Internal Note No. 69-FM-39

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 69-FM-39

February 19, 1969

PRELIMINARY LM ABORT AND CSM RESCUE PLAN FOR APOLLO MISSION G

VOLUME II

RENDEZVOUS FOLLOWING ANYTIME LM LIFT-OFF

MISSION PLANNING AND ANALYSIS DIVISION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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PROJECT APOLLO

PRELIMINARY LM ABORT AND CSM RESCUE PLAN FOR APOLLO MISSION G VOLUME II RENDEZVOUS FOLLOWING ANYTIME LM LIFT-OFF

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1. SUMMARY

The preliminary mission G rendezvous abort and rescue plan for LM anytime lift off is presented in this document. As currently planned, LM lift-off will occur at one discrete time during each CSM revolution. However, if required, rendezvous following anytime lift-off can be accomplished within the systems constraints by using the techniques presented in this report. These rendezvous and rescue techniques can be computed using existing programs. No new systems, or modification of existing systems, are required, and no problem areas have been identified. Since the current policy is to consider only discrete launch times (because no failure which would require anytime lift-off has been identified), the study of anytime lift-off will be concluded upon publication of this document.

A parametric analysis of several candidate rendezvous techniques determined the range of insertion phase angles over which each technique could be used. The results of this analysis are documented in Reference 1. Because of constraints on performance and time, none of the techniques could be used over the full 360-degree range of possible insertion phase angles. This range has been divided into the following three regions:

- Nominal (17.5 to 78.5 degrees)
- Post-Nominal (78.5 to 325 degrees)
- Pre-Nominal (-35 to 17.5 degrees)

In the nominal region, the four impulse coelliptic sequence is performed by the LM. Rescues in this region are accomplished using the four impulse coelliptic sequence by either the CSM alone or with a LM-CSM combination. In the post-nominal region, the four impulse coelliptic sequence is again used; however, it is preceded by a two impulse, high apocynthion dwell maneuver by the CSM. Rescues in the post-nominal

region are accomplished using the CSM high apocynthion dwell maneuver followed by the four impulse coelliptic sequence executed by either the CSM alone or the LM-CSM combination. In the pre-nominal region, the LM performs a maneuver to raise apocynthion immediately following insertion. The CSM then transfers to a 20-nautical mile circular orbit. Rendezvous is then completed by the CSM using the four impulse coelliptic sequence. In the pre-nominal region, rescues are performed using the five or six impulse extended coelliptic sequences. The choice of techniques for each phase angle region is illustrated in Figure 1.

As a verification of this plan, detailed rendezvous simulations were generated for five specific LM lift-off times. These lift-off times were chosen so that each of the rendezvous techniques could be illustrated. The data presented for each technique include relative motion, range, range rate, state vectors after each maneuver, and timelines showing sunlight/shadow and communications blackout regions for each profile.

2. INTRODUCTION

The preliminary mission G rendezvous, abort, and rescue plan for LM anytime lift-off is presented in this document. This report is the second of four volumes covering LM abort and CSM rescue for the lunar landing mission. Volume I contains recommendations for LM abort, CSM rescue, and CSM assist during descent and ascent. Volume III will cover time-critical rendezvous, and Volume IV will cover procedures for aborts during powered descent. Publication of this report, Volume II, concluded the activity related to anytime lift-off, since current policy specifies LM lift-off at one discrete time each CSM revolution. Rendezvous following anytime lift-off can be performed within existing system constraints by using the plan presented in this report.

The LM ascent and rendezvous profiles are being continually updated, and the basic profiles used in this document (described in Reference 2) have been updated during publication of this report. The effect of the changes between the basic profiles and the latest profiles is minor and does not invalidate the analysis of this plan. It should be emphasized that this document should be used as a guide to methodology of rendezvous rather than for precision targeting values. Specific cases are presented in the document to verify the techniques which comprise this plan.

3. SYMBOLS

Vehicle Systems

LM	lunar module
CSM	command service module
SPS	service propulsion system
RCS	reaction control system
IMU	inertial measurement unit
LUMINARY	lunar module computer program
COLOSSUS	command module computer program
PGNCS	primary guidance and navigation control subsystem
AGS	abort guidance subsystem

Ground Systems

MSFN	Manned Space Flight Network
RTCC	Real-Time Computer Center
ARRS	Apollo Real-Time Rendezvous Support Program

Maneuver Designations

CSI	coelliptic sequence initiation
CDH	coelliptic differential height
TPI	terminal phase initiation
TPF	terminal phase finalization
CPM	coelliptic phasing maneuver

Parameters

Φ	phase angle between CSM and LM radius vectors (positive for CSM ahead of LM)
Δh	coelliptic differential altitude (positive for CSM above LM)
ΔV	characteristic velocity increment

4. CONSTRAINTS, GROUNDRULES, AND ASSUMPTIONS

The following constraints, ground rules and assumptions were used in developing the decision flow logic and generating the parametric data presented in Section 6. They also can be applied to the detailed trajectory data of Section 7. Some of the ground rules are used in all Apollo rendezvous studies, while others are related to abort and CSM rescue. The validity of the assumptions should be determined, and any additional constraints or ground rules should be identified.

1. All burns are simulated impulsively.

2. Dispersions, errors, underburns, and overburns are not considered.

3. If all systems perform as specified, most maneuvers are computed onboard the LM or the CSM.

4. Additional crew training is minimized.

5. Out-of-plane situations are not considered.

6. The LM will be tracked for 10 minutes by MSFN following insertion.

7. The LM will check IMU alignment and realign if necessary, beginning at 5 minutes after insertion. This will take precedence over state vector update.

8. The maximum impulsive ΔV budgets for in-plane rendezvous sequences are:

CSM SPS - 790 fps
CSM RCS - 125 fps
LM RCS - 131 fps

9. The maximum ranges for tracking are:

Rendezvous radar - 400 n mi
Sextant - 400 n mi
VHF - 200 n mi

10. The maximum ranges for communication are:

Voice - 550 n mi
Telemetry - 320 n mi

11. The CSM-active CSI and CDH maneuvers are computed onboard the CSM. In addition these maneuvers can be computed in the RTCC or onboard the LM and transmitted to the CSM

12. Maneuver computation in the RTCC requires 7 minutes. Maneuver transmission to, and verification by, the CSM requires 2 minutes.

13. Preparation for a maneuver by either vehicle requires 10 minutes.

14. No maneuver will be performed which inserts either vehicle into an orbit with pericynthion altitude less than 60,000 feet.

15. For any maneuver in a LM-active rendezvous sequence, there must be a provision for CSM rescue in case the LM is unable to perform as required. CSM failures are not considered.

16. The LM onboard state vector must be updated 25 minutes before the CSI maneuver. This constraint may be relaxed for a rendezvous sequence which provides for a second (corrected) CSI maneuver after rendezvous radar tracking is initiated.

17. The LM and the CSM must be in communication at CSI.

18. Coelliptic differential altitudes should be within the range of 10 to 20 nautical miles. The LM will always be below the CSM in its coelliptic orbit.

19. The LM will be the active vehicle during terminal phase, whenever possible. The CSM will be used as a backup in case the LM cannot perform the terminal phase.

20. It is desirable, but not absolutely necessary, for the target vehicle to be in attitude hold during terminal phase.

21. TPI occurs when the passive vehicle is approximately at the midpoint of darkness. For LM lift-off during the first CSM revolution following touchdown, TPI occurs 90 degrees west of the insertion point.

22. The target vehicle travels 130 degrees during terminal phase.

23. Rendezvous, docking, and crew transfer are completed approximately 90 minutes after TPI.

24. Rendezvous, docking, and crew transfer must be completed within 11.5 hours after LM insertion.

5. RENDEZVOUS ABORT AND RESCUE PLAN AND DECISION FLOW LOGIC

The rendezvous abort and rescue plan and the decision flow logic for this plan are presented in this section. The decision flow logic illustrates the implementation of each of the rendezvous techniques in the plan. The results of the parametric analysis of each of these techniques are presented in Section 6.

5.1 Rendezvous Abort and Rescue Plan

Rendezvous following anytime LM lift-off requires rendezvous capability over the entire 360-degree range of possible insertion phase angles. In the parametric study recently completed (Reference 1), no single technique was found which covered the entire range while staying within the constraints on ΔV and LM ascent stage lifetime. The approach used in this study is to divide the phase angle range into three regions: nominal, post-nominal, and pre-nominal. The choice of techniques for each of the regions is illustrated in the flow diagram of Figure 2 and is discussed briefly below. The individual techniques are covered in more detail in another section of this report.

In the nominal region (17.5 degrees to 78.5 degrees) rendezvous is accomplished using the standard four impulse coelliptic sequence. The sequence can be performed by the LM alone, the CSM alone, or a combination of maneuvers by both vehicles (Figures 3a through 3c). In all cases the LM will approach the CSM from below during terminal phase.

In the post-nominal region (78.5 degrees to 325 degrees) the CSM performs a two impulse, high apocynthion dwell sequence. This sequence increases the differential angular rate between the two vehicles so that when the CSM returns to the 60-nautical mile circular parking orbit it will be about 20 degrees ahead of the LM. Rendezvous is then completed with the four impulse coelliptic sequence used in the nominal region. This sequence can be performed by either vehicle alone or by combined maneuver with both vehicles.

The techniques used in the pre-nominal region (-35 degrees to +17.5 degrees) are more complex. Immediately after insertion the LM performs a 100-foot per second horizontal maneuver which raises the apocynthion altitude to about 100 nautical miles. Ten minutes later the CSM initiates a preplanned Hohmann transfer down to a 20-nautical mile circular orbit. From this orbit the CSM completes the rendezvous using the four impulse coelliptic sequence as shown in Figure 3d. If the LM is unable to thrust following insertion, CSM rescue is accomplished using the five or six impulse extended coelliptic sequences shown in Figures 3e and 3f. The five impulse sequence is used for negative insertion phase angles and the six impulse sequence for positive phase angles. In all cases the LM is below the CSM during terminal phase.

5.2 Decision Flow Logic

The decision flow logic for rendezvous abort and rescue following anytime LM lift-off is shown in Figure 4. Telemetry from the LM is received by MSFN during ascent to the 30-nautical mile by 60,000-foot standard insertion orbit, and an estimated insertion phase angle is determined. If the phase angle is in the nominal or post-nominal regions (17.5 degrees to 325 degrees) MSFN will begin 10-minute postinsertion tracking and LM orbit determination. If the CSM has been powered down, it will be instructed to power up at first contact with MSFN. (Since anytime LM lift-off is considered only during the first CSM revolution following LM landing, it is unlikely that the CSM will be powered down.)

If the insertion phase angle is in the nominal region, the LM will check IMU alignment immediately after insertion and realign if necessary. After IMU realignment is verified, the LM and CSM begin tracking each other as soon as contact is established in order to update the LM state vector. The input parameters for the LM-active and CSM-active four impulse coelliptic sequences are determined on the ground and transmitted to the two vehicles. The LM-active coelliptic sequence is computed onboard the LM and in the RTCC. The equivalent operations are also being performed for the computation of the CSM-active coelliptic sequence to be initiated 1 minute after the time for initiation of the LM-active sequence. This is based on the assumption that the coelliptic sequence pre-thrusting programs for CSI and CDH (COLOSSUS P-32 and P-33) are in the CSM computer. If they are not, as is presently the case, then the CSM-active sequence can be computed by the CSI and CDH pre-thrusting programs on board the LM (LUMINARY P-72 and P-73) or in the RTCC and transmitted to the CSM.

