 and 4 with no orbit determination between them removes the ability to fine tune the final transfer orbit.

An operationally better strategy is to incorporate a coasting period in each of the transfer orbits to provide time for orbit determination, thruster calibration, and any necessary retargeting. One advantage of such a sequence is that performing corrections after one instead of two burns lessens the likelihood of errors accumulating and is therefore likely to reduce Doppler errors. Figure 17 demonstrates that a 10 percent error in the first burn of a 350 to 315 km 3-day transfer results in more than 5 hours of TDRS coverage in the off-nominal transfer orbit before Doppler errors exceed the GRO maximums. In addition, this technique provides the capability to make corrections in the final transfer orbit after an off-nominal third burn.

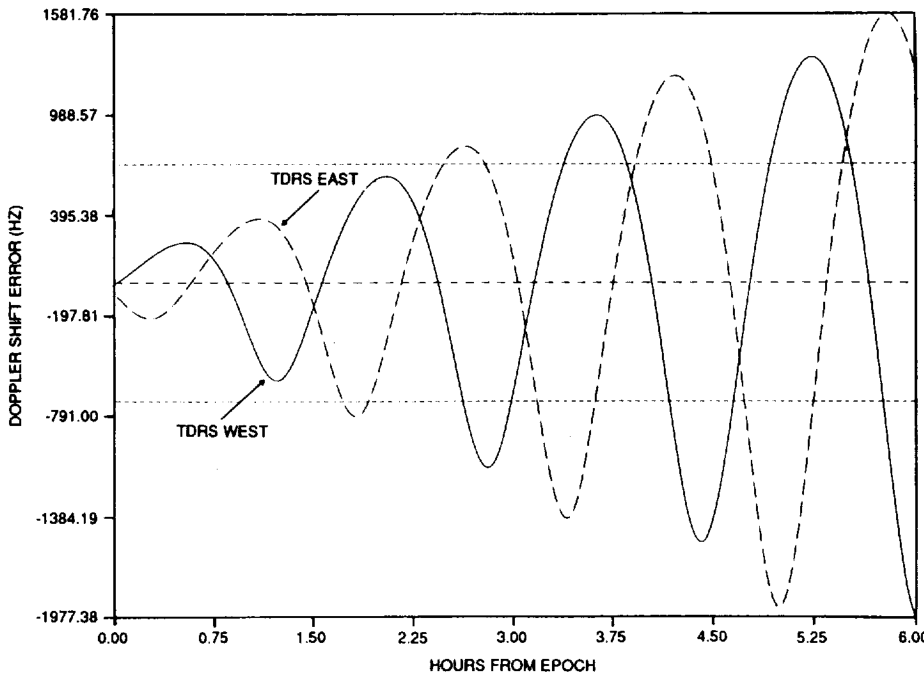

Figure 16. Doppler Shift Error in Phase Orbit After Two Off-Nominal Burns

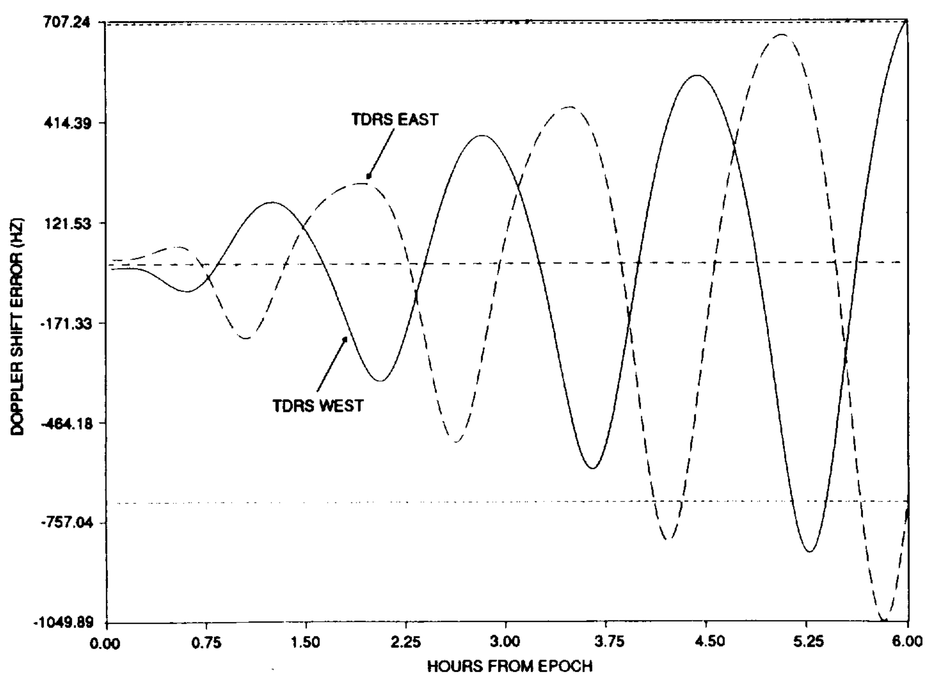

Figure 17. Doppler Shift Error in Transfer Orbit After One Off-Nominal Burn

Assuming this second type of rendezvous sequence is utilized, a typical recovery sequence would proceed as follows. Orbit determination would occur immediately after the first burn during the planned coast in the first transfer orbit. The user spacecraft thrusters would be calibrated using the newly determined orbits. If the actual transfer orbit is not within predetermined tolerances, a new rendezvous solution would be computed and executed. Figure 18, which illustrates such a recovery sequence, shows the off-nominal first burn (burn 0), the planned three-revolution coast period in the first transfer orbit, and the new four-burn solution from this off-nominal orbit.

