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# Orbiter/Payload Proximity Operations

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## Lateral Approach Technique

Mission Planning and Analysis Division

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SHUTTLE PROGRAM

# ORBITER/PAYLOAD PROXIMITY OPERATIONS

# LATERAL APPROACH TECHNIQUE

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| TPI | terminal phase initiation |
| TPM | terminal phase midcourse |
| COAS | crew optical alinement sight |
| CCTV | closed circuit television |
| GN&C | guidance, navigation, and control |
| FAI | final approach initiation |
| GPC | general purpose computer |
| $\Delta V$ | incremental velocity |
| c.g. | center of gravity |
| RCS | reaction control system |
| fps | feet per second |
| n. mi. | nautical miles |
| FOD | Flight Operations Directorate |
| STS | Shuttle transportation system |
| RMS | remote manipulator system |

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## INTRODUCTION

The control of the Orbiter reaction control system (RCS) plume impingement upon the payload during proximity operations will be required. Indications are that significant payload disturbance may result if such control is not implemented; and, as a consequence, the resultant dynamics may exceed the capability of the remote manipulator system and/or crewman to safely stationkeep, track, and grapple a free-flying payload. Additionally, thruster firing constraints may also be derived from other considerations such as payload contamination and/or payload thermal heating.

The capability to control the RCS thruster activity and thereby minimize the plume impingement effects will be directly influenced by the technique employed; therefore, plume impingement considerations will have a major influence on the development and selection of the baseline proximity operations technique(s). Although plume impingement concerns will be a major driver, the selected techniques should be designed and assessed relative to accommodation of the other known or potential flight requirements upon the payloads. Among the major concerns and considerations that should be taken into account and integrated into the design of this flight phase are

1. Applicability to a wide spectrum of payload configurations

2. Ground station contact requirements

3. Lighting compatibility

4. Propellant utilization

5. Duration of activities

Existing proposed techniques currently being investigated are based on in-plane trajectory approaches emphasizing total manual control. The concept proposed in this document for detailed analysis recommends an out-of-plane final approach emphasizing onboard software support for all except the latter segment of the final approach in which manual control is considered mandatory. Following the subsequent detailed assessment of this lateral approach, an overall assessment of the various candidate proximity operations techniques can be made.

Contained in the following sections are descriptions of the various subphases comprising the lateral approach technique and the associated operational assumptions that were made. These assumptions are preliminary at this time and have not been coordinated with other operational elements.

## SUMMARY

The purpose of this report is to present the Mission Planning and Analysis Division's lateral approach concept for proximity operations associated with the retrieval of free-flying payloads. This document is intended to serve as a basis for subsequent analysis, evaluation, and/or modification using both analytical and man-in-the-loop simulations. After the feasibility of this concept is assessed, it can then be evaluated with respect to other candidate proximity operations concepts leading to the establishment of a proximity operations baseline.

The concept, as proposed, is envisioned to provide the capability to accommodate various flight-planning constraints. While the concept requires the Orbiter to have the necessary onboard software and a navigation sensor with acceptable performance accuracy, this capability can also be used for other proximity operations applications (i.e., Orbiter/payload separation, payload inspection, Orbiter/payload joint experimentation, etc.).

## GUIDELINES AND ASSUMPTIONS

The following section describes the underlying set of guidelines and assumptions relating to the proposed design of the proximity operations flight phase. Many of these guidelines and assumptions were based on apparent reasonableness rather than being substantiated with detailed analysis results. It should be emphasized that the following list is preliminary, that significant analysis will be required to prove out the guidelines and assumptions made, and that close coordination with the Flight Operations Directorate (FOD) will be necessary to integrate FOD requirements into the design considerations for this onorbit flight phase. The intent is to subsequently develop an agreed-to set of guidelines and assumptions relating to proximity operations for use by all operations elements in their respective proximity operations activities.

1. Proximity operations requirements will not be levied on any portion of the pre-terminal phase midcourse (TPM) trajectory and operations. The proximity operations phase is to be designed to be compatible with requirements and constraints established under terminal phase initiation (TPI) considerations relative to targeting, navigation, lighting, etc.

2. Trajectory control will be supported by onboard navigation and targeting software. The onboard software, using information from a relative navigation sensor, will determine the appropriate maneuvers to achieve the desired position and display the maneuvers to the crew. The execution of the maneuvers shall be performed manually.

3. Assuming navigation is to be virtually continuous throughout proximity operations, the Orbiter's navigation sensor is to be pointed in the direction of the payload except during the manual control segment of the final approach subphase.

4. All maneuvers performed during proximity operations will utilize the primary RCS.

5. The capability to perform proximity operations should not depend on network availability or ground support for the Shuttle transportation system (STS) or for the payload.

6. It is assumed that the angle between the line of sight to the payload and the line of sight to the Sun should be greater than 30 degrees.

7. Proximity operations subphases should be designed to be relatively insensitive to the specific offset position; i.e., the technique should be applicable to all potential variations in the offset position vector.

8. It is assumed that there is no requirement to provide a manual backup capability to continue proximity operations in the event of system failure during proximity operations although such capability may be considered desirable.

9. The design of the proximity operations phase must accommodate both inertially stabilized and gravity-gradient stabilized payloads.

10. A relative navigation sensor is available to support proximity operations.

11. Attitude maneuvers are assumed to be performed at a 0.5 deg/sec rate.

## LATERAL APPROACH PROXIMITY OPERATIONS CONCEPT DESCRIPTION

### LATERAL APPROACH PROFILE SUMMARY

The initial proximity operations maneuver is performed approximately 20 minutes after the Orbiter establishes an intercepting trajectory with the payload (TPI + 20 minutes). This maneuver (4 fps) is designed to alter the course from that which intercepts the payload to one which achieves a position inplane, at the same altitude, and 2000 feet downrange with respect to the payload. Following this initial maneuver, a series of braking maneuvers (nominal cumulative $\Delta V$ of about 32 fps) is scheduled to arrive at the desired relative position with a low relative velocity. These braking maneuvers will also serve to correct for sensed trajectory dispersions. Finally, at TPI + 43 minutes, the Orbiter arrives at the desired relative position. The relative velocity between the Orbiter and the payload is nulled ($\Delta V$ of about 2.5 fps), and stationkeeping activities are initiated.

Stationkeeping will be comprised of a series of maneuvers designed to maintain the 2000-foot relative position within a TBD envelope, and the duration of the subphase will be dependent on the opportunity frequency available to satisfy specific flight requirements and constraints such as ground station contacts, payload reconfiguration activities. etc. (This subphase may extend for one or more orbits.) Stationkeeping operations are terminated at sunrise of the orbit immediately preceding the final approach to the payload and subsequent payload handling operations. At termination of stationkeeping, the Orbiter then performs a maneuver (nominally a $\Delta V$ of -1.2 fps downrange, -1.7 fps radial, and 2.4 fps out of plane relative to local vertical coordinate system) to transfer from the stationkeeping position to the lateral position from which the final approach trajectory will be initiated (50 feet uprange, 0 feet radial, and 2000 feet out of plane). The transfer time for this trajectory is planned for 18 minutes with a nominal 0-fps midcourse maneuver 9 minutes after initiation of the transfer.

Eighteen minutes after termination of the stationkeeping operations, the Orbiter nominally arrives at the desired lateral position. At this time, a maneuver is performed (nominal $\Delta V$ of 1.2 fps downrange, -1.7 fps radial, and -1.5 fps out of plane) to establish the final approach trajectory. This maneuver is targeted so that the Orbiter arrives at the payload handling envelope 18 minutes after initiation of the final approach maneuver.

Six minutes after the maneuver that establishes this final approach trajectory, a nominal 0-fps midcourse maneuver is performed to preserve the relative approach trajectory in the horizontal plane. Following the midcourse maneuver, the Orbiter then performs an 83-degree pitch maneuver to establish the relative Orbiter/payload configuration for manual control operations. At final approach initiation plus 11 minutes (7 minutes prior to the nominal time of arrival at the payload handling position), manual control operations are initiated with maneuvers subsequently being performed as necessary (normal to the approach path) to maintain the approach. Finally, when the payload has cleared the tail and is above the overhead window and in the crew optical alinement sight (COAS), the nominal approach velocity of 2.5 fps is nulled, and payload handling stationkeeping operations are initiated. This sequence is illustrated in figure 1.

In the event stationkeeping is not required, that phase can be deleted in the aforementioned proximity operations sequence. In such an instance, the initial proximity operations maneuver is targeted directly for the lateral position, with braking maneuvers implemented as described. When the Orbiter arrives at the lateral position, the final approach maneuver is then initiated, thereby bypassing the stationkeeping subphase and the subsequent transfer from stationkeeping to the lateral approach position.

## SUBPHASE DESCRIPTION

This section describes the various subphases that comprise the lateral approach concept for preretrieval proximity operations and the following discussion is intended to serve as a strawman for subsequent detailed evaluation and development of proximity operations techniques. It should be emphasized that additional analysis will be required to substantiate this concept and the associated assumptions. As the detailed analysis proceeds, changes are expected with respect to the definition of detailed parameters.

Transition From a Rendezvous Terminal Approach Trajectory Subphase

Inasmuch as this transition subphase has a direct interface with the terminal approach trajectory, some background information relative to the nominal approach trajectory will be briefly described. This will be followed with a discussion of the transition to an offset position. The transition subphase includes two options for the offset point: one downrange and inplane with the payload and the other directly out of plane with the payload.

Rendezvous Terminal Approach

The rendezvous approach trajectory, established prior to the entrance into the initial segment of proximity operations, will be initiated nominally from a specified relative geometry between the Orbiter and the payload. Specifically, the payload will nominally be at an altitude 10 nautical miles above the Orbiter at an elevation angle of 27 degrees up from the Orbiter's local horizontal. The maneuver to establish this trajectory (TPI) is targeted to place the Orbiter on an intercepting trajectory with the payload. The resultant approach trajectory will therefore have established the initial conditions for the transition to the desired offset position. These initial conditions include not only the relative position and velocity between the Orbiter and the payload but also Earth and solar relative parameters.

For a cooperative payload (i.e., one with an active transponder that permits long-range rendezvous radar tracking), midcourse maneuvers may be scheduled after the TPI maneuver. This (or these) maneuver is for the purpose of correcting for errors in the TPI maneuver, and they are targeted to preserve an intercept at the previously planned time. Typically, in past programs, two midcourse maneuvers have been planned (TPI + 12 minutes and 24 minutes). In transitioning from this intercept trajectory to an offset position, the "second midcourse" will be the first maneuver in the proximity operations sequence, and the targeting criteria will be changed accordingly.

For a rendezvous with a passive payload, which is the baseline technique, radar tracking must be deferred until the Orbiter is within skin track range. The current specification is approximately 10 nautical miles for a target with a 1-meter$^2$ radar cross section. This then restricts the earliest time for a maneuver using rendezvous radar data to approximately TPI + 20 minutes (ref. 1). This maneuver, therefore, will be considered the first maneuver of the proximity operations sequence; and, thus, no midcourse maneuver, per se, will be planned for the passive rendezvous case.

Figure 2 illustrates, schematically, the relative geometry desired for initiation of the terminal approach trajectory and also the approach geometry at the time of arrival to the payload. Table I presents a typical sequence of events associated with the rendezvous terminal approach, and figure 3 illustrates the nominal relative motion profile associated with this approach trajectory. The time history of relative parameters is shown in figure 4.

Transition to an Offset Position: Option 1 - In-Plane Offset Position

At about TPI + 20 minutes, a maneuver is performed to alter the desired course of the Orbiter from one that intercepts the payload to one which is inplane, at the same altitude, and 2000 feet ahead of the payload. Since, theoretically, this relative position is stable between the two vehicles (from orbital mechanics considerations solely) and thus propellant requirements should be minimized for maintaining this relative position, this option for the offset position would be selected in the event subsequent stationkeeping is required prior to the establishment of the final approach trajectory. A period of stationkeeping between the rendezvous terminal approach and the final approach decouples the dynamic interrelationship between the two phases, thereby permitting additional flight constraints to be imposed without major flight design impacts on either of the previously noted adjacent flight segments. This selected offset and the ensuing stationkeeping would support requirements based on acquiring specific ground stations prior to final approach initiation (FAI), observing and/or configuring the payload for capture, or waiting for optimum lighting, etc.

The initial transition maneuver is computed based on relative information obtained from the rendezvous radar and processed in the guidance, navigation, and control (GN&C) software. The targeted conditions that will be supplied to the general purpose computer (GPC) for this maneuver will be the desired offset position (2000 feet downrange, 0 feet radial, and 0 feet out of plane). The time of arrival at this desired offset position will be the intercept time used for TPI targeting (approximately TPI + 33 minutes). This initial maneuver will not only alter the trajectory in order to arrive at the desired offset point but also correct for dispersions in the rendezvous terminal approach trajectory. During the entire transition phase to the offset position (including during maneuvers), the radar and COAS are kept boresighted at the target. The maneuvers are computed by the onboard software and displayed to the crew in Orbiter body components for manual execution. In this manner, the maneuvers are applied without having to break track attitude.