The LM will perform the coelliptic sequence initiation (CSI) maneuver at the appropriate time. If CSI is performed satisfactorily, an updated coelliptic differential height (CDH) maneuver will be computed on board the LM. At the same time, the CSM will be computing a backup CDH maneuver. As before, if the CSM does not have this capability (COLOSSUS P-33) then the backup CDH will be computed onboard the LM (LUMINARY P-73) or in the RTCC and transmitted to the CSM. The LM will then perform CDH. When the two vehicles are in coelliptic orbits, the LM and the CSM will each compute their own terminal phase initiation (TPI) maneuvers. The LM will perform TPI if possible; if not, the TPI will be performed by the CSM. The midcourse correction and braking maneuvers will be computed and performed in the same way.

If the LM was unable to perform CSI then the CSM would perform the CSI maneuvers which it computed. The CSM will then compute an updated CDH maneuver and perform it at the proper time. If the LM performed CSI but was unable to perform CDH, then the CSM would perform its precomputed CDH maneuver. In either case, all terminal phase maneuvers are computed on board both vehicles and are performed by the LM if possible.

When the insertion phase angle is in the post-nominal region, the CSM will perform the high apocynthion dwell sequence before the coelliptic sequence is performed. The CSM will remain in the dwell orbit one, two, or three revolutions depending upon the insertion phase angle. When the phase angle is less than 135 degrees, the CSM will stay one revolution; less than 230 degrees, two revolutions; and less than 325 degrees, three revolutions. If the CSM is to stay two or three revolutions, then the LM will be powered down. The first dwell maneuver is computed in the RTCC and transmitted to the CSM. LM postinsertion tracking, maneuver computation and transmission, and maneuver preparation require a total of 29 minutes. This is equivalent to about 87 degrees of travel angle in the CSM 60-nautical mile circular parking orbit. Therefore, if the insertion phase angle is less than 273 degrees, the first dwell maneuver will be performed over LM pericynthion, and if it is greater than 273 degrees, the dwell maneuver will be performed 29 minutes after LM insertion.

The CSM will be tracked after the first dwell maneuver, and the dwell orbit will be determined. If a correction maneuver is necessary for the two- and three-revolution cases, it will be computed in the RTCC and transmitted to the CSM. The correction will be performed at the next pericynthion passage. The second dwell maneuver (recircularization) is computed in the RTCC and transmitted to the CSM. After recircularization, the CSM orbit is determined by MSFN and transmitted to the LM. Rendezvous is then completed using the coelliptic sequence described above.

If, during ascent from the surface, the predicted phase angle is in the pre-nominal range then the LM will prepare for a 100-foot per second thrust immediately after insertion. The LM is powered down after performing the maneuver and is tracked for 10 minutes by MSFN. If the 100-foot per second maneuver was performed satisfactorily, the CSM will initiate a preplanned Hohmann transfer to a 20-nautical mile circular orbit 10 minutes after insertion. The input parameters for the coelliptic sequence are selected by MSFN and transmitted to the CSM. The CSM computes a coelliptic sequence with CSI occurring at the second passage over the LM pericynthion and CDH occurring one revolution later. This fixes the coelliptic differential altitude (Δh) at about 10 nautical miles. After performing CSI, the CSM computes an updated CDH maneuver and performs it at the proper time. The decision flow logic for computation and performance of terminal phase maneuvers is the same as for the coelliptic sequence in the nominal phase angle region.

If the LM does not perform the maneuver at insertion, then one of the extended coelliptic sequences will be used for CSM rescue. For negative phase angles (-35 degrees to 0 degree) the five impulse sequence is used. The coelliptic phasing maneuver (CPM) is computed in the RTCC and transmitted to the CSM. This maneuver is performed on the first passage over LM apocynthion and inserts the CSM into a high dwell orbit. The CSM remains in this orbit three revolutions. The CSI maneuver is computed on board the CSM and is performed over LM apocynthion. The CSM then computes a CDH maneuver to occur one half revolution later over LM pericynthion. The LM is powered up, if possible, and rendezvous is completed using the standard LM-active terminal phase.

For positive phase angles (0 degree to 17.5 degrees) the six impulse sequence is used. At first passage over LM apocynthion the CSM performs a preplanned Hohmann maneuver which inserts it into a 60-nautical mile by 10-nautical mile elliptical orbit. CPM is computed in the RTCC and transmitted to the CSM CPM is performed over LM pericynthion one-half revolution after the Hohmann maneuver. This orbit is generally lower than the LM orbit (but not less than 10 nautical miles circular) so that the CSM can gain on the LM. The CSM remains in this orbit for three and one-half revolutions. CSI is performed over LM apocynthion, and the remainder of the sequence is the same as the five impulse extended coelliptic sequence.

6. DETAILED RENDEZVOUS ABORT AND RESCUE SEQUENCES

The results of the parametric analysis of the rendezvous techniques are presented in this section. The CSM and LM performance requirements and the total rendezvous time are shown for each rendezvous and rescue technique. In addition, the input parameters called for in the decision flow logic of Section 5.2 are presented. The methods for computing these input parameters are defined so that they can be recalculated in the event of minor changes in the rendezvous profiles.

6.1 Nominal Phase Angle Region

The four impulse coelliptic sequence (CSI, CDH, TPI, and TPF) is the standard technique for Apollo rendezvous. For the anytime LM liftoff problem it can be used throughout the nominal phase angle region. There are four independent variables that may be used to shape the standard coelliptic sequence: time for CSI, transfer orbit apsis at which CDH is performed, time of TPI, and elevation angle of the vehicle-to-vehicle line-of-sight at TPI. For the lunar rendezvous case the elevation angle is fixed to allow thrusting nearly along the line of sight. The times of CSI and TPI are constrained by the location of the maneuvers to a given time or the given time plus a certain number of complete revolutions. This results in the actual variables used in this study being the revolution in which CSI is performed, the transfer orbit apsis at which CDH is performed, and the revolution in which TPI is performed. CSI is a horizontal impulse performed at the specified time and inserts the active vehicle into the transfer orbit. CDH is performed at the desired apsis of the transfer orbit and inserts the active vehicle into a coelliptic orbit. The coelliptic orbit is one in which the apocynthion and pericynthion altitudes differ from the corresponding altitudes of the target orbit by the same amount, the coelliptic differential altitude (Δh). The variables used are chosen so that the elevation angle of the line of sight between the two vehicles will be a desired value at the specified time of TPI. The third maneuver, TPI, is performed nearly along the line of sight and inserts the active vehicle into an orbit which intercepts the target vehicle after it has traveled 130 degrees. The final maneuver, TPF, cancels the relative velocity at intercept. This sequence can be performed by the LM or the CSM alone or with combined maneuvers by both vehicles.

6.1.1 LM-Active rendezvous. - CSI is performed 50 minutes after LM pericynthion on the first, second, or third revolution. CDU is performed at the first or second apocynthion crossing (first or third apsis) after CSI. TPI is performed when the CSM is 90 degrees west of LM insertion orbit pericynthion during the first or second revolution in the coelliptic orbit.

The selection of the above mentioned parameters for any particular phase angle is a function of the bounds on coelliptic differential altitude (Δh). This can be seen in Figure 5 which presents the choice of input

parameters and the resultant Δh for the entire nominal phase angle region. At 17.5 degrees, CSI is performed 50 minutes after insertion, CDH occurs at the first apocynthion, and TPI is performed during the first revolution in the coelliptic orbit (when the CSM is 90 degrees west of LM insertion on its second revolution). This results in a value of Δh of 10 nautical miles, which is the lower bound on this parameter. As phase angle increases, Δh also increases and reaches its upper bound of 20 nautical miles at about 21.6 degrees. For larger phase angles, the TPI time is increased one CSM period while maintaining CSI time at 50 minutes and CDH at the first apocynthion. At 21.6 degrees the resultant Δh is 8.5 nautical miles, and Δh remains below 10 nautical miles for phase angles less than about 23.1 degrees. If these values are truly unacceptable, then it would be necessary to delay LM lift-off by about one-half minute to allow the CSM to move 1.5 degrees farther ahead of the LM at insertion. This sequence is used for phase angles up to 28.8 degrees at which point CDH can be moved to the third apsis crossing (second apocynthion) while maintaining the previous values for CSI time and TPI revolution. The range for this sequence is from 28.8 to 35.6 degrees which corresponds to Δh variation between the permissible limit of 10 to 20 nautical miles. From 35.6 degrees to 39.2 degrees CSI time is maintained at 50 minutes after insertion, CDH still occurs at the third apsis, and TPI time is increased by one CSM revolution.

The four impulse sequence discussed above comprise the basic scheme for using the LM-active coelliptic sequence rendezvous. It can be seen in Figure 5 that the Δh profile for phase angles between 39.2 and 60.9 degrees is a duplicate of the previous profile between 17.5 and 39.2 degrees. The only difference is that CSI occurs one LM period later, and TPI occurs one CSM period later. For instance, if the insertion phase angle is 41.3 degrees then CSI occurs at 168.9 minutes (one LM period plus 50 minutes) after insertion, CDH is performed at the first apsis, and TPI occurs when the CSM is 90 degrees west of the LM insertion pericynthion on the third CSM revolution. The resultant Δh, 15 nautical miles, is the same as for the equivalent sequence performed one revolution earlier at an insertion phase angle of 19.6 degrees. For phase angles between 60.9 and 78.5 degrees, the basic sequence repeats once more, in part, by increasing CSI and TPI times by one or more revolutions.

The performance and total rendezvous time for the LM-active coelliptic sequence are presented in Figure 6. The ΔV requirements for CSI, CDH, TPI, and total of all four impulses are presented in the figure. A comparison of Figures 5 and 6 shows the correlation between ΔV requirements and Δh. CSI and CDH ΔV decreases as Δh increases, while TPI and total ΔV increase with Δh. The maximum total impulsive ΔV is 131 feet per second. The values for total rendezvous time were calculated by adding 90 minutes to the TPI times of Figure 5. This is about the time required to complete terminal phase braking, docking, and crew transfer. The maximum time requirement is 587 minutes, which is within the LM ascent stage lifetime of 11.5 hours.

6.1.2 CSM-Active rendezvous. - This sequence is used as a backup in case the LM cannot perform CSI at the desired time. If this happens, the CSM then initiates the sequence by performing CSI 1 minute after the LM would have done so. CDH is performed at the first or third apsis crossing (in this case first or second pericynthion) after CSI. The CSM is then in an orbit which is coelliptic with, and above, the LM insertion orbit. The time of TPI is determined by requiring the LM to be 90 degrees west of the insertion pericynthion in whichever revolution TPI is to occur. For any particular revolution this time is a constant regardless of phase angle since the LM always starts at pericynthion.

In selecting input parameters for this sequence, the profile established for the LM-active sequence is followed as closely as possible. Thus CSI always occurs 1 minute after the LM-active CSI time, CDH occurs at the same apsis crossing, and TPI is performed during the same coelliptic revolution. The input parameters and the resultant Δh are presented in Figure 7. It can be seen that Δh for the CSM-active sequence is lower than for the LM-active sequence. The performance and total rendezvous time requirements are presented in Figure 8. The ΔV requirements for CSI, CDH, TPI, and total of all four impulses are presented in the figure. The relationships between ΔV and Δh discussed in Section 6.1.1 are also apparent for the CSM-active case. The maximum total impulsive ΔV is 140 feet per second. The total rendezvous time (TPI time plus 90 minutes) is also shown in the figure. The maximum time requirement is about 565 minutes, which is less than the LM ascent stage lifetime of 11.5 hours.