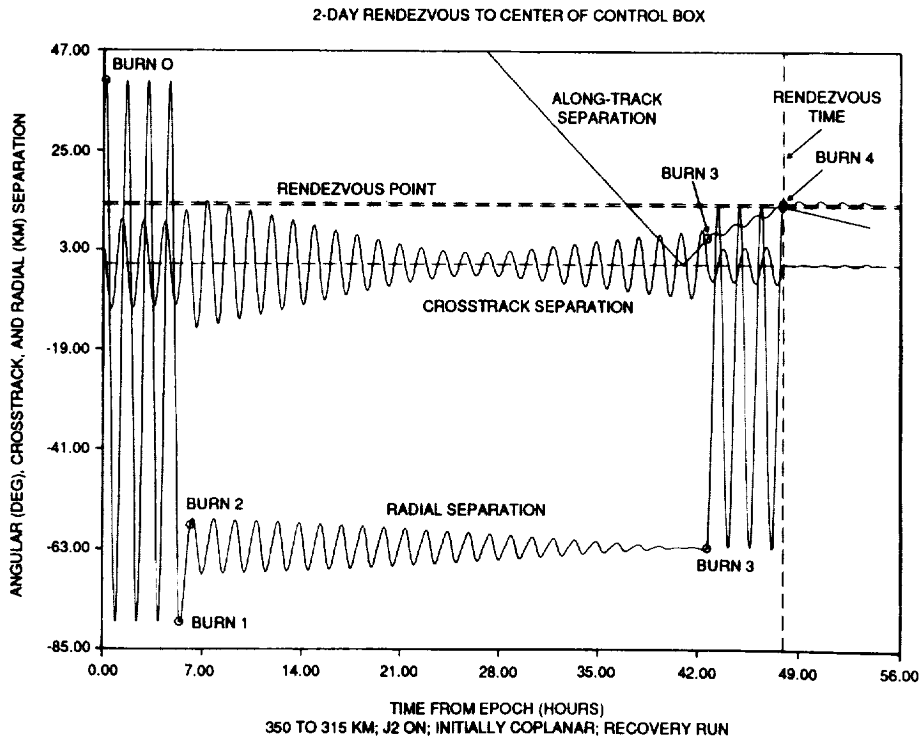

Figure 18. Two-Day Rendezvous to Center of Control Box

5. CONCLUSIONS

This paper has considered active rendezvous between a low-Earth orbit user spacecraft and the STS Shuttle. It demonstrates that rendezvous with the Shuttle requires that user spacecraft be able to execute coplanar or noncoplanar transfers in a specified amount of time from any initial orientation with the Shuttle. This general requirement, together with safety considerations and the desire to minimize ΔV expenditures, makes a rendezvous sequence consisting of a series of Hohmann transfers a desirable technique.

The general characteristics of such a rendezvous sequence are described. Specifically, relationships between phase orbit altitude and ΔV and the initial conditions of the sequence are explored in detail. Phase-orbit altitude is demonstrated to be essentially a linear function of the phase angle, with slope inversely related to the time of the rendezvous. The ΔV of such a sequence is demonstrated to be a function of the phase angle, with the maximum value being determined by the duration of the sequence and the altitude of the user spacecraft.

The final portion of the document considers relevant issues associated with the application of such a sequence in the operational environment. Rendezvous solutions that satisfy Shuttle tolerances are demonstrated. Techniques for ensuring that adequate spacecraft separations are maintained at all times are discussed. Bias angles for minimizing the number of necessary plane changes and strategies for guaranteeing proper lighting and coverage characteristics are considered. Finally, two methods for recovering from off-nominal burns are presented.

REFERENCES

1. Lyndon B. Johnson Space Center (JSC) Missions Operations Directorate, *Rendezvous Options*, D. J. Pearson, April 1987

2. --, *Rendezvous Techniques Options*, D. J. Pearson, February 1987

3. NASA, S-84-05028, *Spacecraft Standard Retrieval Policy*

4. Rockwell STSOC, *The Rendezvous Control Box*, C. G. M. de Bont, May 1987

5. NSTS 07700, *System Description and Data Design - Payload Deployment and Retrieval System*, Volume XIV, Appendix 6, May 1988 (Draft)

6. Computer Sciences Corporation, CSC/TM-87/6013, *Noncoplanar Rendezvous and the Biasing Technique*, J. R. Herrnstein and J. P. Carrico, April 1989