The current assumption is that the Orbiter -Z axis (payload bay) is not only alined along the vehicle-to-vehicle line of sight but also that the Orbiter X-body axis is out of plane. Since the resultant center of mass lies in the payload horizontal plane, this orientation would minimize the orbital mechanics effects for the stationkeeping phase; hence, it would appear to be preferred for stationkeeping. It is further assumed desirable to be in this attitude at the time the stationkeeping position is reached, thereby eliminating the requirement to do an attitude maneuver (rotation about the line of sight) at that time. Consequently, the Orbiter was assumed to have maneuvered to this attitude prior to the initial transition maneuver.

It should be noted that the initiation time of this initial transition maneuver of TPI + 20 minutes was based on acquiring a passive payload at 10 nautical miles, approximately 8 minutes prior to the maneuver for adequate navigation and maneuver preparation activities. If the payload presents a smaller reflective surface to the radar, the acquisition range, and hence time from TPI, will occur later in the trajectory. The expected acquisition range associated with the payload of interest must be defined before flight.

Subsequent to the execution of the initial transition maneuver, a series of additional maneuvers is planned for the dual purpose of braking to the offset point and providing a capability to correct for dispersions. These maneuvers, in concert, should aid in reducing the Orbiter position error ellipse about the planned offset point.

In the targeting strategy, all transition phase maneuvers, both the initial maneuver and the transition phase braking maneuvers, are targeted for the same offset position as described previously. Whereas the initial transition maneuver was targeted to a time of arrival of TPI + 33 minutes, it will be necessary to delay the time of arrival for each of the planned braking maneuvers in order to effect a braking to the offset position by means of gradual reduction in the approach velocity.

A preliminary set of time-based braking gates (including the initial transition maneuver) is given in table II. These maneuvers assume a maximum delay from the initial theoretical intercept time of 10 minutes. In actuality, the number of gates and the specific initiation and transfer times may be modified, depending on subsequent detailed analysis and further defined flight constraints. Preliminary analysis shows, however, that 3 minutes between maneuver corrections is adequate since navigation is occurring throughout this subphase.

As previously noted, the initial transition maneuver is performed at TPI + 20 minutes. Subsequent braking maneuvers are assumed to occur at TPI + 28, 31, 34, 37, and 40 minutes. The final braking gate (TPI + 40 minutes) is targeted to achieve the offset position within 3 minutes of this maneuver. The final maneuver of this proximity operations subphase is envisioned to occur at the predicted time of arrival at the offset position based on the final braking gate (e.g., TPI + 43 minutes). At this time, the relative rates between the Orbiter and the payload will be nulled using the appropriate sensor and software displays. After this velocity nulling maneuver, the stationkeeping subphase will be initiated. (See "Proximity Operations Stationkeeping.")

Table III contains a typical sequence of events associated with the transition to the in-plane offset position. Figure 5 contains the nominal relative motion profile associated with this trajectory subphase, and figure 6 describes the time history of the important relative parameters.

## Transition to an Offset Position: Option 2 - Out-of-Plane Offset Position

Conceptually, this option is implemented generally as described in the preceding section with the exception that this alternative specifies that the trajectory be targeted directly for an out-of-plane offset position from which the lateral final approach is initiated, thus bypassing the stationkeeping activity. This option is conceived to be invoked when there is no requirement or desire to perform proximity operations stationkeeping prior to performing the final approach. Consequently, time and propellant savings are potentially realized.

The initial transition maneuver is performed at TPI + 20 minutes and targeted to achieve an Orbiter center of gravity (c.g.) offset position relative to the payload center of gravity of about 50 feet downrange (trailing), 0 feet radial, and 2000 feet out of plane. Flexibility exists as to which side (left or right) of the orbital plane would be targeted. It is assumed for the present that this selection would be based on the position of the Sun relative to the orbital plane; i.e., by maneuvering the Orbiter to the same side of the payload orbital plane as that of the Sun, the final approach is facilitated in that the line of sight between the Orbiter and the Sun tends to be opposite the Orbiter-to-payload line of sight thereby minimizing visual interference created by the Sun. The significance of this consideration increases with the magnitude of the beta angle. For beta angles near 0 degrees, either side may be chosen inasmuch as the line of sight from the Orbiter to the Sun is approximately normal to the approach trajectory (Orbiter-to-payload line of sight). It will be known before flight which side of the orbital plane should be selected. In terms of the downrange position, flight design flexibility exists here also as to whether the Orbiter center of mass leads or trails the payload. Among the considerations that will affect the selection of the "sense" of this offset position will be the orientation of the payload grapple fixture (i.e., whether or not it is leading or trailing if only one exists) and differential drag effects. If the payload design is one in which the grapple fixture concern can be deleted (i.e., multiple grapple fixtures on the payload, payload capability to orient to an attitude compatible with Orbiter preferences, etc.), the downrange position may be biased to the side (leading or trailing) that accommodates differential drag effects (if significant) during the final approach phase. The actual magnitude of the desired downrange position will be determined from the final approach trajectory, the remote manipulator system (RMS) capture envelope, the relative orientation of the Orbiter during the manual segment of the final approach, and the payload dimensions and orientation.

As previously discussed ("Transition to an Offset Position: Option 1 - In-Plane Offset Position"), the initial transition maneuver is followed by a series of braking maneuvers. The braking maneuver targeting and navigation concept for this option is as described for achieving an in-plane leading position, and the transition phase braking gates are assumed to remain as given in table II with one notable exception. For the in-plane offset position, it was assumed that the final maneuver of the transition subphase nulled the relative velocity on time and that the stationkeeping subphase was subsequently invoked. Since the premise underlying this option assumes no stationkeeping requirement, the maneuver to null the relative velocity is deleted and replaced with the initial final approach maneuver. To clarify, a scenerio is briefly described:

The initial transition maneuver to the out-of-plane position and braking maneuvers 1 through 5 are targeted and executed in a standard manner. After braking maneuver 5 has been executed, the transition subphase (see "Final Approach") is initiated. After the execution of braking maneuver 5, the relative state vector is then propagated to the offset arrival time (TPI + 43 minutes) and the initial maneuver of the final approach subphase is determined and executed based on the appropriate targeting parameters and criteria associated with the phase.

The Orbiter is assumed to be in track attitude (radar boresighted along the line of sight) during this transition phase (similar to the previous option). However, the preferred attitude of the Orbiter during the final approach is assumed to be the Orbiter Y-axis (wing) pointed toward the Earth, the Orbiter longitudinal axis parallel to the velocity vector, and the payload bay pointed along the line of sight. The sense of the described Orbiter longitudinal axis, posigrade or retrograde, will be determined by the desired downrange offset position, either leading or trailing. Therefore, pending detailed evaluation, it is assumed that the Orbiter will maneuver to the desired final approach maneuver attitude prior to the initiation of the final approach maneuver (retaining navigation sensor lockon to the payload).

A typical sequence of events for transitioning to an out-of-plane offset position is given in table IV. The nominal relative motion profile, both in-plane and out-of-plane motion, is contained in figure 7. Finally, the time history of the relevant relative motion parameters is shown in figure 8.

Proximity Operations Stationkeeping

This subphase is initiated after the termination of the transition to the offset position. For the purpose of this document, this subphase occurs after the relative rates are initially nulled (approximately TPI + 43 minutes). At this point, the appropriate onboard software targeting parameters are loaded into the GPC for stationkeeping, namely the desired position (2000 feet downrange, 0 feet radial, and 0 feet out of plane), initiation time, and arrival time at the stationkeeping position. Based on the current estimate of relative position and velocity as measured by the navigation sensor and processed by the navigation software, maneuvers are computed (in body axes) so that the relative trajectory passes through the desired stationkeeping position at the specified time. Rendezvous navigation occurs throughout the stationkeeping subphase; therefore, the Orbiter remains in track attitude with the payload bay boresighted at the target. After each maneuver, relative state information is processed for the purpose of computing the necessary corrective maneuver to maintain the stationkeeping envelope. One concept for maintaining the stationkeeping envelope is to continually target for the desired stationkeeping position at predetermined fixed intervals with a predetermined fixed transfer time. In lieu of results from a detailed analysis, it is proposed that the maneuver interval be synchronized to correspond to the targeted arrival time at the desired offset position. This appears to be reasonable in that the initial maneuver, if performed perfectly, will only cause the relative trajectory to achieve the requested position - not velocity. Therefore, a maneuver would normally be required at the stationkeeping point to achieve a static situation. The selection of the transfer times will need to be evaluated against such parameters as propellant requirements, stationkeeping envelope, etc. The excursion envelope about the desired stationkeeping position will be a function of both the maneuver frequency and the time interval to move back to the desired position. Obviously, tradeoffs are involved in the selection of these time-related targeting parameters. This concept does provide a predictable maneuver schedule that can conceivably be tailored, within the flight requirements and system performance limitations imposed, to ease the crew workload relative to trajectory monitoring, etc. Although the duration of the stationkeeping may potentially be for as long as required to accommodate flight requirements (ground coverage, payload reconfiguration, etc.), termination of this phase is assumed to occur at approximately orbital sunrise in order that all activities associated with the subsequent final approach can be accomplished in daylight at generally favorable Sun angles.

A typical stationkeeping maneuver sequence of events (for one orbit) is given in table V. For purposes of illustration, maneuvers were assumed to be scheduled at 10-minute intervals, and no maneuver less than 0.3 fps was applied. Figure 9 shows the relative motion associated with the above assumed sequence, and figure 10 illustrates the time history of the key relative parameters.

Transition From Stationkeeping to Final Approach Initiation

At approximately orbital sunrise following the required stationkeeping period, the Orbiter performs a maneuver designed to transfer from the stationkeeping position to the desired position from which the final approach to the payload will be initiated, nominally -50, 0, 2000 feet, uprange, radial, and out of plane, respectively. This maneuver is preceded by Orbiter tracking of the payload, supported by onboard software determination of the required maneuver magnitude, and targeted to achieve the desired offset position relative to the payload 18 minutes later.

The desired lateral position from which the final approach will be initiated will be based on the nominal closing velocity desired at the time of arrival of the Orbiter to the payload. This value currently is approximately 2.5 fps. The strategy behind the selection of the transfer time is primarily to ensure that the final approach maneuver does not require thrusting in the direction of the payload. It is therefore desirable to plan the trajectory such that the Orbiter is moving away from the payload laterally at the time of the final approach initiation maneuver.

Following the execution of the initial transfer maneuver, the Orbiter tracks the payload using the onboard navigation system. During this period of time, the Orbiter's payload bay is kept boresighted along the Orbiter-to-payload line of sight.

Midway through this transfer trajectory (i.e., transfer initiation plus 9 minutes) a midcourse maneuver is scheduled to correct for trajectory dispersions.[a] (This maneuver is nominally 0 fps.) Computed in the GN&C using relative state information supplied by the Orbiter onboard relative navigation system, the midcourse maneuver is targeted to achieve the desired offset position at the planned final approach initiation time (midcourse maneuver plus 9 minutes). Note that there is no plan to stationkeep at the lateral position prior to initiation of the final approach.

After the execution of the midcourse maneuver, the Orbiter continues to track the payload, updating the relative state vector in preparation for initiation

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[a]It may subsequently be ascertained that several midcourses are desirable that can easily be incorporated.

of the final approach trajectory. During this coast phase following the midcourse maneuver, the Orbiter achieves the desired attitude for the final approach; namely, the navigation sensor (payload bay) pointed towards the payload, the wing radially toward the Earth, and the Orbiter longitudinal axis parallel to the inertial velocity vector.

The typical sequence of events associated with this phase is given in table VI. The relative motion profile and time history of pertinent relative parameters are contained in figures 11 and 12.

## Final Approach

This subphase is divided into two segments. The initial segment establishes and alines the final approach trajectory using the Orbiter onboard navigation system and the GN&C computer. The required maneuvers are computed by the GN&C and displayed to the crew for execution. The second segment of this subphase provides the necessary vernier control of the final approach trajectory using manual techniques to arrive within the payload handling stationkeeping envelope.

This subphase may be initiated from either (a) the transition from a rendezvous terminal approach trajectory to an offset position directly out of plane of the payload (see "Transition to an Offset Position: Option 2 - Out-of-Plane Offset Position") or (b) from the transition from stationkeeping to final approach initiation subphase (see "Transition From Stationkeeping to Final Approach"). For (a) above, the final approach activities are assumed to be initiated after the final braking gate TPI + 40 minutes for the typical illustration contained in this document. For (b) above, the final approach activities are assumed to be initiated following the midcourse maneuver at stationkeeping termination plus 9 minutes. Regardless of which of the above subphases precedes the final approach, the technique concept is identical for the establishment of the final approach trajectory.