6.1.3 LM-active CSI, CSM-active CDH. - This sequence is used as a backup in case the LM performs CSI but is unable to perform CDH at the desired time. The CSM then performs CDH immediately after the LM would have done so. The resultant CSM orbit will be coelliptic with, and above, the transfer orbit into which the LM was inserted at CSI. The coelliptic differential altitude generally will be greater than for the LM-active case, since the CSM is past apocynthion of the LM transfer orbit when CDH is performed. This will cause TPI to be performed earlier than in the LM-active case as a result of the larger differential angular rate in the coelliptic orbits. The performance and time requirements, and the resultant differential height are presented in Figure 9. A comparison of Figures 9 and 5 shows the difference in Δh mentioned above. The ΔV for CDH, TPI, and total of the three CSM-active impulses are presented in Figure 9 (ΔV for LM-active CSI was presented in Figure 6). It can be seen that the maximum total CSM-active impulsive ΔV requirement is 137 feet per second. (From Figure 6, the maximum LM-active CSI ΔV is 56 feet per second.) It can also be seen in the figure that the maximum total rendezvous time is about 530 minutes.

6.2 Post-Nominal Phase Angle Region

The CSM high apocynthion dwell sequence is used in the post-nominal phase angle region (78.5 degrees to 325 degrees). The CSM is inserted into an elliptical dwell orbit with 60-nautical mile pericynthion altitude and an apocynthion altitude which may be as great as 321 nautical miles. The

CSM remains in this dwell orbit one, two, or three revolutions, then recircularizes at pericynthion. During this time the LM has gained on the CSM as a result of the increased differential angular rate between the two orbits. Rendezvous is then completed using the LM-active four impulse coelliptic sequence.

The high apocynthion dwell maneuvers are computed in the RTCC This means that, based on assumptions 6, 12, and 13, the following operations must be performed before the sequence can be initiated. The LM is tracked by MSFN for 10 minutes following insertion, and its orbit is determined. Maneuver computation in the RTCC requires 7 minutes. Transmission of the maneuver to, and verification by the CSM requires 2 minutes. Preparation for the maneuver requires 10 minutes. Thus, a total of 29 minutes will elapse before the first dwell maneuver can be performed. This corresponds to about 87 degrees of CSM travel in the 60-nautical mile lunar parking orbit. Thus, for insertion phase angles not greater than 273 degrees, the dwell sequence can be initiated on the first CSM passage over LM pericynthion. For phase angles between 273 and 325 degrees, the sequence will be initiated 29 minutes after LM insertion.

The apocynthion altitude of the dwell orbit is chosen so that, after recircularization, the LM can perform a coelliptic sequence similar to the one used after a lift-off at the nominal time. In the desired sequence, CSI occurs 50 minutes after LM pericynthion, CDH is performed at the first apsis, Δh is 10 nautical miles, and TPI occurs 90 degrees west of LM pericynthion during the first revolution in the coelliptic orbit. The input parameters used for computing the dwell sequence and the subsequent LM-active coelliptic sequence are presented in Figure 10. For phase angles between 78.5 degrees and 135 degrees the CSM remains in the dwell orbit one revolution. At 135 degrees the apocynthion altitude of 321 nautical miles requires 300 feet per second for each impulse, or 600 feet per second total for the dwell sequence. At this point, however, the CSM can remain in the dwell orbit two revolutions and the required apocynthion altitude drops to 153 nautical miles. The two revolution sequence can be used for phase angles up to 230 degrees, at which point the apocynthion altitude is again up to 321 nautical miles and the total ΔV requirement is 600 feet per second. From 230 degrees to 325 degrees the three revolution sequence is used. A slight change in slope of the altitude curve can be seen at 273 degrees as a result of the change in location of the dwell maneuvers. This effect is more apparent in the upper graph showing the times of the dwell maneuvers. The time of CSI and TPI for the LM-active coelliptic sequence are also shown in Figure 10.

The total performance requirements and total rendezvous time are shown in Figure 11. The ΔV curve shows a maximum CSM SPS requirement of 600 feet per second. The LM-active coelliptic sequence requires 127 feet per second of the LM RCS ΔV allowance. If CSM rescue is necessary, this could require an additional 131 feet per second. Thus, the maximum CSM ΔV requirement for the post-nominal phase angle region is 731 feet per second, which is within the allowance for in-plane CSM rescue. The total rendezvous time was calculated by adding 90 minutes to the TPI times of Figure 10. The maximum total time requirement is 680 minutes, which is just under the 11.5-hour (690-minute) LM ascent stage lifetime.

6.3 Pre-Nominal Phase Angle Region

The pre-nominal phase angle region (-35 degrees to +17.5 degrees) is the most difficult region. The region sequence requires a 100-foot per second thrust by the LM immediately after insertion, raising the apocynthion altitude to about 100 nautical miles. The CSM then performs a preplanned Hohmann transfer to a 20-nautical mile circular orbit. From this orbit the CSM performs the four impulse coelliptic sequence. If the LM cannot thrust after insertion, then the CSM will rescue the LM using the five or six impulse extended coelliptic sequences. The five impulse sequence will be used for negative phase angles and the six impulse sequence for positive phase angles.

6.3.1 CSM-active rendezvous following LM thrust at insertion. - Immediately after insertion into the 30-nautical mile by 60,000-foot standard orbit, the LM performs a preplanned 100-foot per second positive horizontal thrust. This raises the LM apocynthion altitude to 104 nautical miles. Ten minutes later the CSM initiates a Hohmann transfer to 20 nautical miles, circularizing one-half revolution later at pericynthion. The CSM gains on the LM while in this low orbit. On the second passage over LM pericynthion the CSM performs CSI, transferring to an elliptical orbit with apocynthion altitude greater than 20 nautical miles. It remains in this orbit one revolution and then performs CDH at the second apsis (first pericynthion). Since this maneuver is always performed at 20 nautical miles and over LM pericynthion, the resultant Δh is always about 10 nautical miles. The CSM coelliptic orbit is always 114 nautical miles by 20 nautical miles. TPI occurs during the first coelliptic revolution when the LM is 90 degrees west of pericynthion.

The input parameters and performance requirements for this sequence are presented in Figure 12. Since the LM thrust and the CSM Hohmann transfer are preplanned, the only input required are the CSI and TPI times. CSI time is a function of insertion phase angle; whereas, TPI is a constant 383.1 minutes after LM insertion. The apocynthion altitude after CSI is shown in Figure 12. Notice that for a phase angle of about -26.5 degrees (LM ahead) the altitude is equal to 114 nautical miles, the apocynthion altitude of the coelliptic orbit. For phase angles less than this value, both CSI and CDH are positive maneuvers. Since they both occur at the same altitude and the resultant orbit is always the same, then the total ΔV is a constant. For phase angles greater than -26.5 degrees, the CSM gains too much phase angle prior to CSI and must go higher than the coelliptic orbit to allow the LM to regain some. This results in a negative CDH maneuver. The maximum total CSM ΔV for all six impulses is about 625 feet per second, which is within the allocation for in-plane CSM rescue. The total time from insertion to completion of docking and crew transfer is about 473 minutes, well within the LM ascent stage lifetime.

6.3.2 CSM rescue using the five impulse extended coelliptic sequence. - This rescue technique is used for negative insertion phase angles (-35 degrees to 0 degree). The coelliptic phasing maneuver (CPM) is computed in the RTCC and transmitted to the CSM. It is performed on the first passage over LM insertion orbit apocynthion and transfers the CSM to a high phasing orbit. LM postinsertion tracking, maneuver computation, and maneuver transmission and verification require a total of

19 minutes. There is sufficient time to perform these operations before the CSM loses communications with MSFN for all candidate landing sites. The CSM remains in the phasing orbit for three full revolutions allowing the LM to catch up. CSI is performed over LM apocynthion and inserts the CSM into a 60-nautical mile by 25-nautical mile transfer orbit. CDH is performed one-half revolution later and inserts the CSM into a coelliptic orbit with a Δh of 15 nautical miles above the LM orbit. TPI is performed during the first coelliptic revolution when the LM is 90 degrees west of insertion orbit pericynthion.

The input parameters and performance requirements for this sequence are presented in Figure 13. The time of the CPM maneuver is dependent on phase angle, while the CSI and TPI times are constant at 500 and 587 minutes, respectively. The apocynthion altitude of the phasing orbit reaches a maximum value of 362 nautical miles. The maximum total ΔV requirement for CPM, CSI, and CDH is 748 feet per second. However, the CDH ΔV is a constant 20 feet per second and could be performed by the RCS. This leaves a maximum CSM SPS ΔV requirement of 728 feet per second. The total time from insertion to docking and crew transfer is 677 minutes, just within the LM ascent stage lifetime.

6.3.3 CSM rescue using the six impulse extended coelliptic sequence. - This rescue technique is used for positive insertion phase angles (0 to 17.5 degrees). At the first passage over LM insertion orbit apocynthion the CSM performs a Hohmann transfer to a 60-nautical mile by 10-nautical mile orbit. The CPM maneuver is computed in the RTCC and transmitted to CSM when it resumes contact with MSFN. CPM is performed at first pericynthion of the Hohmann transfer orbit which is set to occur over LM insertion pericynthion. The CSM is inserted into a low phasing orbit at CPM and remains in this orbit for three and one-half revolutions. CSI occurs at apocynthion of the phasing orbit and CDH is performed one-half revolution later over LM orbit pericynthion. The CSM will then be a coelliptic orbit with a Δh of 10 nautical miles above the LM. TPI occurs during the first coelliptic revolution when the LM is 90 degrees west of insertion.

The input parameters and performance requirements for the six impulse sequence are presented in Figure 14. The times of the Hohmann transfer and CPM maneuvers are functions of insertion phase angle. CSI time is nearly constant at 502 minutes, and TPI occurs at 587 minutes, the same as in the five impulse sequence. The apocynthion altitude of the phasing orbit is as low as 12.5 nautical miles which is safely above the minimum permissible altitude of 60,000 feet. The maximum total ΔV requirement for this sequence is 188 feet per second which is well below the CSM in-plane rescue ΔV budget. The total time from insertion to docking and crew transfer is 677 minutes, just within the LM ascent stage lifetime.

7. EXAMPLES OF RENDEZVOUS FOLLOWING ANYTIME LIFT-OFF

A set of detailed examples has been generated to illustrate the application of the anytime lift-off rendezvous plan. Five LM lift-off times were chosen during the first CSM revolution after LM landing. The insertion phase angles corresponding to the five lift-off times fall into all three regions of the 360-degree range: two in the nominal region, one in the post-nominal, and two in the pre-nominal. For each lift-off time, the applicable rendezvous and rescue sequences were generated using a Keplerian Program. Each case was initialized with state vectors at LM insertion resulting from an integrated simulated lift-off from Lunar Landing Site II-P-2 (longitude 34.0 E, latitude 2.75 N) on 18 August 1969. The CSM is in a 58.27-nautical mile by 58.04-nautical mile lunar parking orbit (referenced to the mean lunar radius). The LM is inserted into a 28.48-nautical mile by 9.06-nautical mile elliptical orbit. These actual orbits are lower than the corresponding target orbits used in the parametric analysis of the rendezvous techniques. Therefore, some variation in the geometric, performance, and time parameters is expected. This is handled, as it would be if the sequences were computed in real time, by varying the input parameters until an acceptable sequence is computed. The variation in insertion phase angle with lift-off time during the first CSM revolution is shown in Figure 15. The five cases are noted in the figure. The primary rendezvous technique is documented for each of the five lift-off times. In addition, the CSM-rescue profiles are documented for the two cases in the pre-nominal region, since they are significantly different from the primary profiles. Data are presented in the form of relative motion, range and range rate versus time, state vectors after each maneuver, and profile timeline showing sunlight/shadow and communications blackouts for each vehicle.

7.1 Lift-off at Touchdown

LM lift-off at touchdown results in an insertion phase angle of 23.0 degrees, near the lower limit of the nominal region. The input parameters for the LM-active coelliptic sequence can be found in Figure 5. CSI occurs 50 minutes after insertion, CDH is at the first apsis (first apocynthion) of the transfer orbit, and TPI occurs 260 minutes after insertion during the second revolution of the coelliptic orbit. The maneuvers and state vectors after each maneuver are presented in Table I. The ΔV's for each maneuver compare favorably with those in Figure 6. The rendezvous timeline is presented in Figure 16. Data on sunlight/shadow and communications blackouts are shown in the figure. The relative motion of the LM with respect to the CSM is shown in Figure 17. The section of the curve representing about one and one-third revolutions in the coelliptic orbit is straight because both vehicles are in circular orbits, thus the altitude difference is constant. The vehicle-to-vehicle range and range rate are shown in Figure 18 as functions of time from LM insertion. The discontinuities in the range rate curve at the maneuver times represent the component of ΔV along the line of sight between vehicles. Thus, at TPI, the discontinuity is equal to the magnitude of the impulse presented in Table I.

The input parameters for the CSM-active coelliptic sequence are found in Figure 7. CSI occurs 51 minutes after LM insertion, one minute after the LM CSI time. CDH is at the first apsis (first pericynthion) of the transfer orbit. TPI occurs at about 250 minutes after insertion. The resultant Δh is 10 nautical miles. The maneuvers and state vectors after each maneuver are presented in Table II. The mission timelines, relative motion, and range and range rate are nearly identical to those for the LM-active case, thus are not presented. The only discernible difference is in the coelliptic portion of the relative motion plot. Since the two orbits are elliptical, there is a slight variation (less than +0.5 nautical mile) in the differential altitude around the orbits. There is negligible difference in the timelines and range and range rate plots. The same holds true for the case of CSM rescue after a LM-active CSI maneuver. The maneuvers and state vectors after each maneuver are presented in Table III. The timeline, relative motion, and range and range rate are not shown since they are nearly identical to the data presented in Figures 16, 17, and 18.

7.2 Lift-off 17 Minutes after Touchdown

LM-lift-off 17 minutes after touchdown results in an insertion phase angle of 74.6 degrees, near the upper limit of the nominal region. The input parameters from Figure 5 are: CSI time of 287.9 minutes from insertion (50 minutes after pericynthion on the third revolution), CDH at the third apsis (second apocynthion), and TPI at about 480 minutes after insertion. The maneuvers and state vectors after each maneuver are presented in Table IV. The rendezvous timeline is presented in Figure 19. The relative motion of the LM with respect to the CSM is shown in Figure 20. The two peaks prior to CSI represent apocynthion crossings in the LM insertion orbit. The third apsis CDH is also apparent in the figure. The coelliptic differential height is 16 nautical miles. The vehicle-to-vehicle range and range rate are shown in Figure 21 as functions of time from insertion. The range rate plot exhibits the same oscillatory motion seen in the relative motion plot. Even so, the range rate is always negative, that is, the range is reduced monotonically.

The input parameters for the CSM-active coelliptic sequence are found in Figure 7. These parameters are similar to those used in the LM-active sequence. When the sequence was computed for these state vectors, the resultant Δh was above 15 nautical miles. The maneuvers and state vectors after each maneuver are presented in Table V. As in the previous case discussed in Section 7.1, the rendezvous timeline, relative motion, and range and range rate plots are so similar to those for the LM-active sequence that it is unnecessary to present them in this report. This also holds true for CSM rescue following LM-active CSI. The maneuvers and state vectors after each maneuver are presented in Table VI for this sequence.

7.3 Lift-off 60 Minutes after Touchdown

LM lift-off 60 minutes after touchdown results in an insertion phase angle of 205 degrees, near the middle of the post-nominal region. The input parameters for the CSM-active high apocynthion dwell and the following LM-active coelliptic sequence are found in Figure 10. The first dwell maneuver is performed over LM pericynthion 50 minutes after insertion and inserts the CSM into a dwell orbit with an apocynthion altitude of 279 nautical miles. The CSM recircularizes after two complete dwell revolutions, then the LM performs a coelliptic sequence with CSI occurring 386 minutes after insertion, CDH at the first apsis, and TPI occurring at 478 minutes during the first coelliptic revolution. The predicted Δh would have been 15 nautical miles below the CSM; however, for these state vectors it is 16 nautical miles. The maneuvers and state vectors after each maneuver are presented in Table VII. The rendezvous timeline with sunlight/shadow and MSFN communication blackout times is shown in Figure 22. The relative motion of the LM with respect to the CSM is shown in Figure 23. Since the LM travels one revolution more than the CSM, the curvilinear relative motion of the entire profile is meaningless. Therefore, the data shown in Figure 23 start at 285 minutes after insertion, about 45 minutes before CSM recircularization. The vehicle-to-vehicle range and range rate are shown in Figure 24 as functions of time.

In the event of a LM failure during the coelliptic sequence, the CSM can perform the entire sequence or can rescue the LM after the LM-active CSI. Since the primary purpose of this case is to illustrate the operation of the high apocynthion dwell sequence, the coelliptic sequence rescue data are not presented in this report. These data have been generated and are available.

7.4 Lift-off 100 Minutes after Touchdown

LM lift-off 100 minutes after insertion results in an insertion phase angle of 326.5 degrees (or -33.5 degrees), near the lower limit of the pre-nominal region. The input parameters for the primary rendezvous sequence are found in Figure 12. The LM performs a 100-foot per second positive horizontal thrust immediately after insertion. This raises the LM apocynthion altitude to about 103 nautical miles for the given state vectors. The CSM initiates a Hohmann transfer to 20 nautical miles 10 minutes later, and circularizes at the first pericynthion. The CSM performs a CSI maneuver 236 minutes after insertion, at the second passage over LM pericynthion. The transfer orbit between CSI and CDH is really a phasing orbit since CDH is performed one revolution after CSI, again over LM pericynthion. The resultant Δh is always the difference between 20 nautical miles and the LM pericynthion altitude and will be on the order of 10 nautical miles. TPI occurs 383.1 minutes after insertion, during the first coelliptic revolution. The maneuvers and state vectors after each maneuver are presented in Table VIII. The rendezvous timeline is shown in Figure 25. The CSM is in contact with MSFN during all maneuvers except Hohmann transfer circularization. The relative motion of the CSM with respect to the LM is shown in Figure 26. The relative motion exhibits some oscillation above and below the LM. This is a result of the

relatively high eccentricity of the LM orbit. The range and range rate are shown in Figure 27 and also exhibit this oscillation.

In case the LM cannot perform the required thrust after insertion, CSM rescue is performed using the five impulse extended coelliptic sequence. The input parameters for this sequence are found in Figure 13. The coelliptic phasing maneuver, CPM, is performed over LM apocynthion 71 minutes after insertion. The CSM is inserted into a phasing orbit with an apocynthion altitude of 323 nautical miles. It stays in this orbit three complete revolutions, then performs CSI at about 500 minutes after insertion, again over LM apocynthion. CDH occurs at the first apsis (first pericynthion) and TPI occurs during the first coelliptic revolution, about 587 minutes after insertion. The maneuvers and state vectors after each maneuver are presented in Table IX. The rendezvous timeline is shown in Figure 28. There is sufficient time for LM postinsertion tracking CPM computation in the RTCC, and CPM transmission and verification before the CSM loses MSFN contact. The relative motion of the CSM with respect to the LM is shown in Figure 29. The major portion of the phasing orbit is not shown since presentation in the curvilinear system is not representative of the relative motion. The range and range rate are shown in Figure 30 as functions of time.

7.5 Lift-off 116 Minutes after Touchdown

LM lift-off 116 minutes after touchdown results in an insertion phase angle of 15 degrees, near the upper limit of the pre-nominal region. The input parameters for the primary rendezvous sequence are found in Figure 12. As in Section 7.4, the LM performs a 100-foot per second thrust immediately after insertion, raising its apocynthion altitude to about 103 nautical miles. Ten minutes later the CSM initiates a Hohmann transfer to 20 nautical miles, then circularizes at first pericynthion passage. The CSM performs CSI 221 minutes after insertion on its second passage over LM pericynthion. CDH occurs at the second apsis (first pericynthion) and, as in Section 7.4, the resultant Δh is on the order of 10 nautical miles. TPI occurs 383.1 minutes after insertion, during the first coelliptic revolution. The maneuvers and state vectors after each maneuver are presented in Table X. The rendezvous timeline is shown in Figure 31. The relative motion of the CSM with respect to the LM is shown in Figure 32. The oscillatory motion characteristic of this rendezvous technique is apparent from the figure. It also shows up in the range and range rate data of Figure 33.

If the LM cannot perform the required thrust at insertion, CSM rescue is accomplished using the six impulse extended coelliptic sequence. The input parameters for this sequence are found in Figure 14. The Hohmann transfer to a 10-nautical mile pericynthion altitude occurs 54 minutes after LM insertion, over LM apocynthion. CPM is performed 57 minutes later at pericynthion of the Hohmann transfer orbit. The apocynthion altitude of the phasing orbit is 26.5 nautical miles. The CSM remains in the phasing orbit three and one-half revolutions then, at apocynthion, performs CSI approximately 502 minutes after LM insertion. CDH occurs at the first apsis (in this case first pericynthion) and TPI occurs during the first coelliptic revolution. The maneuvers and state vectors after

each maneuver are presented in Table XI. The rendezvous timeline is shown in Figure 34. The relative motion of the CSM with respect to the LM is presented in Figure 35, and the vehicle-to-vehicle range and range rate is presented in Figure 36. The relative motion appears to indicate that this is not the best possible rendezvous technique. For instance, the CSM passes within about 9 nautical miles of the LM 100 minutes after insertion, then moves away before completing the rendezvous. It would be possible at this point to insert the CSM into a stable orbit with the LM, then perform terminal phase. However, it should be noted that while this could be done for this particular phase angle, it could not be performed throughout the pre-nominal phase angle region.

8. CONCLUSIONS

Rendezvous following LM anytime lift-off can be performed within the current performance and time constraints. There is CSM rescue capability after a LM failure throughout the 360-degree degree phase angle. The rendezvous techniques used in this plan can be computed on existing programs. No new systems or modification of existing systems are required. No problem areas, other than apparently unavoidable mission complexity, were discovered during the evaluation of this plan.