The following sections describe the concepts for the control of the trajectory during both segments of the final approach. Table VII contains a typical sequence of events for the entire final approach phase, and figures 13 and 14 show the relative motion profile and relative parameter time histories. The relative motion during this entire phase, referenced to the Orbiter body coordinate system, is illustrated in figure 15.

### Final Approach Alinement Segment

The final approach initiation maneuver will be determined using the onboard GN&C computer. This maneuver will be targeted to achieve two specific conditions: (1) the Orbiter will intersect the payload orbital plane 18 minutes after initiation of the final approach transfer (i. e., an out-of-plane position of 0 feet) and (2) the Orbiter will intercept the desired nominal approach path at the time of the planned midcourse correction maneuver assumed to occur 6 minutes after the final approach initiation maneuver. In the nominal situation, the Orbiter center of mass lies at the same altitude as that of the payload. Therefore, neglecting the effects of drag and other perturbations, the relative motion lies solely in the horizontal plane directed parallel to the angular momentum vector. Since the out-of-plane and in-plane motion are decoupled, the nominal downrange and radial displacement remain constant throughout the transfer. Control of this downrange and radial position is important for manual trajectory control considerations and to ensure that the Orbiter ends up within the acceptable payload handling stationkeeping envelope. Therefore, in response to anticipated position dispersions at the final approach initiation point and the desire to maintain the approach trajectory in the horizontal plane, it is assumed desirable to establish the nominal approach trajectory early in the final approach subphase time line by scheduling a midcourse maneuver. Thus, by targeting the final approach maneuver to achieve the desired in-plane position at the time of this midcourse correction, the midcourse maneuver (when executed) would nominally null the in-plane velocity, and the nominal approach trajectory would then be achieved. Subsequent to performing the initial final approach maneuver, the Orbiter then tracks the payload using the onboard navigation sensor. During this coast, the Orbiter is nominally flying an attitude where the payload bay is directed towards the target, the wing is alined along the radius vector, and the Orbiter longitudinal axis is parallel to the inertial velocity vector. This attitude minimizes the orbital mechanics disturbances in that the Orbiter center of mass lies in the payload horizontal plane.

At FAI + 6 minutes, the Orbiter performs a midcourse maneuver (nominally zero) as determined from the onboard software and displayed to the crew for execution. This midcourse is performed on time and is targeted to intercept the nominal approach path at the time manual control is initiated - FAI + 11 minutes (a 5-minute transfer time). There is no adjustment made to the approach (out of plane) velocity in order to preclude the chance of directing the Orbiter RCS plume toward the payload and thereby producing translational and rotational disturbances. This planned midcourse maneuver will strive to achieve only the desired position at the specified time. If a position error (non-nominal) occurs at the time of the midcourse maneuver, a relative velocity normal to the desired approach path will exist at the nominal time the Orbiter path intersects the desired approach trajectory. The onboard software, when computing the planned midcourse maneuver at FAI + 6 minutes, will also compute the relative velocity normal to the approach path at FAI + 11 minutes (manual control initiation). The crew will null those computed velocity components and begin manual control of the approach trajectory.

Following the midcourse maneuver, the Orbiter continues to coast in final approach alinement attitude for an assumed 1 minute prior to transitioning into the attitude for the manual control segment of the final approach. This 1 minute is assumed adequate for final assessment of the trajectory before initiating manual operations. For the present, it is assumed that after the manual control attitude is achieved, the onboard navigation sensor will not be available to provide range and range rate information. Therefore, this delay time provides the crew with the last opportunity to obtain the approach distance and velocity based on postmaneuver tracking measurements. At FAI + 7 minutes, the manual control segment is initiated.

Manual Control Segment

At FAI + 7 minutes, the Orbiter performs an 83-degree pitch maneuver at 0.5 deg/sec to establish the Orbiter body orientation required for this segment of the final approach. In this attitude, the Orbiter wings remain normal to the horizontal plane (plane of the final approach trajectory). However, the Orbiter longitudinal axis is now parallel to the nominal approach path with the Orbiter tail leading. The payload bay lies in the horizontal plane pointed downrange. Approximately 3 minutes are required for this attitude maneuver. The payload, which prior to the attitude maneuver was visible through the Orbiter overhead window/COAS, has now translated relative to the Orbiter body axis such that it is now observed through the aft-facing forward bulkhead windows and/or closed-circuit television (CCTV). Following the Orbiter pitch maneuver, 1 minute is allowed for monitoring and observation. At FAI + 11 minutes, the maneuvers required to null the velocity components normal to the nominal approach path (as determined by the GN&C targeting software prior to the midcourse maneuver) are applied. Nominally, this is a 0-fps maneuver.

From this point (FAI + 11 minutes) to arrival at the payload handling stationkeeping position, the control is performed manually using visual aids and cues (ref. 2). Until the payload has cleared the vertical tail and is in view of the overhead window, no thrusting parallel to the approach path is performed. All maneuvers are constrained to be normal to the approach path. A prime objective during the early portion of this manual control segment will be to establish the trajectory accurately to preclude the use of the +Z thrusters when the payload is within TBD degrees of the thruster centerline (thereby minimizing plume impingement effects).

Finally, at FAI + 18 minutes, the relative approach velocity of nominally 2.5 fps is removed by application of the +X RCS jets followed by the maneuvers necessary for stationkeeping in support of payload handling operations.

An alternate concept for the final approach subphase is to control the trajectory using the radar and the COAS. For this option, the Orbiter is not required to perform the pitchover attitude maneuver but rather remains in a constant attitude (payload bay facing the payload as previously specified for the final approach alinement segment) throughout this entire subphase. Maintenance of the approach trajectory is provided by controlling the relative motion normal to the approach path, thereby keeping the payload in the COAS with its leading edge alined with the forward/aft COAS crosshair.

Because this relative trajectory results in the payload bearing directly towards the Orbiter, an Orbiter braking maneuver is performed by inhibiting the +Z primary RCS thrusters and by the simultaneous firing of the Orbiter +X and -X primary RCS jets to take advantage of the thrust in the Z direction that is generated from the engine cant and scarfing characteristics.

Constraining the leading edge of the payload to be at the center of the COAS will minimize the plume impingement on the payload resulting from the ±X jets. Since this braking maneuver is extremely inefficient (about 250 pounds of propellant for 1 fps +Z), it will be highly desirable to minimize the approach velocity, which may dictate a change in the targeted lateral position from 2000 feet to between 500 to 1000 feet. This concept is illustrated in figure 16.

## CONCLUDING REMARKS

This report has presented the Mission Planning and Analysis Division's lateral approach concept for proximity operations associated with the retrieval of free-flying payloads. This proposed technique is predicated on the feasibility of utilizing onboard software for the establishment and maintenance of the proximity operations trajectory, thereby permitting flexibility in the trajectory design to satisfy anticipated operational considerations and constraints such as lighting, plume impingement and contamination, RCS propellant utilization including management of the forward RCS tank usage, etc.

It is emphasized that this concept will require further assessment including extensive analytical and man-in-the-loop simulations and analysis. The capability of the Orbiter onboard navigation sensor and the associated GN&C software will be a major consideration as to the feasibility of this concept. It is expected that modification to this technique relative to specific details will be encountered based on the analysis results. After sufficient analysis has been performed relative to this lateral approach technique, an evaluation can then be made with respect to other existing proximity operations concept proposals, resulting in the establishment of a proximity operations baseline.

## REFERENCES

1. Grossman, E. P.; and Jones, A. K.: Software Supported Feasibility Study Final Report, MDAC TM 1.4-MAB-149, July 5, 1977.

2. Wilson, S. W.: A Proposed Terminal Approach Strategy for Shuttle Payload Retrieval, TRW Report 28415-H005-R0-00, May 31, 1977.

TABLE I.- TYPICAL RENDEZVOUS TERMINAL APPROACH SEQUENCE OF EVENTS

| Time, min[a] | Event | Range between Orbiter/payload, n. mi. | Maneuver, fps |
|---|---|---|---|
| TPI - 47 | Begin startracker onboard navigation | 69 | -- |
| TPI - 17 | Enter darkness; terminate onboard navigation | 38 | -- |
| TPI | Rendezvous terminal approach initiation | 22 | 21.5 |
| TPI + 12 | Radar skin track acquisition | 10 | -- |
| TPI + 17 | Exit darkness | 6 | -- |
| TPI + 20[b] | Midcourse | 4.5 | Nominally 0 |
| TPI + 33[b] | Impulsive braking | 0 | 28 |

[a]References from initiation of rendezvous terminal approach.

[b]Included only for reference.

TABLE II.- TYPICAL TRANSITION PHASE BRAKING GATES

| Transition phase | Initiation time, min from TPI | Targeted time of arrival, min from TPI | Targeted transfer time, min |
|---|---|---|---|
| Transition maneuver initiation[a] | 20 | 30 | 13 |
| Braking 1 | 28 | 35 | 13 |
| Braking 2 | 31 | 35 | 7 |
| Braking 3 | 34 | 39 | 6 |
| Braking 4 | 37 | 41 | 5 |
| Braking 5 | 40 | 43 | 4 |
| Stationkeeping initiation[b] | 43 | -- | -- |
| Final approach initiation[b] | 43 | -- | -- |

[a]Included for reference.

[b]Included for reference (another subphase).

TABLE III.- TYPICAL TRANSITION TO OFFSET SEQUENCE OF EVENTS - IN-PLANE OPTION

| Time, min[a] | Event | Range between Orbiter/payload | Maneuver, fps[b] |
|---|---|---|---|
| TPI + 12 | Radar skin track acquisition | 10 n. mi. | |
| TPI + 17 | Exit darkness | 6 n. mi. | |
| TPI + 20 | Transition initiation | 4.5 n. mi. | 4 |
| TPI + 28 | Transition braking maneuver 1 | 10 000 ft | 8 |
| TPI + 31 | Transition braking maneuver 2 | 6 500 ft | 7.9 |
| TPI + 34 | Transition braking maneuver 3 | 4 300 ft | 6.9 |
| TPI + 37 | Transition braking maneuver 4 | 3 100 ft | 5.4 |
| TPI + 40 | Transition braking maneuver 5 | 2 400 ft | 3.8 |
| TPI + 43 | Null relative velocity; initiate stationkeeping subphase | 2 000 ft | 2.5 |

[a]Referenced from initiation of rendezvous terminal approach.

[b]Assumed to be applied as components.

TABLE IV.- TYPICAL TRANSITION TO OFFSET SEQUENCE OF EVENTS -

OUT-OF-PLANE OPTION

| Time, min[a] | Event | Range between Orbiter/payload | Maneuver, fps[b] |
| --- | --- | --- | --- |
| TPI + 12 | Radar skin track acquisition | 10 n. mi. | |
| TPI + 17 | Exit darkness | 6 n. mi. | |
| TPI + 20 | Transition initiation maneuver | 4.5 n. mi. | 3.7 |
| TPI + 28 | Transition braking maneuver 1 | 9400 ft | [illegible] |
| TPI + 31 | Transition braking maneuver 2 | 5600 ft | 8.4 |
| TPI + 34 | Transition braking maneuver 3 | 3400 ft | 7.1 |
| TPI + 37 | Transition braking maneuver 4 | 2300 ft | 5.3 |
| TPI + 40 | Transition braking maneuver 5 | 2050 ft | 3.8 |
| TPI + 43 | Final approach initiation | 2000 ft | 3.1 |

[a]Referenced from initiation of rendezvous terminal approach.

[b]Assumed to be applied as components.

TABLE V.- TYPICAL PROXIMITY OPERATIONS STATIONKEEPING SEQUENCE OF EVENTS[a]

| Time, hr:min[b] | Event | Range between Orbiter/payload, ft | Maneuver,[c] fps |
|---|---|---|---|
| TPI + 0:43 | Initiate proximity operations stationkeeping | 2050 | |
| TPI + 0:53 | Stationkeeping correction | 2066 | 0.4 |
| TPI + 1:03 | Stationkeeping correction | 2056 | 0 |
| TPI + 1:13 | Stationkeeping correction; enter darkness | 1900 | .7 |
| TPI + 1:23 | Stationkeeping correction | 2000 | 0 |
| TPI + 1:33 | Stationkeeping correction; terminate proximity operations stationkeeping operations and begin preparation for transitioning to final approach lateral position | 2100 | .6 |
| TPI + 1:47 | Exit darkness; initiate transition maneuver[d] to final approach initiation position | 2000 | 5.3 |

[a]One orbit duration assumed for illustrative purposes.

[b]Referenced from initiation of rendezvous terminal approach.

[c]Assumed to be applied as components.

[d]Nominal.

NOTE: An initial position dispersion of 50 ft (all components) was assumed; data based on corrections every 10 minutes and not applied if $\Delta V$ less than 0.3 fps.