The performance and total time requirements for rendezvous (LM-active with CSM assist if specified in the sequence) are presented in Figure 37. The independent variable in this case is time between touch-down and LM lift-off, which is directly related to insertion phase angle. This figure is a summary of data presented in Figures 6, 11, and 12. The maximum CSM SPS impulsive ΔV requirement of about 625 feet per second occurs at the end of the pre-nominal phase angle region (phase angle of 17.5 degrees). The maximum LM RCS impulsive ΔV requirement of 131 feet per second occurs at several points in the nominal region. The maximum total time to rendezvous of 680 minutes occurs for the three revolution high apocynthion dwell (phase angles from 230 to 325 degrees).

The performance and total time requirements for CSM rescue of an inactive LM are presented in Figure 38, again as a function of lift-off time during the first CSM revolution following LM landing. This figure is a summary of data presented in Figures 8, 11, 13, and 14. The maximum CSM impulsive ΔV requirement of 731 feet per second occurs at three points in the post-nominal phase angle region (phase angles of 135, 230, and 325 degrees). The maximum total time requirement of 680 minutes, as in the LM-active case, occurs throughout the three revolution high apocynthion dwell.

The multi-impulse rendezvous and rescue techniques used in the pre-nominal region, while satisfying performance and time requirements, begin to look less attractive when studied in detail and compared to waiting until lift-off can occur in the nominal region. The relative motion plots show the CSM moving ahead of and behind, and in some cases, above and below the LM. The total time requirement for CSM rescue in this region approaches the 11.5-hour LM ascent stage lifetime. The ΔV requirements are considerably higher than for CSM rescue from the nominal sequence, and the CSM pericynthion altitude goes as low as 10 nautical miles. To alleviate these problems it is desirable to delay the LM lift-off for a maximum of 18 minutes, allowing it to occur in the nominal region if possible.

Table I. Maneuver and State Vectors After Each Maneuver During Rendezvous for Lift-off at LM Touchdown - LM-Active Coelliptic Sequence

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	0:06:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	336.4170
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
CSI	0:56:52.0	CSM				6,055,751.4	0.000115	170.8131	-141.3961	-163.4914	128.1886
		LM	53.0	0.0	53.0	5,931,221.2	0.010406	170.8131	-44.3085	-163.3403	17.5432
CDH	1:48:44.7	CSM				6,055,751.4	0.000115	170.8131	-141.3961	-163.4914	285.6600
		LM	28.1	0.6	28.1	5,993,028.2	0.000117	170.8131	-141.5059	-163.3403	277.2106
TPI	4:26:41.5	CSM				6,055,751.4	0.000115	170.8104	-141.3961	-163.4914	45.0971
		LM	15.2	-7.1	16.9	6,027,261.1	0.005931	170.8104	-111.2025	-163.4735	13.6074
TPF	5:09:31.1	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	175.0971
		LM	12.7	18.2	22.2	6,055,750.0	0.000115	170.8061	-141.4977	-163.4914	175.1987

Table II. Maneuvers and State Vectors After Each Maneuver During Rendezvous for Lift-off at LM Touchdown - CSM-Active Coelliptic Sequence

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	0:06:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	336.4170
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
CSI	0:57:52.0	CSM	-54.1	0.0	54.1	5,936,177.8	0.020221	170.8061	170.0812	-163.4914	179.7466
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	164.6574
CDH	1:55:30.0	CSM	-27.6	1.5	27.6	5,875,118.6	0.010042	170.8061	171.6511	-163.4914	358.4614
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	350.5052
TPI	4:17:14.2	CSM	-15.0	7.3	16.8	5,842,792.7	0.010257	170.8094	139.3425	-163.3531	121.2866
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	87.5622
TPF	4:57:33.1	CSM	-12.2	-19.0	22.6	5,816,441.5	0.010144	170.8131	171.8006	-163.3402	217.5618
		LM				5,816,443.6	0.010143	170.8131	171.8002	-163.3403	217.5622

Table III. Maneuvers and State Vectors After Each Maneuver During Rendezvous for Lift-off at LM Touchdown - LM-Active CSI, CSM Rescue

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	0:06:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	336.4170
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
CSI	0:56:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	128.1886
		LM	53.0	0.0	53.0	5,931,221.2	0.010406	170.8131	-44.3085	-163.3403	17.5432
CDH	1:48:44.7	CSM	-27.4	7.6	28.4	5,994,545.1	0.010296	170.8061	-44.3085	-163.4914	188.7366
		LM				5,931,221.2	0.010406	170.8131	-44.3085	-163.3403	179.9999
TPI	4:25:30.9	CSM	-15.1	9.9	18.2	5,961,105.8	0.009661	170.8072	-10.0287	-163.3690	277.9608
		LM				5,931,221.2	0.010406	170.8131	-44.3085	-163.3403	310.9289
TPF	5:07:01.6	CSM	-13.7	-17.1	21.9	5,931,220.4	0.010406	170.8131	-44.3087	-163.3402	80.9292
		LM				5,931,221.2	0.010406	170.8131	-44.3085	-163.3403	80.9289

Table IV. Maneuvers and State Vectors After Each Maneuver During Rendezvous for Lift-off 17 Minutes After Touchdown - LM-Active Coelliptic Sequence

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	0:23:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	27.9954
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
CSI	4:57:08.7	CSM				6,055,751.4	0.000115	170.8131	-141.3961	-163.4914	137.5360
		LM	45.0	0.0	45.0	5,913,363.5	0.007615	170.8131	-51.2098	-163.3403	24.4437
CDH	7:41:02.2	CSM				6,055,751.4	0.000115	170.8131	-141.3961	-163.4914	275.0162
		LM	20.6	0.6	20.6	5,958,393.7	0.000117	170.8131	-141.4507	-163.3403	270.2542
TPI	8:23:37.3	CSM				6,055,751.4	0.000115	170.8098	-141.3961	-163.4914	44.2817
		LM	23.5	-11.9	26.4	6,010,968.4	0.009120	170.8098	-113.4443	-163.4766	14.3078
TPF	9:06:27.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	174.2817
		LM	20.0	27.1	33.7	6,055,748.2	0.000116	170.8061	-141.3850	-163.4914	174.2705

Table V. Maneuvers and State Vectors After Each Maneuver During Rendezvous for Lift-off 17 Minutes After Touchdown - CSM-Active Coelliptic Sequence

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	0:23:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	27.9954
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
CSI	4:58:08.7	CSM	-46.6	0.0	46.6	5,952,358.6	0.017461	170.8061	179.4221	-163.4914	179.7532
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	164.6569
CDH	7:51:35.2	CSM	-20.4	-7.3	21.7	5,906,892.4	0.009988	170.8061	171.6510	-163.4914	7.6175
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	3.9500
TPI	8:17:30.7	CSM	-23.2	10.5	25.6	5,856,497.7	0.011794	170.8091	125.0733	-163.3540	136.2352
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	87.5476
TPF	8:57:50.0	CSM	-18.5	-30.5	35.7	5,816,441.4	0.010144	170.8131	171.8006	-163.3402	217.5471
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	217.5475

Table VI. Maneuvers and State Vectors After Each Maneuver During Rendezvous for Lift-off 17 Minutes After Touchdown - LM-Active CSI, CSM Rescue

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	0:23:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	27.9954
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
CSI	4:57:08.7	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	137.5360
		LM	45.0	0.0	45.0	5,913,363.5	0.007615	170.8131	-51.2098	-163.3403	24.4437
CDH	7:41:02.2	CSM	-20.0	2.8	20.2	6,010,824.1	0.007491	170.8061	-51.2098	-163.4914	184.8892
		LM				5,913,363.5	0.007615	170.8131	-51.2098	-163.3403	179.9999
TPI	8:23:54.5	CSM	-23.6	14.0	27.6	5,958,405.5	0.008507	170.8080	18.4023	-163.3624	247.3004
		LM				5,913,363.5	0.007615	170.8131	-51.2098	-163.3403	314.8620
TPF	9:05:14.0	CSM	-20.5	-28.4	35.0	5,913,361.2	0.007614	170.8131	-51.2113	-163.3403	84.8634
		LM				5,913,363.5	0.007615	170.8131	-51.2098	-163.3403	84.8620

Table VII. Maneuvers and State Vectors After Each Maneuver During Rendezvous for Lift-off 60 Minutes After Touchdown

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	1:06:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	158.4585
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
Dwell	1:57:53.7	CSM	258.8	-0.4	258.8	6,722,228.1	0.099217	170.8131	172.0322	-163.4914	0.0000
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	164.7509
Recircularization	6:35:18.6	CSM	-259.0	0.0	259.0	6,055,270.7	0.000000	170.8131	-7.9678	-163.4914	180.0000
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	339.3245
CSI	7:31:45.6	CSM				6,055,270.7	0.000000	170.8131	-7.9678	-163.4914	351.3677
		LM	44.7	0.0	44.7	5,912,842.4	0.007544	170.8131	-51.6396	-163.3403	24.7959
CDH	8:21:05.5	CSM				6,055,270.7	0.000000	170.8131	-7.9678	-163.4914	141.1281
		LM	20.4	0.0	20.4	5,957,452.4	0.000000	170.8131	122.4359	-163.3403	5.9243
TPI	9:03:08.2	CSM				6,055,270.7	0.000000	170.8088	-7.9678	-163.4914	268.7673
		LM	23.6	-12.0	26.6	6,010,263.3	0.009060	170.8088	-115.2237	-163.4814	13.9867
TPF	9:45:57.5	CSM				6,055,270.7	0.000000	170.8061	-7.9678	-163.4914	38.7672
		LM	20.1	27.2	33.8	6,055,268.2	0.000000	170.8061	-175.6879	-163.4914	206.4872

Table VIII. Maneuvers and State Vectors After Each Maneuver During Rendezvous for Lift-off 100 Minutes After Touchdown

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	1:46:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	279.8194
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
LM Dwell	1:47:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	282.9956
		LM	100.0	0.0	100.0	6,042,218.4	0.047117	170.8131	174.5287	-163.3403	0.6957
CSM Hohmann	1:56:52.0	CSM	-52.5	-0.5	52.5	5,939,608.8	0.019478	170.8061	-11.0917	-163.4914	180.0000
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	28.1064
Circularization	2:54:28.1	CSM	-52.8	0.0	52.8	5,823,918.2	0.000000	170.8061	-11.0918	-163.4914	0.0000
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	203.5408
CSI	5:43:15.6	CSM	86.6	0.0	86.6	6,016,537.7	0.032015	170.8061	172.1576	-163.4914	0.0000
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	357.6170
CDH	7:40:42.5	CSM	38.9	9.6	40.1	6,108,412.8	0.046606	170.8061	174.3795	-163.4914	357.9781
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	355.3243
TPI	8:06:59.8	CSM	-16.9	3.7	17.4	6,069,335.4	0.045322	170.8118	166.7357	-163.3429	84.6058
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	75.3893
TPF	8:49:40.9	CSM	-11.9	-25.3	28.0	6,042,216.9	0.047117	170.8131	174.5286	-163.3403	205.3893
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	205.3893

Table IX. Maneuvers and State Vectors After Each Maneuver During CSM Rescue for Lift-off 100 Minutes After Touchdown

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	1:46:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	279.8194
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
CPM	2:57:32.8	CSM	306.7	0.4	306.7	6,866,058.9	0.117946	170.8061	170.8061	-7.9718	0.0000
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	226.9614
CSI	10:07:04.3	CSM	-360.1	0.0	360.1	5,937,933.3	0.019923	170.8061	171.5287	-163.4914	0.4403
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	172.0409
CDH	11:04:30.5	CSM	-26.8	0.1	26.8	5,878,627.7	0.010036	170.8061	171.6511	-163.4914	359.8800
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	357.2556
TPI	11:32:31.2	CSM	-15.9	7.7	17.8	5,844,327.5	0.010384	170.8093	137.5662	-163.3532	123.1598
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	87.5826
TPF	12:12:50.0	CSM	-12.9	-20.3	24.0	5,816,440.9	0.010144	170.8131	171.8008	-163.3403	217.5819
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	217.5826

Table X. Maneuvers and State Vectors After Each Maneuver During Rendezvous for Lift-off 116 Minutes After Touchdown

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	2:02:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	328.3638
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
LM Dwell	2:03:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	331.5625
		LM	100.0	0.0	100.0	6,042,218.4	0.047117	170.8131	174.5287	-163.3403	0.69571
CSM Hohmann	2:12:52.0	CSM	-52.6	0.0	52.6	5,939,485.1	0.019458	170.8061	37.4850	-163.4914	180.0000
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	28.1064
Circularization	3:10:28.0	CSM	-52.8	0.0	52.8	5,823,917.1	0.000000	170.8061	-142.5150	-163.4914	180.0000
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	203.5353
CSI	5:44:07.5	CSM	284.3	0.0	284.3	6,521,638.6	0.106986	170.8061	172.0319	-163.4914	0.0000
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	311.5243
CDH	7:56:40.3	CSM	158.7	10.2	159.1	6,108,388.9	0.046606	170.8061	174.3796	-163.4914	357.8637
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	355.2096
TPI	8:22:59.2	CSM	-16.9	3.7	17.4	6,069,327.5	0.045318	170.8118	166.7401	-163.3428	84.5688
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	75.3571
TPF	9:05:40.2	CSM	-11.9	-25.3	28.0	6,042,216.9	0.047117	170.8131	174.5286	-163.3402	205.3571
		LM				6,042,218.4	0.047117	170.8131	174.5287	-163.3403	205.3570

Table XI. Maneuvers and State Vectors After Each Maneuver During CSM Rescue for Lift-off 116 Minutes After Touchdown

Maneuver	Maneuver Time from Touchdown (hr:min:sec)	Vehicle	Horizontal ΔV Component (fps)	Vertical ΔV Component (fps)	Total ΔV (fps)	Semimajor Axis (ft)	Eccentricity (nd)	Inclination (deg)	Argument of Pericynthion (deg)	Longitude of Ascending Node (deg)	Mean Anomaly (deg)
Insertion	2:02:52.0	CSM				6,055,751.4	0.000115	170.8061	-141.3961	-163.4914	328.3638
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	0.1988
Hohmann	2:57:11.3	CSM	-66.5	0.4	66.5	5,909,693.8	0.024796	170.8061	172.0282	-163.4914	180.0000
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	175.3665
CPM	3:54:21.0	CSM	-46.6	0.0	46.6	5,807,511.6	0.007638	170.8061	172.0108	-163.4914	0.0000
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	359.6955
CSI	10:24:11.3	CSM	13.5	0.0	13.5	5,836,087.9	0.002704	170.8061	172.0055	-163.4914	180.0083
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	176.7973
CDH	11:20:17.3	CSM	19.9	-0.3	19.9	5,879,299.5	0.010034	170.8061	171.6510	-163.4914	0.3473
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	357.7015
TPI	11:48:09.6	CSM	-16.0	7.8	18.0	5,844,621.8	0.010409	170.8093	137.2303	-163.3532	123.5085
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	87.5808
TPF	12:28:28.4	CSM	-13.1	-20.5	24.3	5,816,442.1	0.010144	170.8131	171.7999	-163.3403	217.5810
		LM				5,816,443.6	0.010144	170.8131	171.8002	-163.3403	217.5807