TABLE VI.- TYPICAL TRANSITION FROM STATIONKEEPING TO FINAL APPROACH

INITIATION SEQUENCE OF EVENTS

| Time, hr:min[a] | Event | Range between Orbiter/payload, ft | Maneuver,[b] fps |
|---|---|---|---|
| TPI + 1:47 | Sunrise; initiate maneuver to transition from stationkeeping to final approach initiation position | 2000 (nominal) | 5.3 |
| TPI + 1:56 | Midcourse correction; begin preparation for final approach initiation maneuver | 1645 | Nominally 0 |
| TPI + 2:05 | Final approach initiation maneuver | 2000 | 4.4 |

[a]Referenced from initiation of rendezvous terminal approach and assumes approximately 1 hour of stationkeeping.

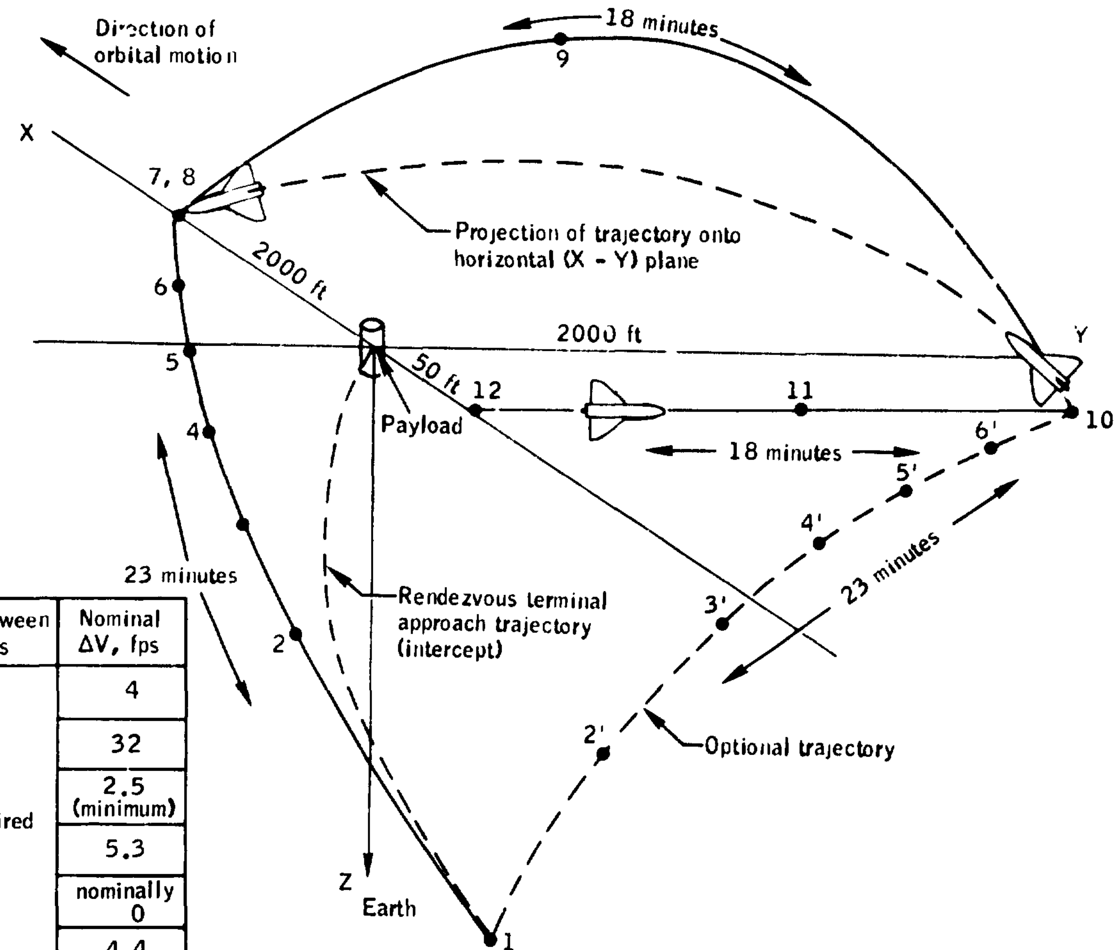
[b]Assumed to be applied as components.

TABLE VII.- TYPICAL FINAL APPROACH SEQUENCE OF EVENTS

| Time, hr:min[a] | Time from final approach initiation, min | Event | Range between Orbiter/payload, ft | Maneuver,[b] fps |
| --- | --- | --- | --- | --- |
| TPI + 1:56 | FAI - 9 (FAI - 3) | Begin preparation for final approach initiation maneuver | 1645 (2046) | |
| TPI + 2:05 (TPI + 0:43) | FAI + 0 | Final approach initiation maneuver | 2000 (2000) | 4.4 (3.1) |
| TPI + 2:11 (TPI + 0:49) | FAI + 6 | Midcourse correction | 1564 | Nominally 0 |
| TPI + 2:12 (TPI + 0:50) | FAI + 7 | Begin maneuver to manual control attitude | 1462 | |
| TPI + 2:12 (TPI + 0:53) | FAI + 10 | Complete attitude maneuver | 1115 | |
| TPI + 2:16 (TPI + 0:54) | FAI + 11 | Null onboard computed body Y, Z relative velocity components; initiate manual control | 989 | Nominally 0 |
| TPI + 2:23 (TPI + 1:01) | FAI + 18 | Braking; initiate payload handling stationkeeping | 50 | 2.5 |

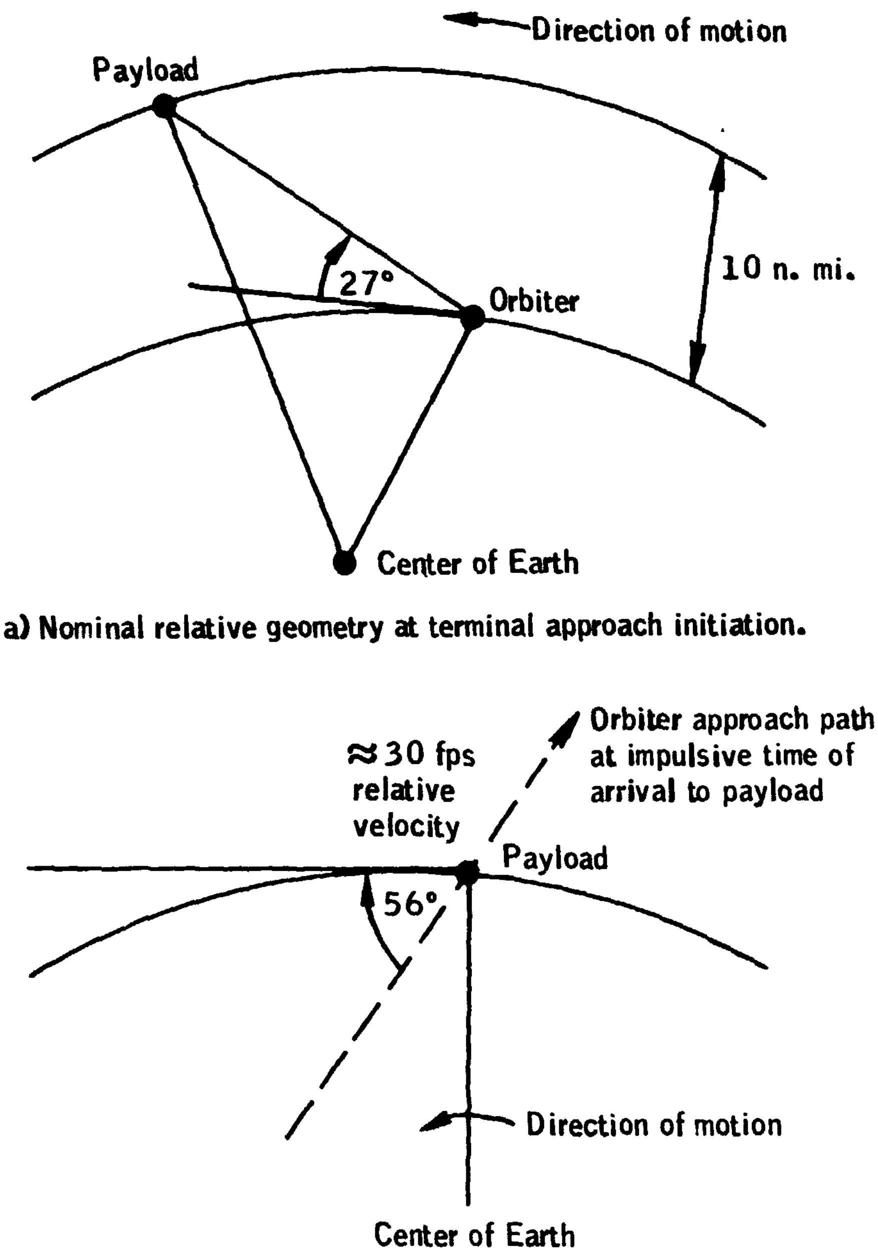
[a]Numbers in parentheses denote the option of transitioning from the rendezvous terminal approach trajectory directly to the out-of-plane offset position (see "Transition From a Rendezvous Terminal Approach Trajectory"). Referenced from initiation of rendezvous terminal approach.

[b]Assumed to be applied as components.




| Event no. | Event | Time between events | Nominal ΔV, fps |
|---|---|---|---|
| 1 | Transition mvr to offset position | | 4 |
| 2-6 | Transition braking maneuvers | 23 | 32 |
| 7 | Initiate stationkeeping | As required | 2.5 (minimum) |
| 8 | Transition to lateral position | 9 | 5.3 |
| 9 | Midcourse maneuver | 9 | nominally 0 |
| 10 | Final approach initiation | 6 | 4.4 |
| 11 | Final approach midcourse | 12 | nominally 0 |
| | Braking | | 2.5 |

Figure 1.- Overview of lateral approach technique for proximity operations.




(a) Nominal relative geometry at terminal approach initiation.



(b) Approach geometry at impulsive time of arrival to payload.

Figure 2.- Rendezvous terminal approach relative geometry.

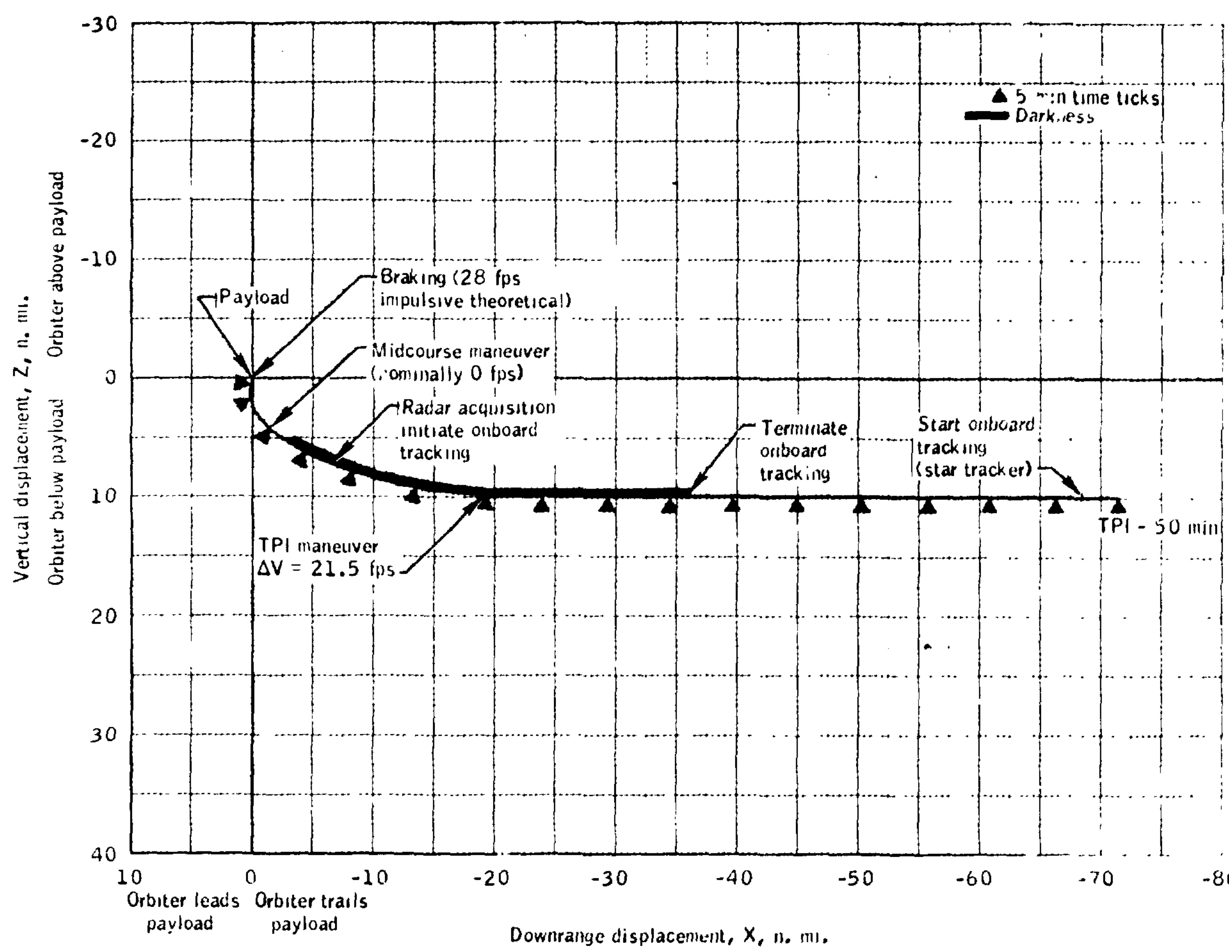



Figure 3.- Typical relative motion profile for the rendezvous terminal approach trajectory.