PRIMARY RENDEZVOUS SEQUENCES

LM-ACTIVE FOUR IMPULSE COELLIPTIC SEQUENCE

CSM-ACTIVE HIGH APOCYNTHION DWELL FOLLOWED BY LM-ACTIVE FOUR IMPULSE COELLIPTIC SEQUENCE

LM-THRUST AT INSERTION CSM HOHMANN TRANSFER TO LOW CIRCULAR ORBIT, CSM-ACTIVE FOUR IMPULSE COELLIPTIC SEQUENCE

RESCUE RENDEZVOUS SEQUENCES

CSM-ACTIVE FOUR IMPULSE COELLIPTIC SEQUENCE

FOUR IMPULSE COELLIPTIC SEQUENCE WITH LM-ACTIVE CSI AND CSM-ACTIVE CDH

CSM-ACTIVE FIVE IMPULSE EXTENDED COELLIPTIC SEQUENCE

CSM-ACTIVE SIX IMPULSE EXTENDED COELLIPTIC SEQUENCE

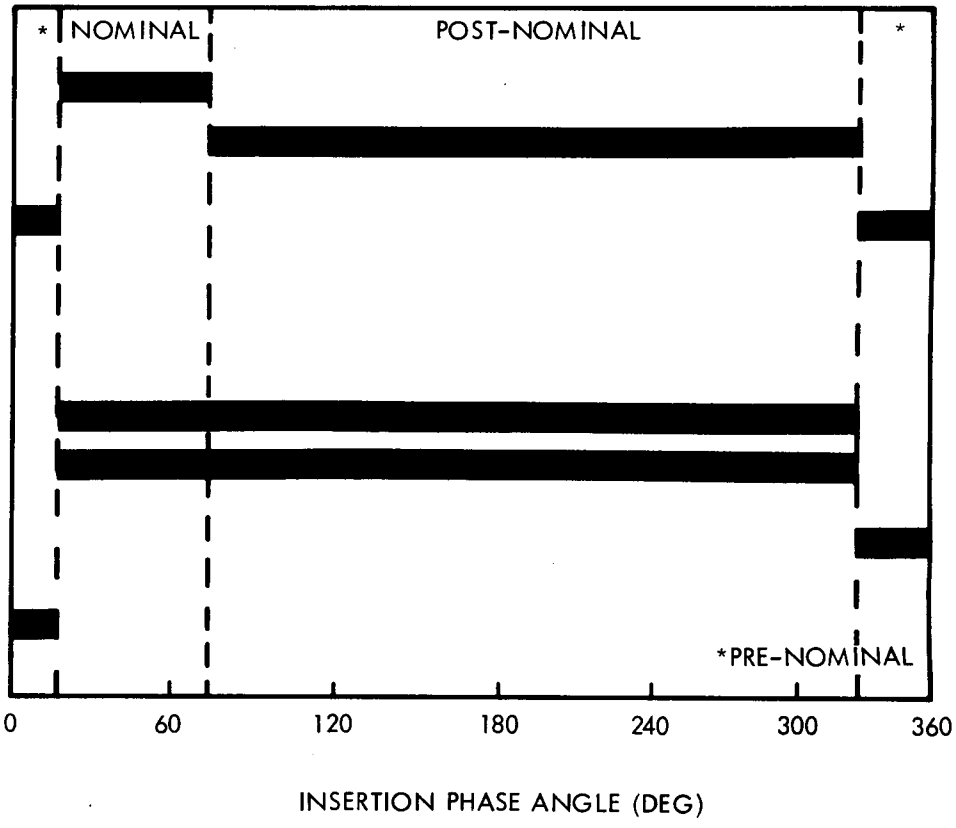


Figure 1. Regions of Applicability of Rendezvous and Rescue Techniques

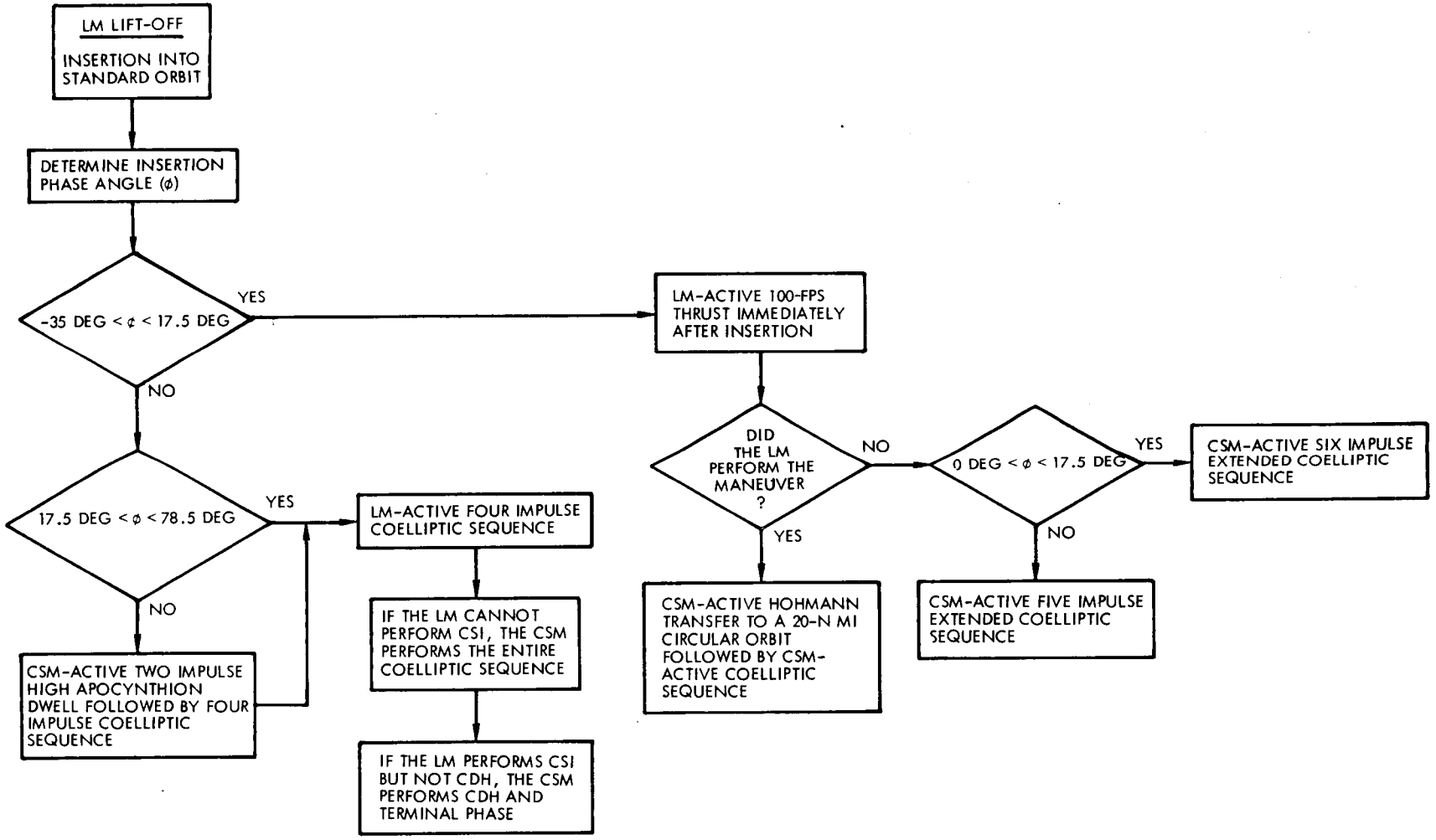


Figure 2. Selection of Rendezvous Techniques Following Anytime LM Lift-off

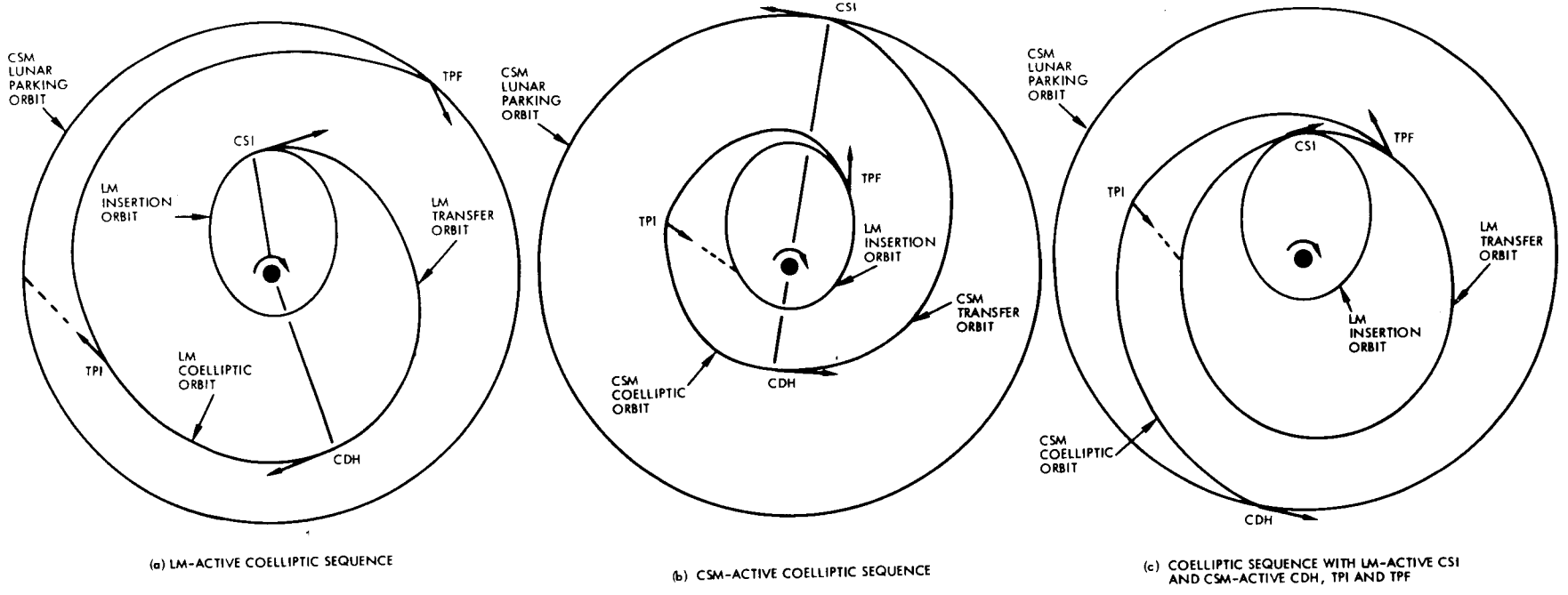


Figure 3. Geometric Illustrations of Rendezvous Techniques

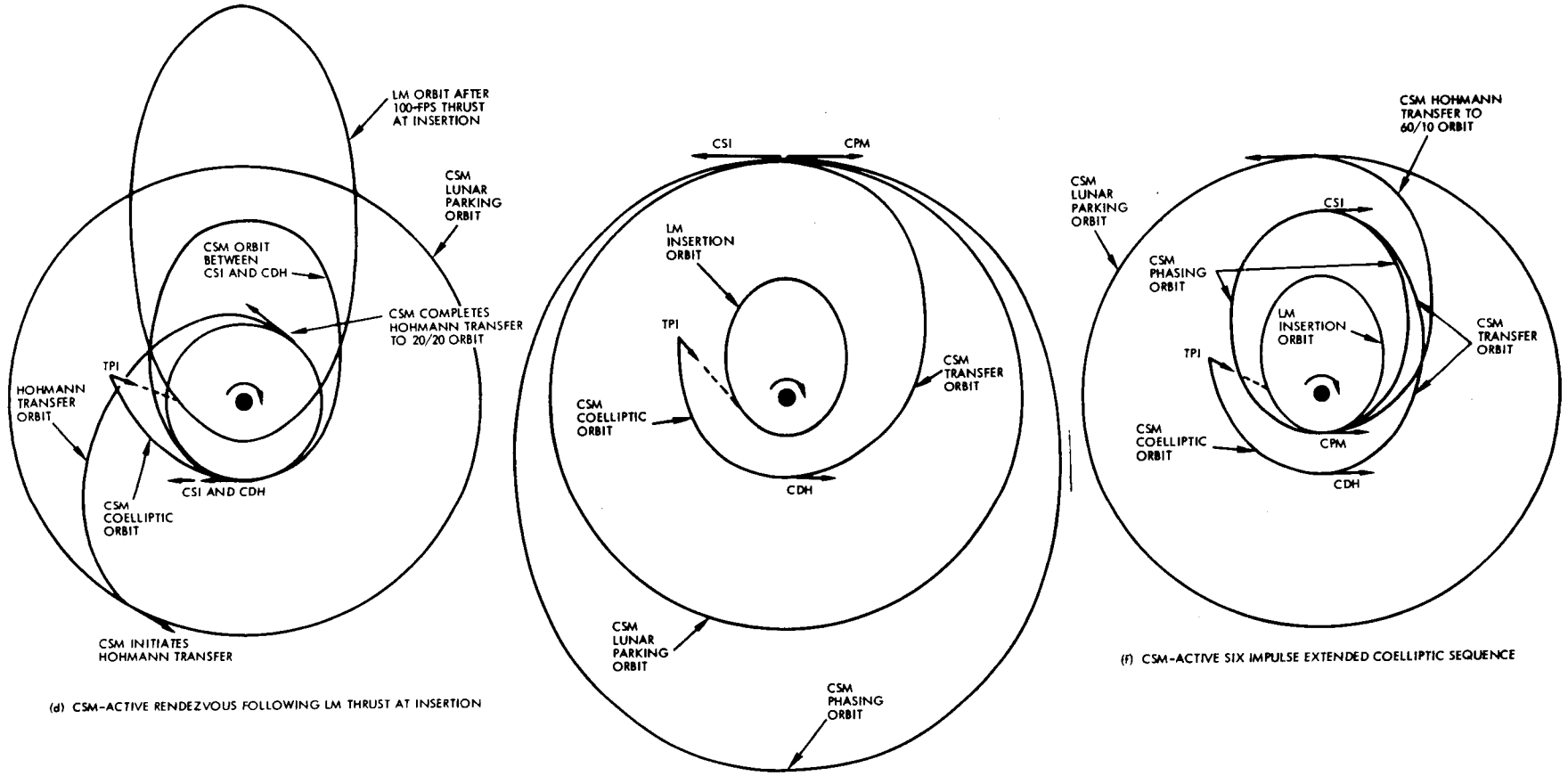


Figure 3. Geometric Illustrations of Rendezvous Techniques (Continued)