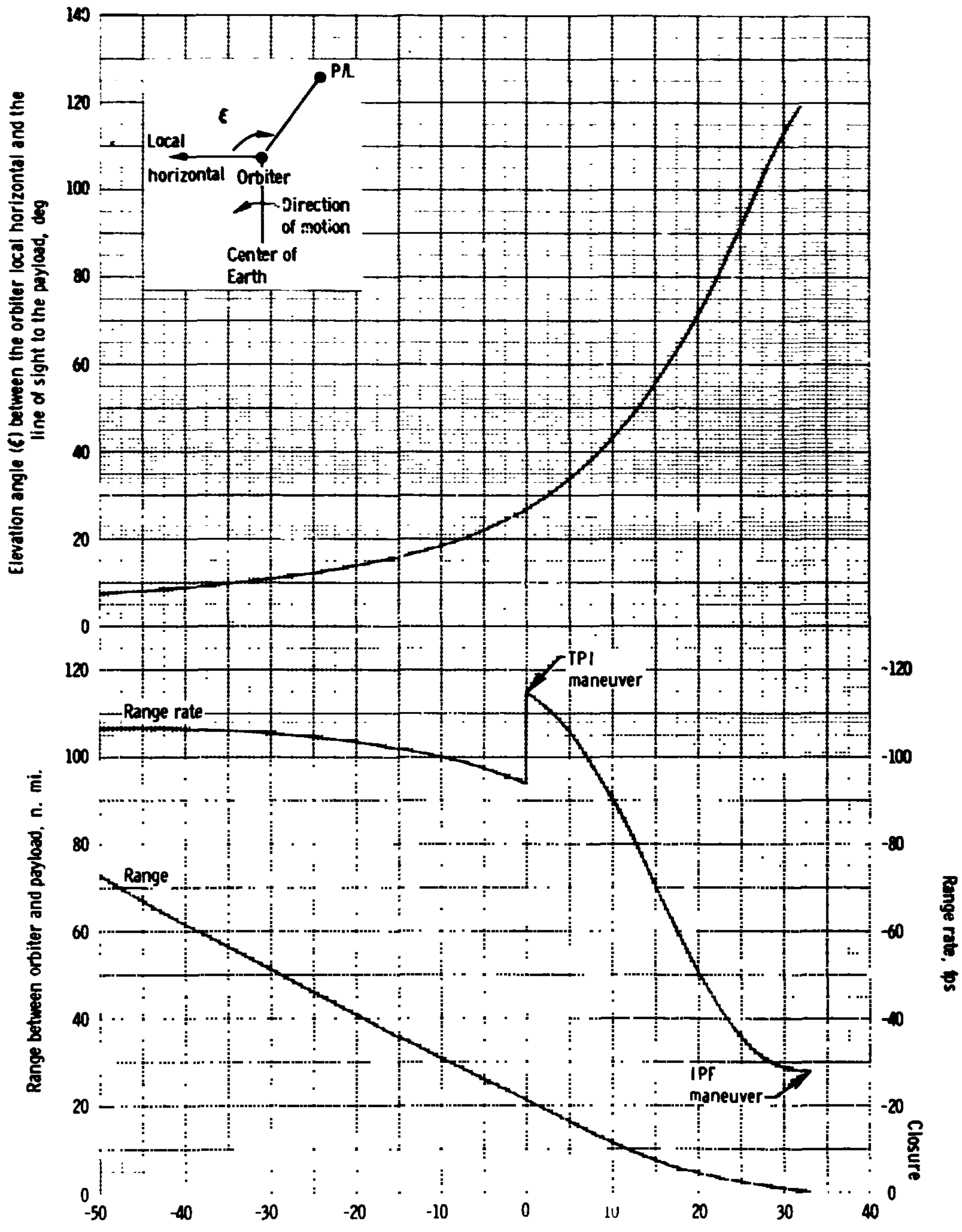
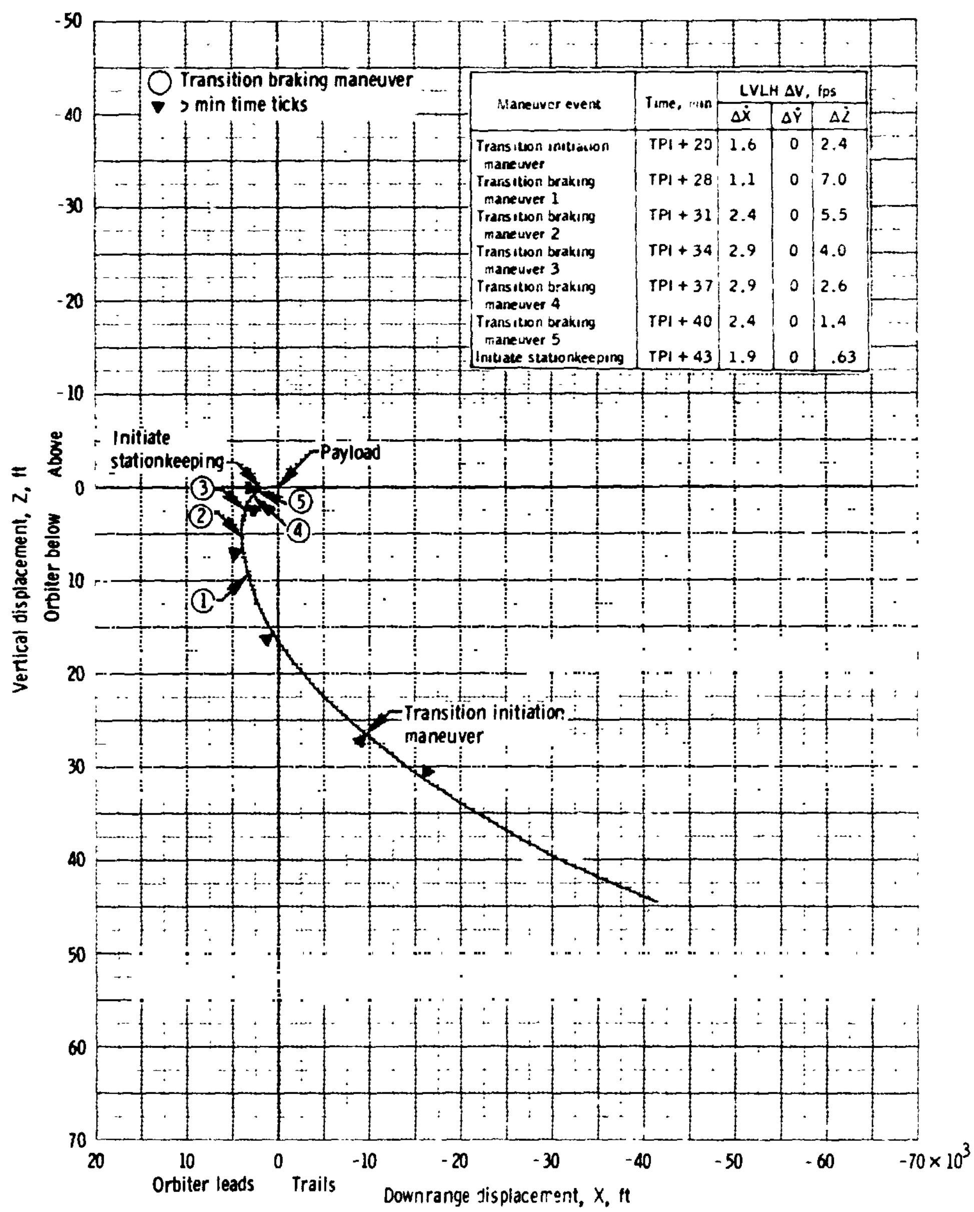



Figure 4. - Time history of relative motion parameters during rendezvous terminal approach.




| Maneuver event | Time, min | LVLH ΔV, fps | | |
|---|---|---|---|---|
| | | $\Delta\dot{X}$ | $\Delta\dot{Y}$ | $\Delta\dot{Z}$ |
| Transition initiation maneuver | TPI + 20 | 1.6 | 0 | 2.4 |
| Transition braking maneuver 1 | TPI + 28 | 1.1 | 0 | 7.0 |
| Transition braking maneuver 2 | TPI + 31 | 2.4 | 0 | 5.5 |
| Transition braking maneuver 3 | TPI + 34 | 2.9 | 0 | 4.0 |
| Transition braking maneuver 4 | TPI + 37 | 2.9 | 0 | 2.6 |
| Transition braking maneuver 5 | TPI + 40 | 2.4 | 0 | 1.4 |
| Initiate stationkeeping | TPI + 43 | 1.9 | 0 | .63 |

Figure 5.- Orbiter motion relative to the payload during the transition from a rendezvous terminal approach to an inplane offset position.

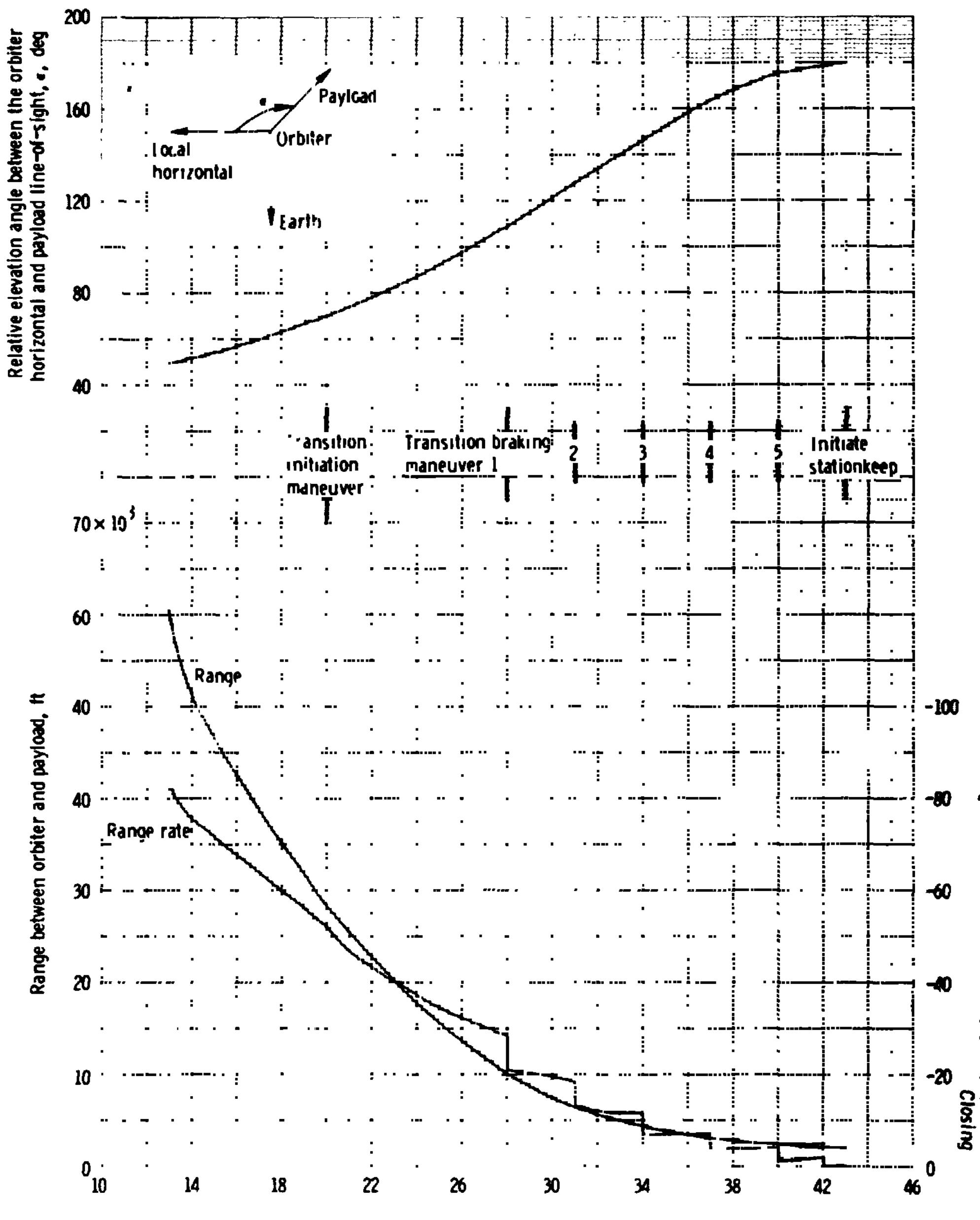
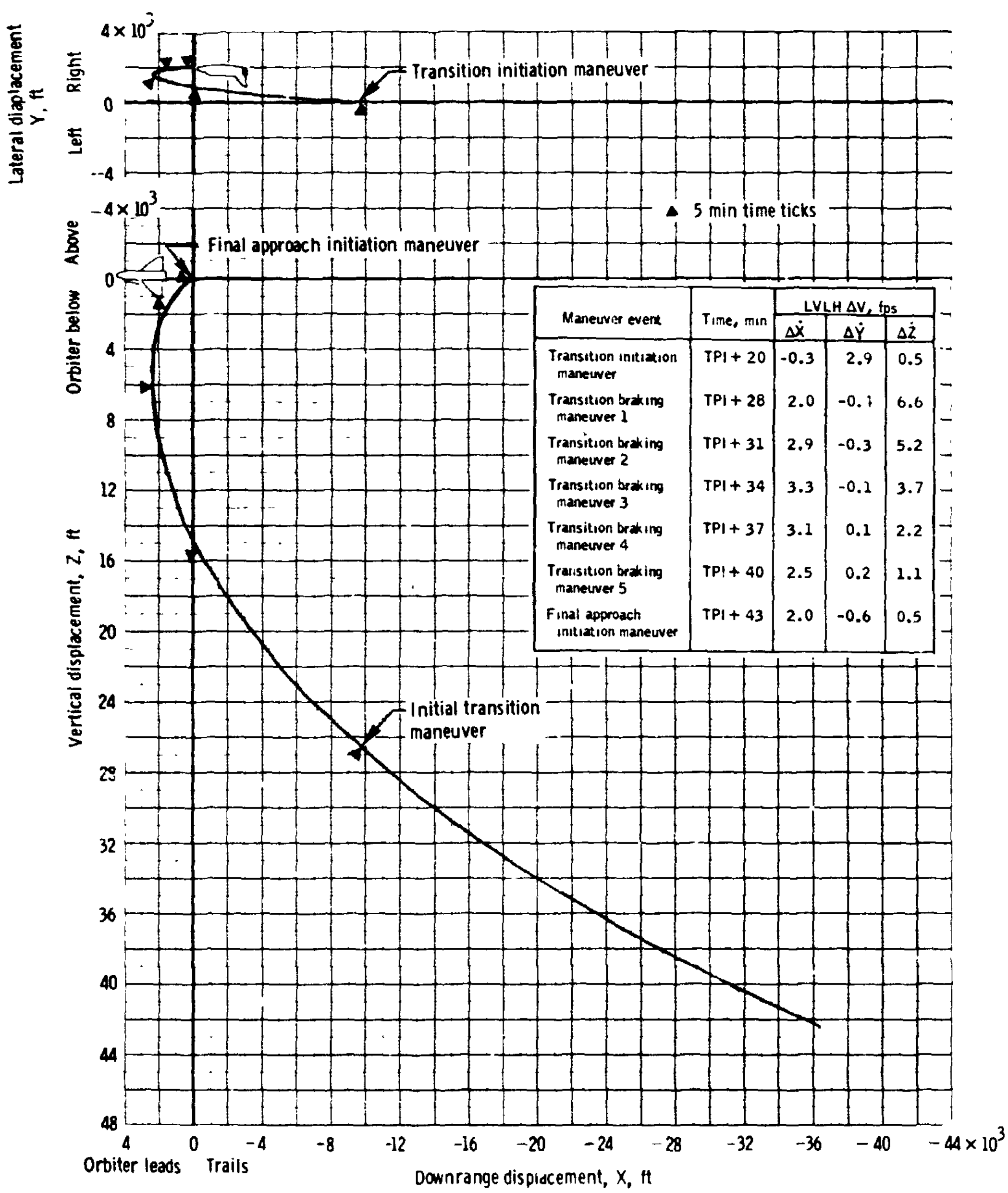



Figure 6.- Time history of relative parameters during the transition from a rendezvous terminal approach to an inplane offset position.




| Maneuver event | Time, min | LVLH ΔV, fps | | |
|---|---|---|---|---|
| | | $\Delta\dot{X}$ | $\Delta\dot{Y}$ | $\Delta\dot{Z}$ |
| Transition initiation maneuver | TPI + 20 | -0.3 | 2.9 | 0.5 |
| Transition braking maneuver 1 | TPI + 28 | 2.0 | -0.1 | 6.6 |
| Transition braking maneuver 2 | TPI + 31 | 2.9 | -0.3 | 5.2 |
| Transition braking maneuver 3 | TPI + 34 | 3.3 | -0.1 | 3.7 |
| Transition braking maneuver 4 | TPI + 37 | 3.1 | 0.1 | 2.2 |
| Transition braking maneuver 5 | TPI + 40 | 2.5 | 0.2 | 1.1 |
| Final approach initiation maneuver | TPI + 43 | 2.0 | -0.6 | 0.5 |

Figure 7. - Orbiter motion relative to the payload during the transition from a rendezvous terminal approach to an out-of-plane offset position.

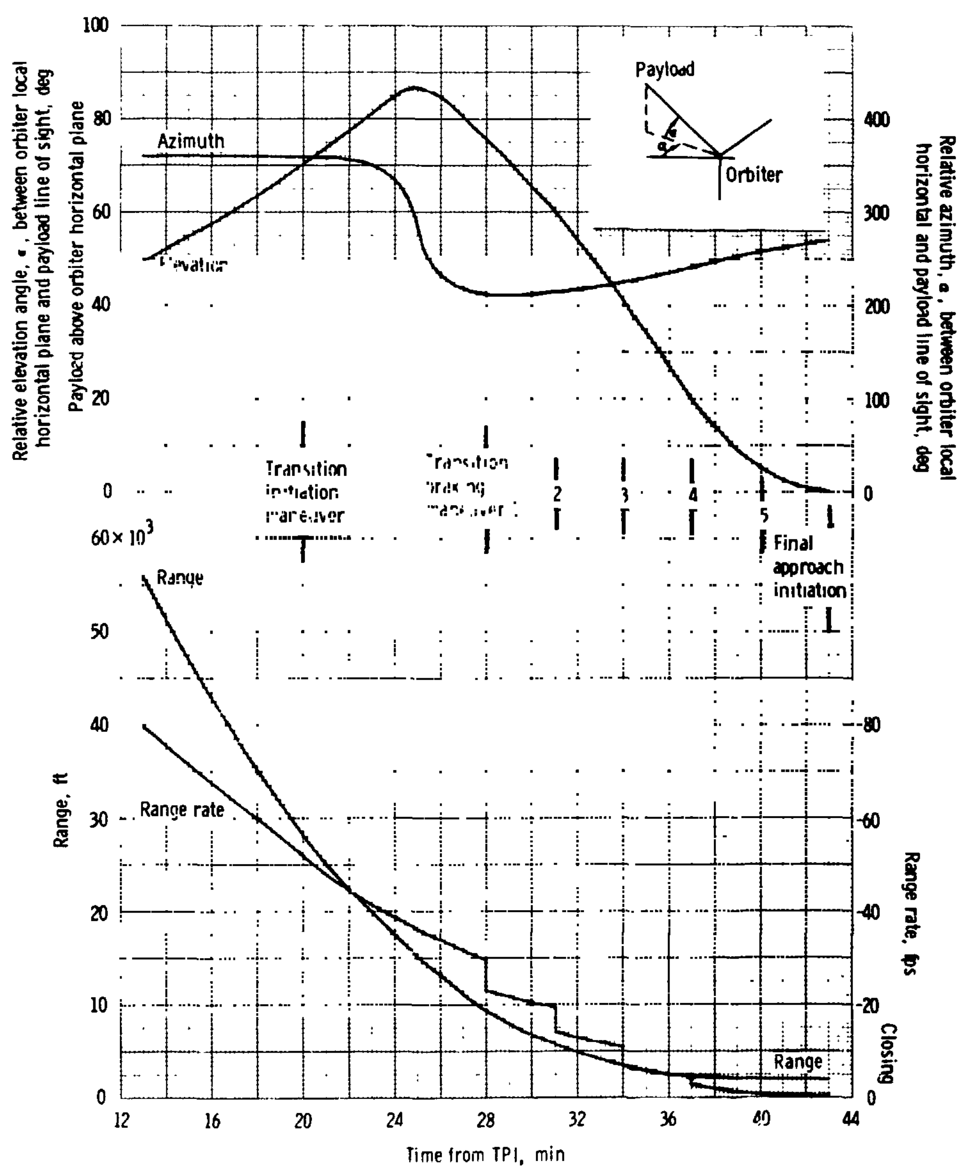



Figure 8.- Time history of relative parameters between orbiter and payload during the transition from a rendezvous terminal approach to an out-of-plane offset position.

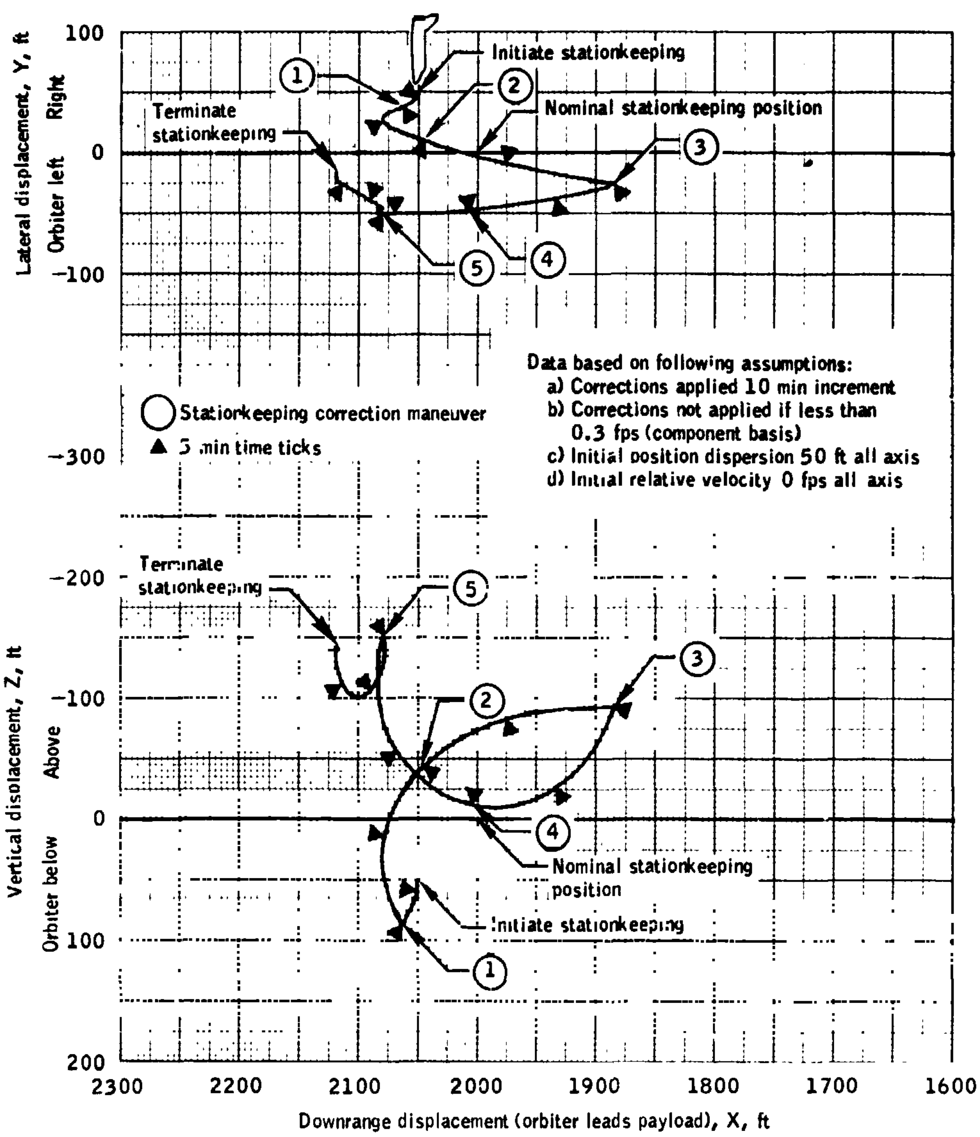



Figure 9.- Typical orbiter motion relative to the payload during stationkeeping.

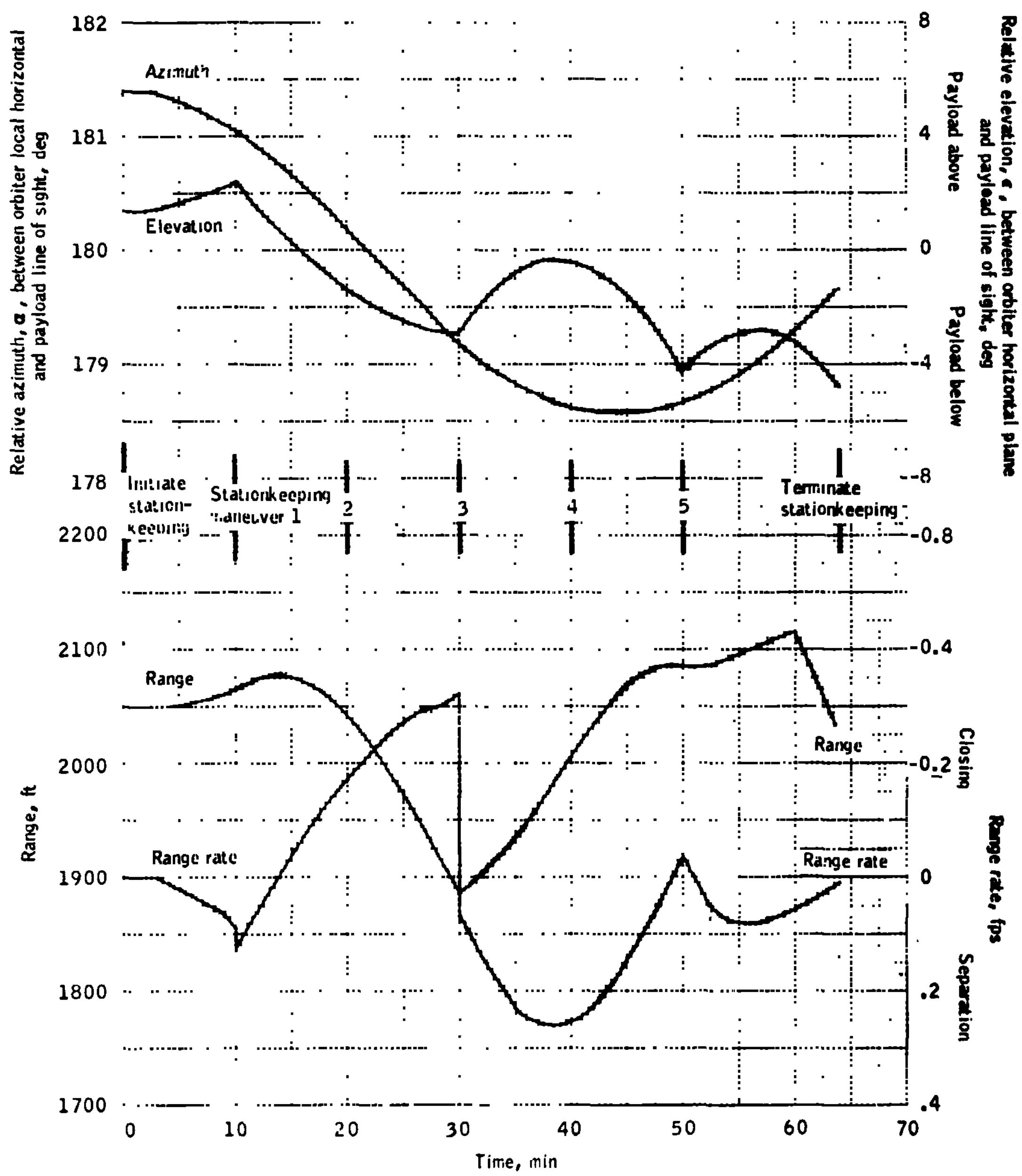



Figure 10.- Time history of relative motion parameters between orbiter and payload during stationkeeping.

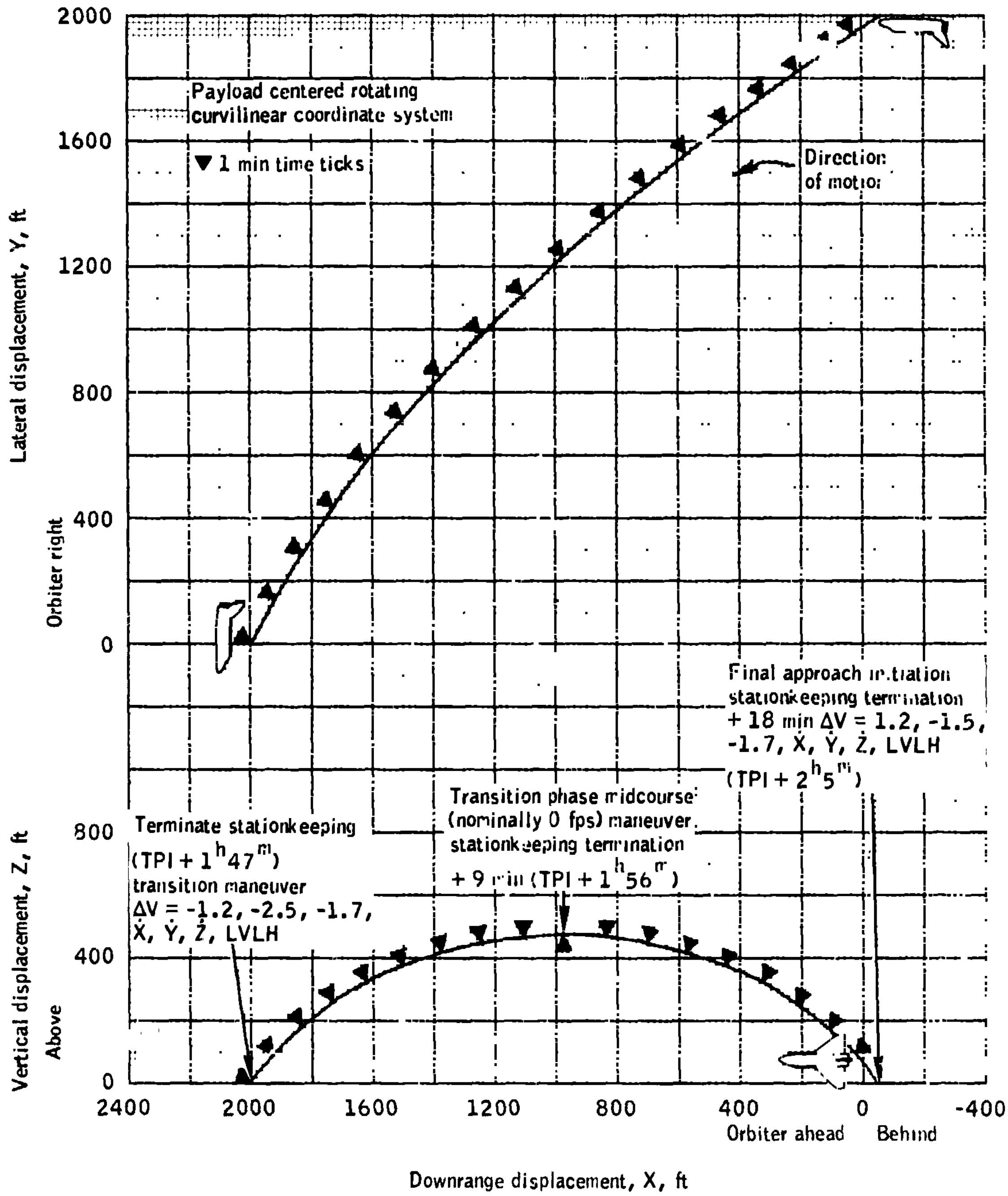



Figure 11.- Orbiter motion relative to the payload during the transition from stationkeeping to final approach initiation.

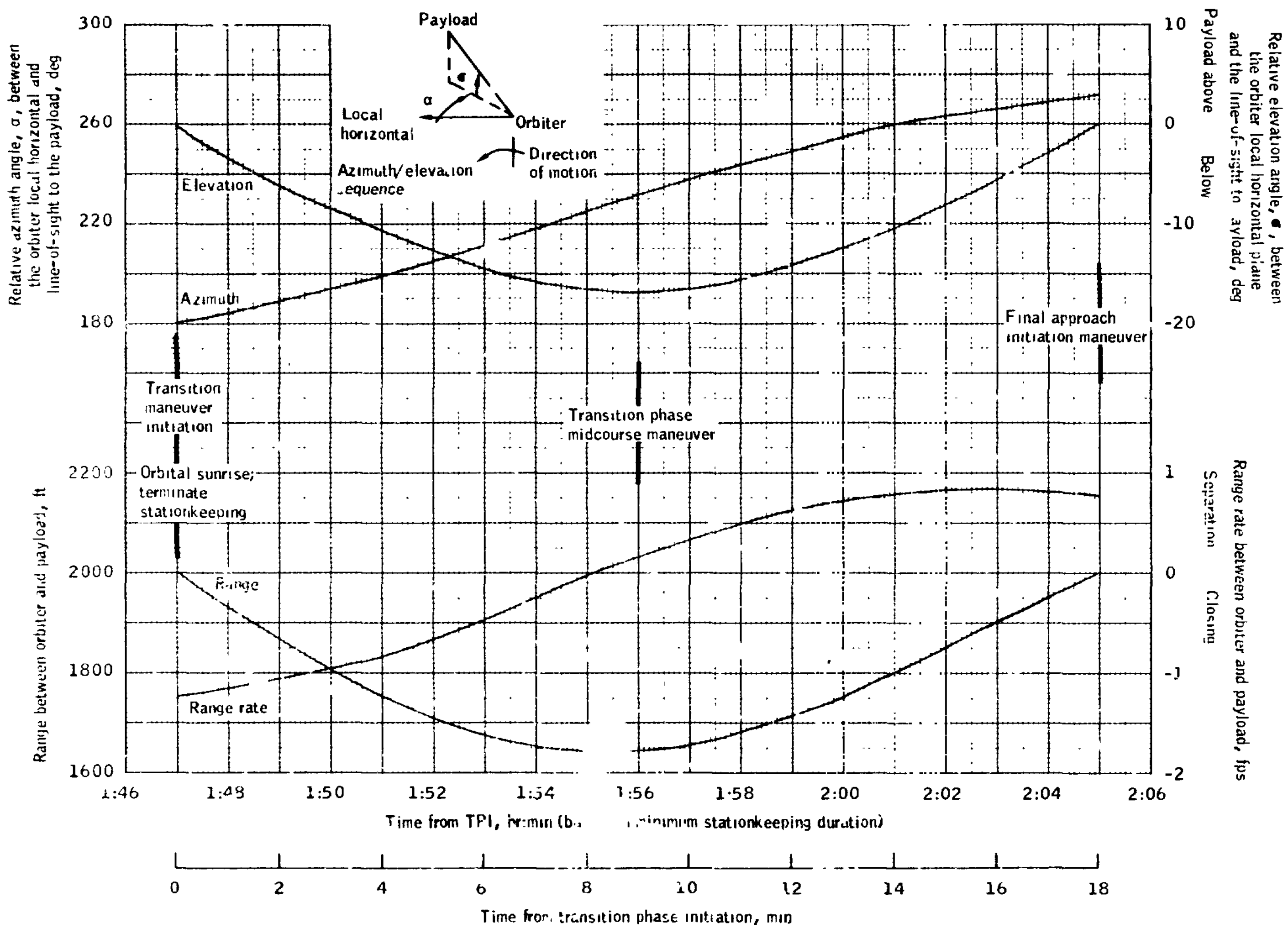



Figure 12.- Relative parameter time history during the transition from stationkeeping to final approach initiation.

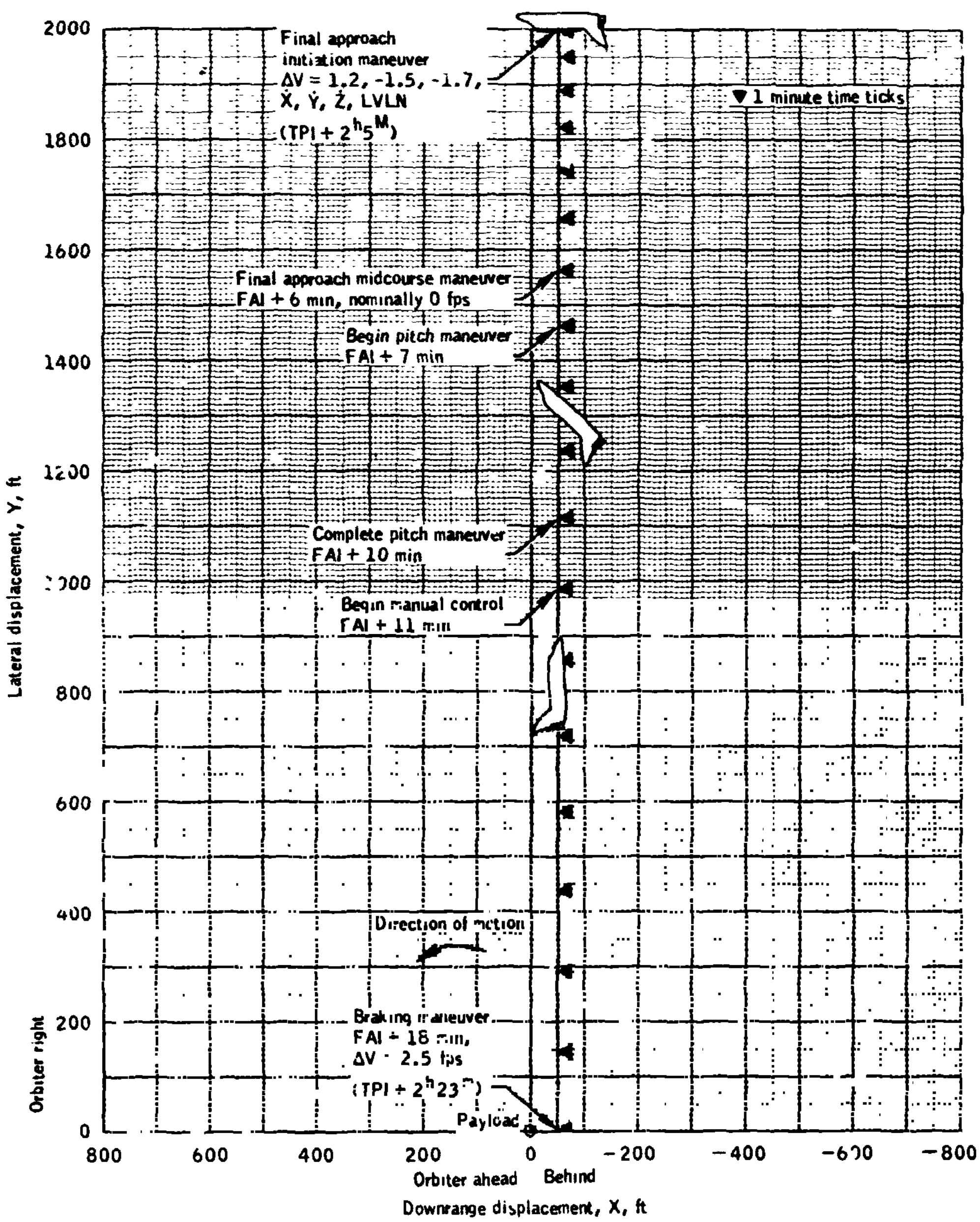



Figure 13.- Orbiter motion relative to the payload during the final approach phase.

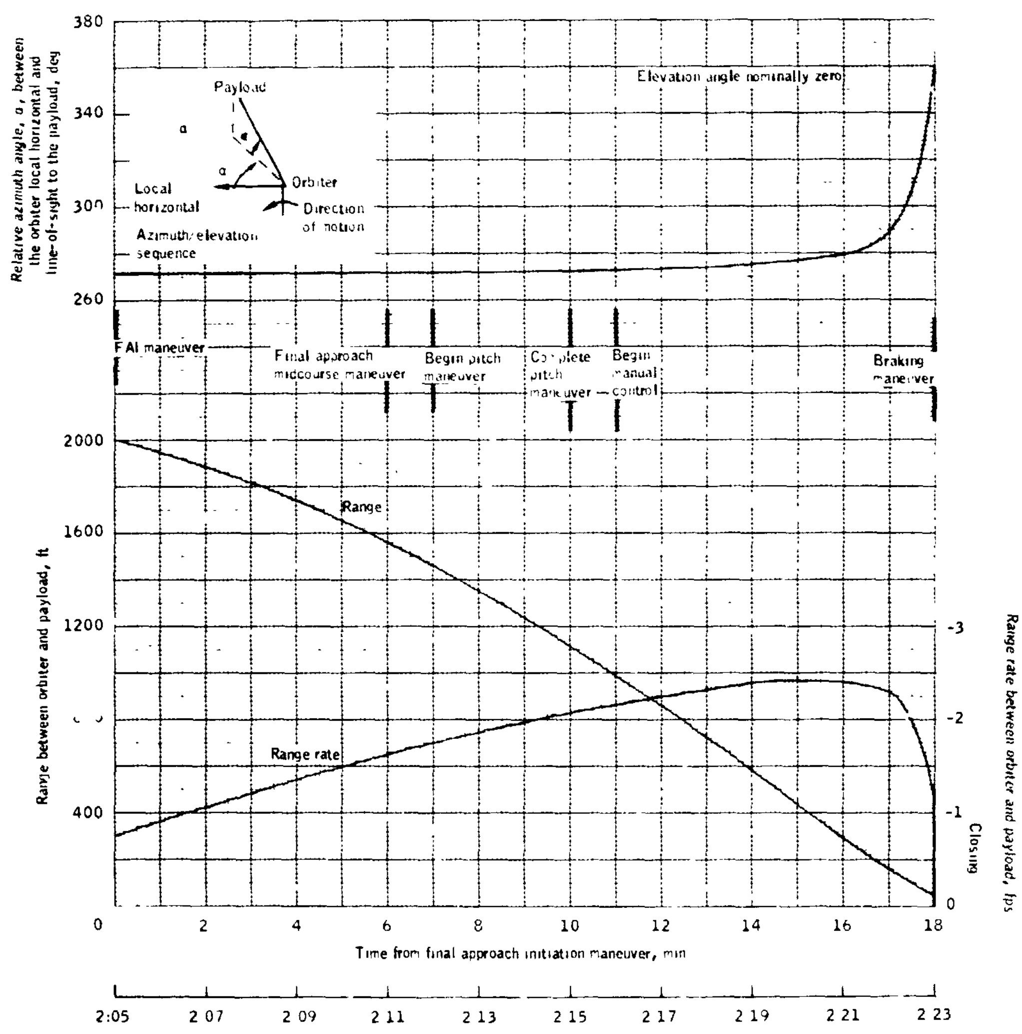



Figure 14.- Relative parameter time history during the final approach phase.

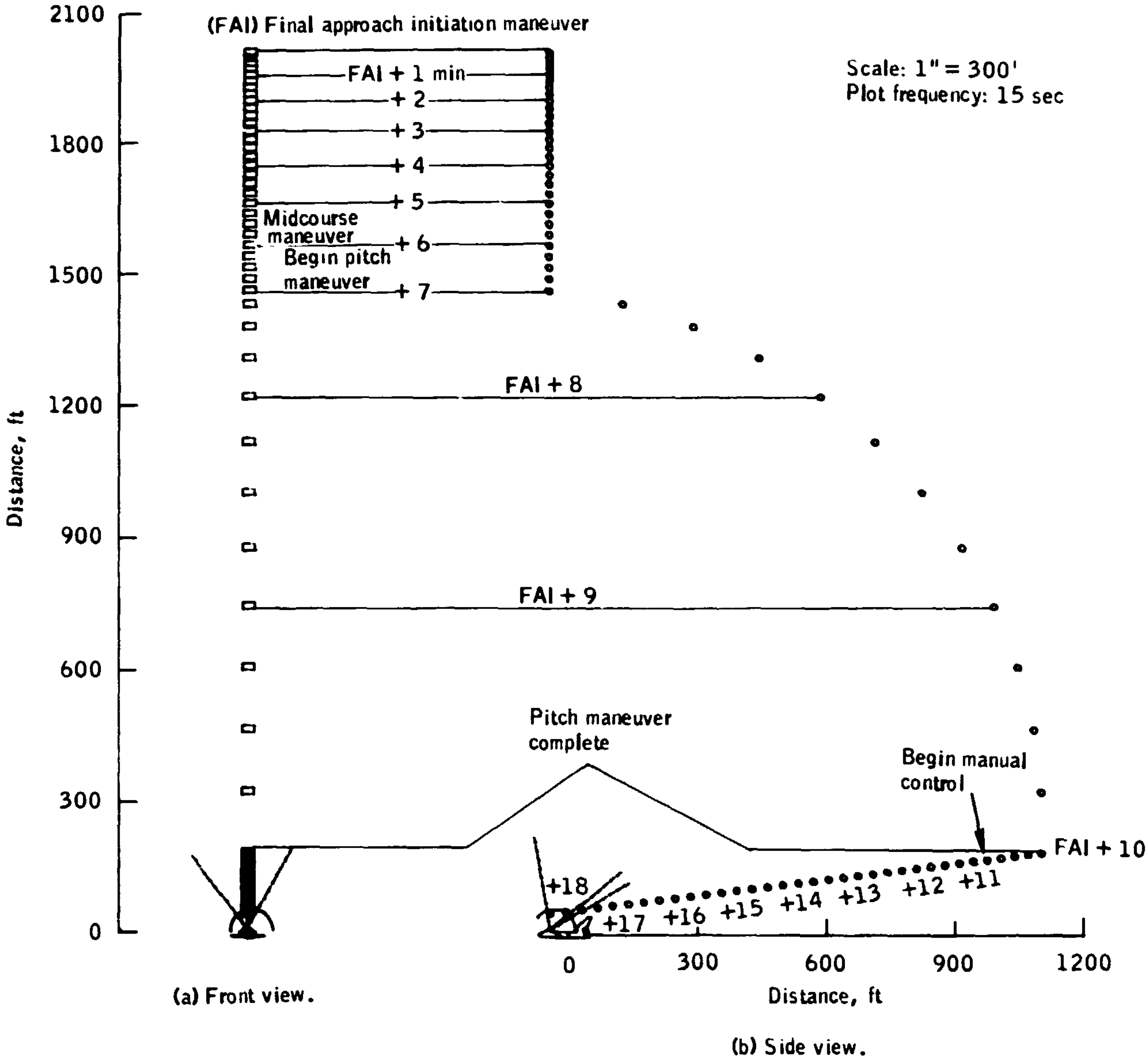



Figure 15.- Final approach relative motion referenced to the orbiter body coordinate system (tail-first manual control option).

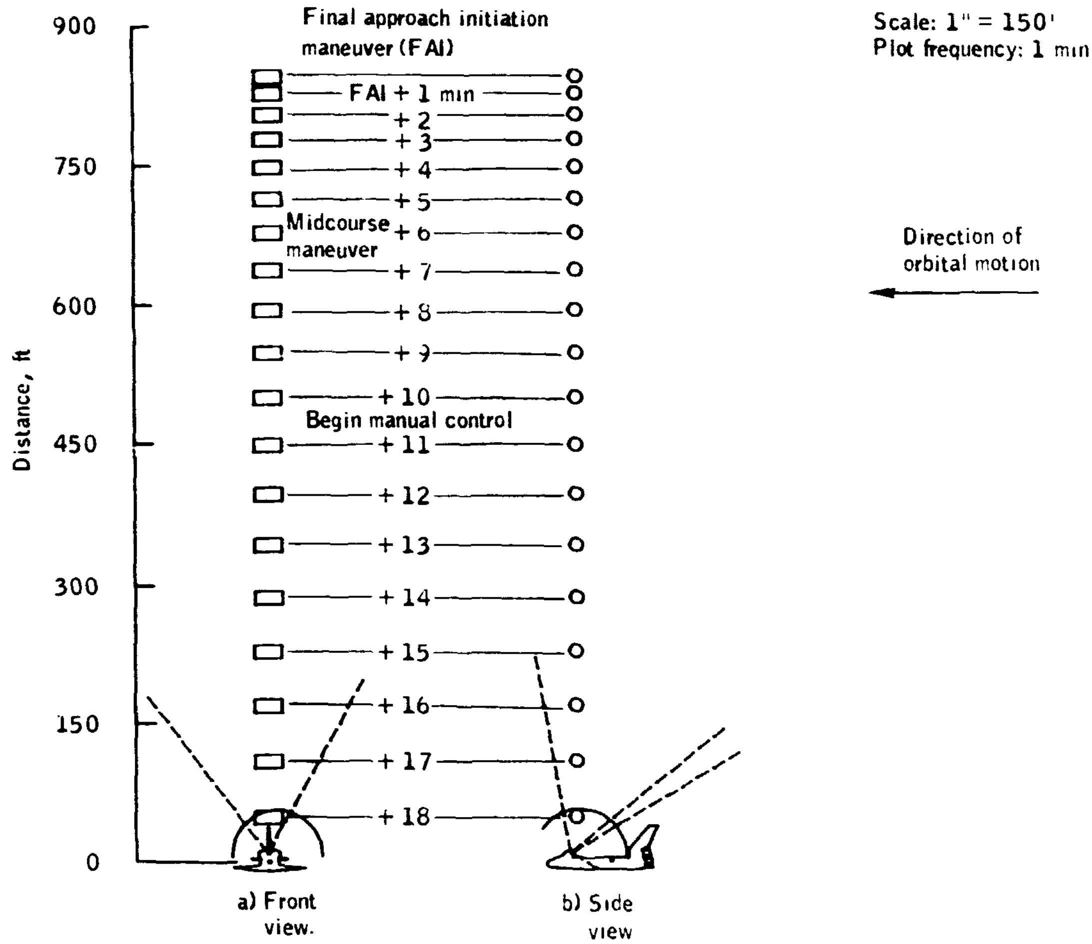



Figure 16.- Final approach relative motion referenced to the orbiter body coordinate system (COAS manual control option).