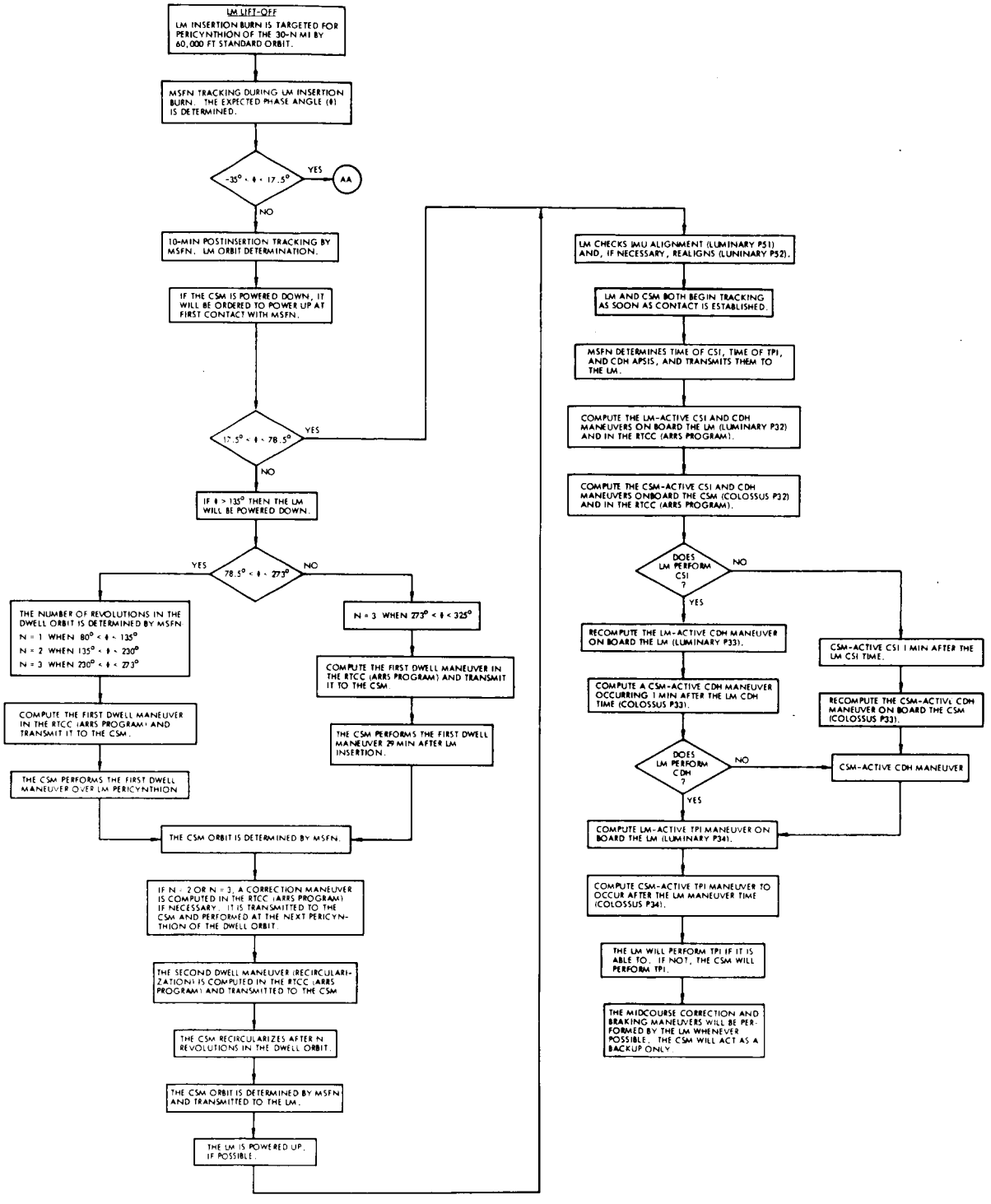


Figure 4. Decision Flow Logic for Rendezvous Following Anytime Lift-off

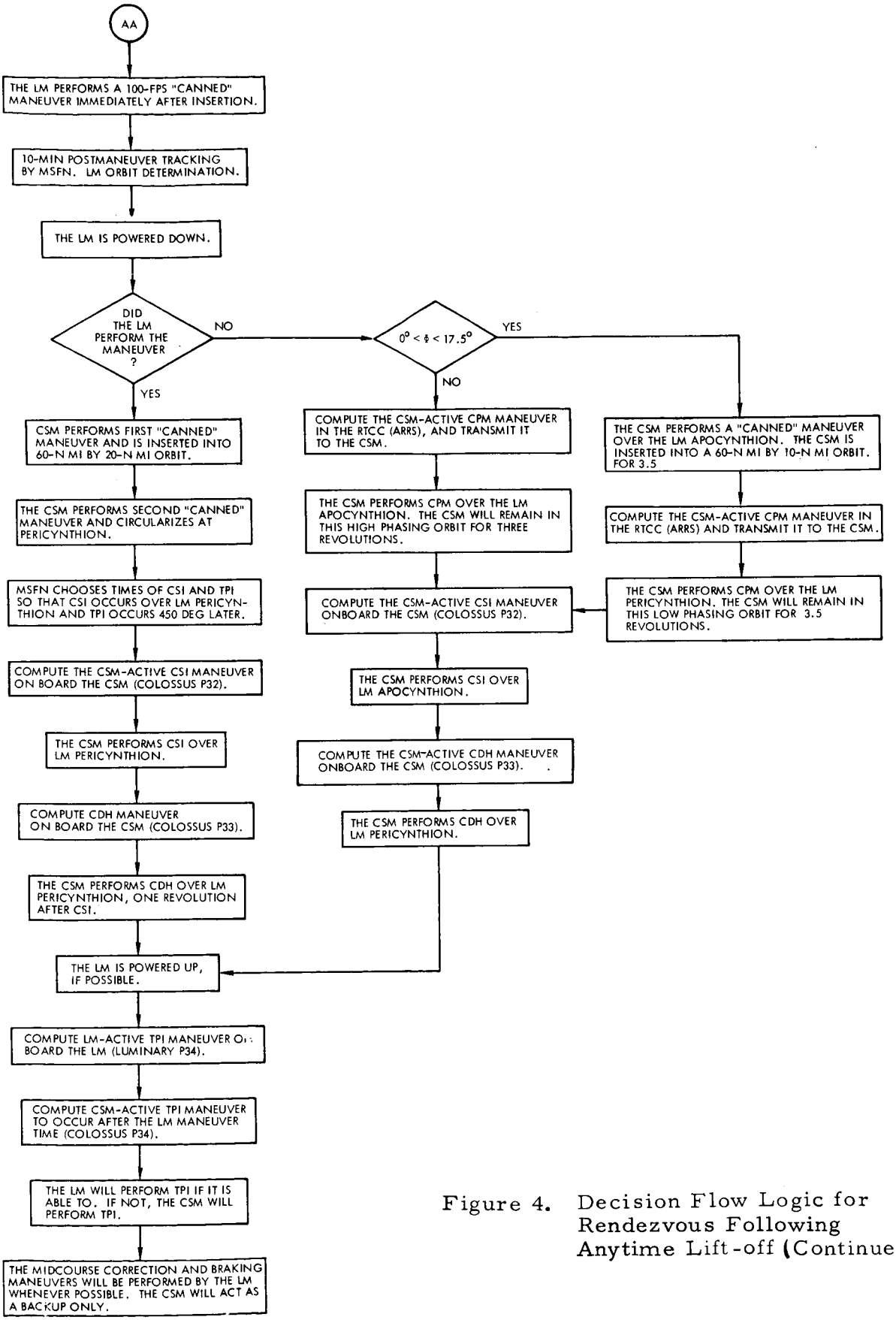


Figure 4. Decision Flow Logic for Rendezvous Following Anytime Lift-off (Continued)

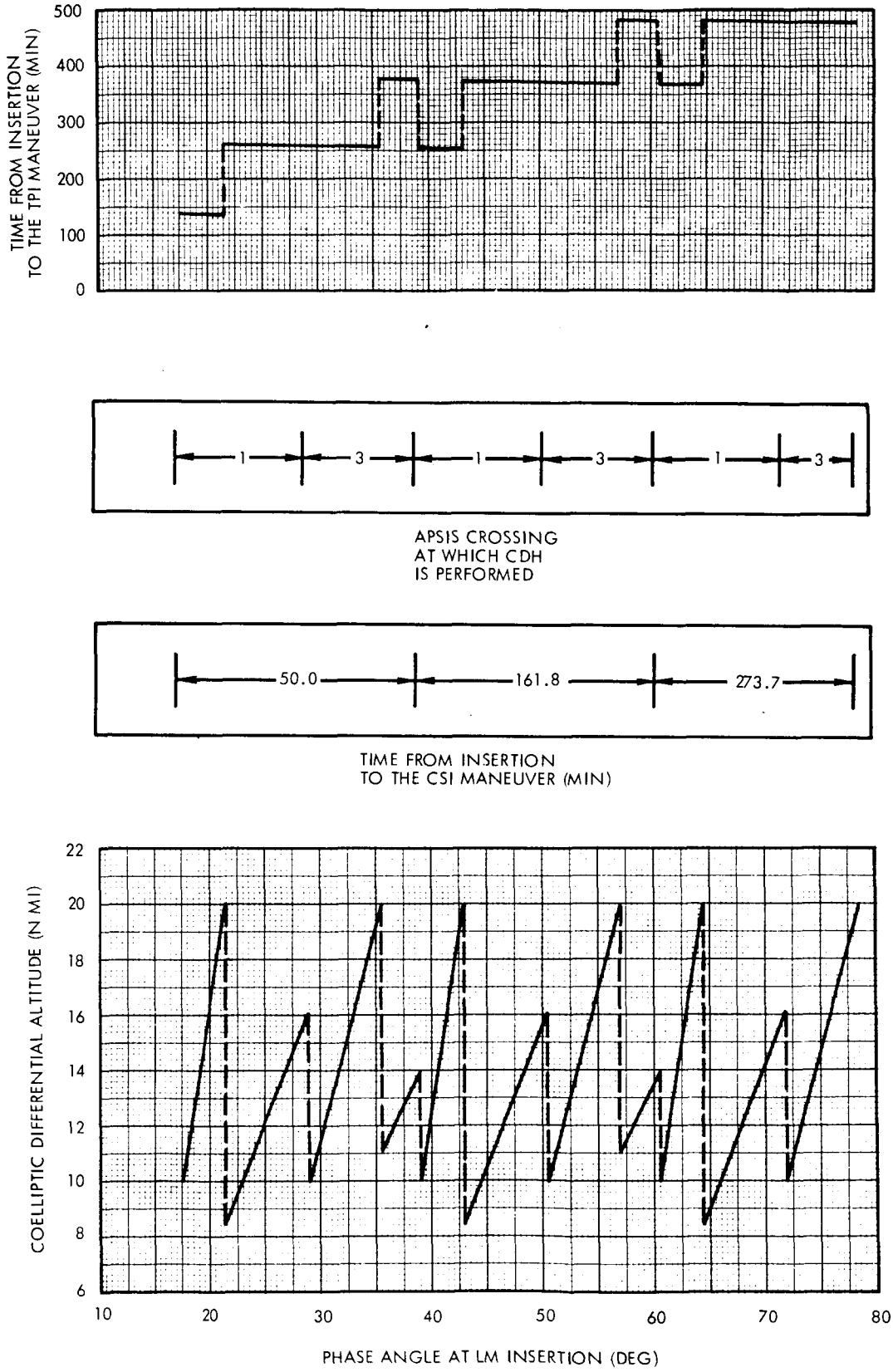


Figure 5. Input Parameters and Resultant Coelliptic Differential Altitude for the LM-Active Four Impulse Coelliptic Sequence

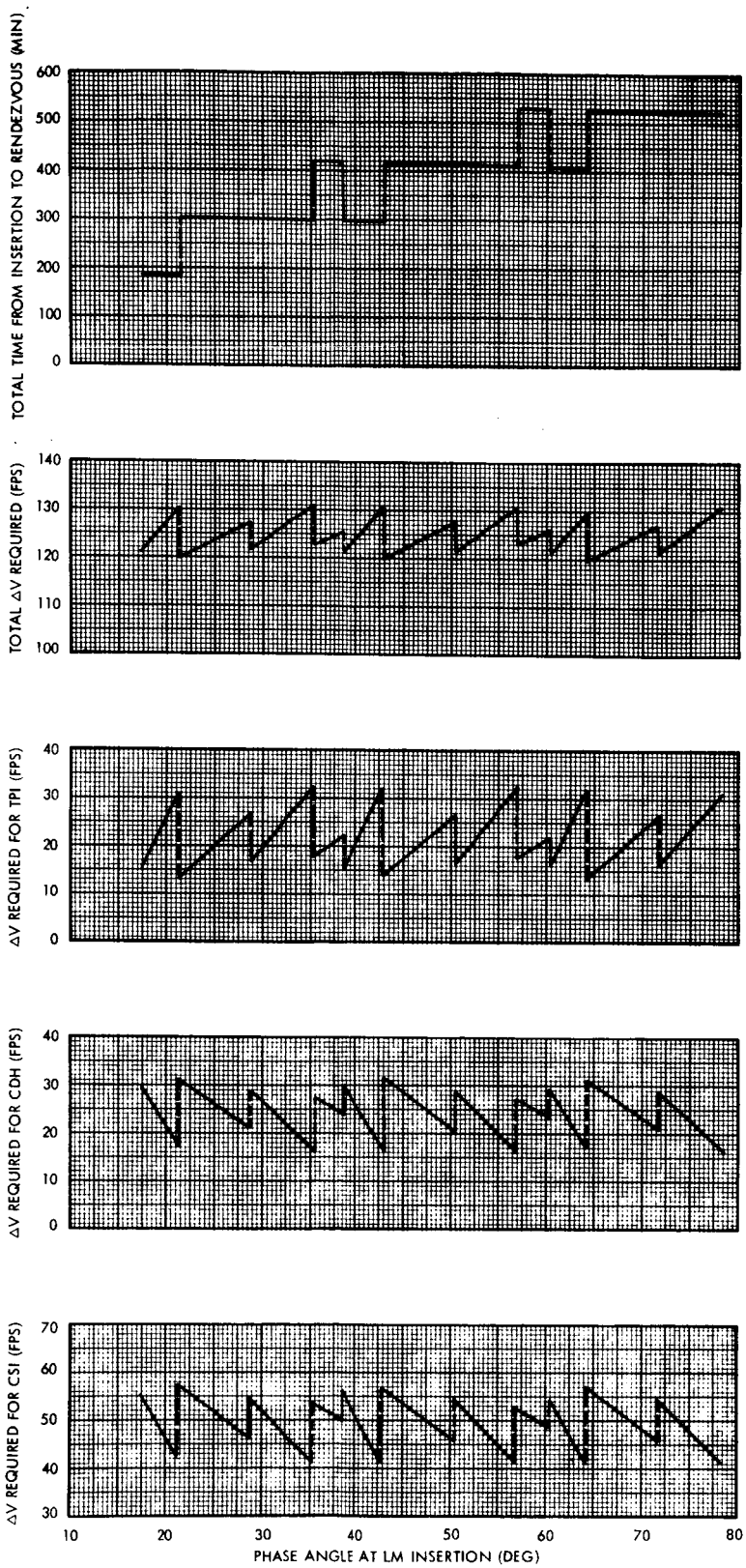


Figure 6. Performance and Time Requirements for the LM-Active Four Impulse Coelliptic Sequence

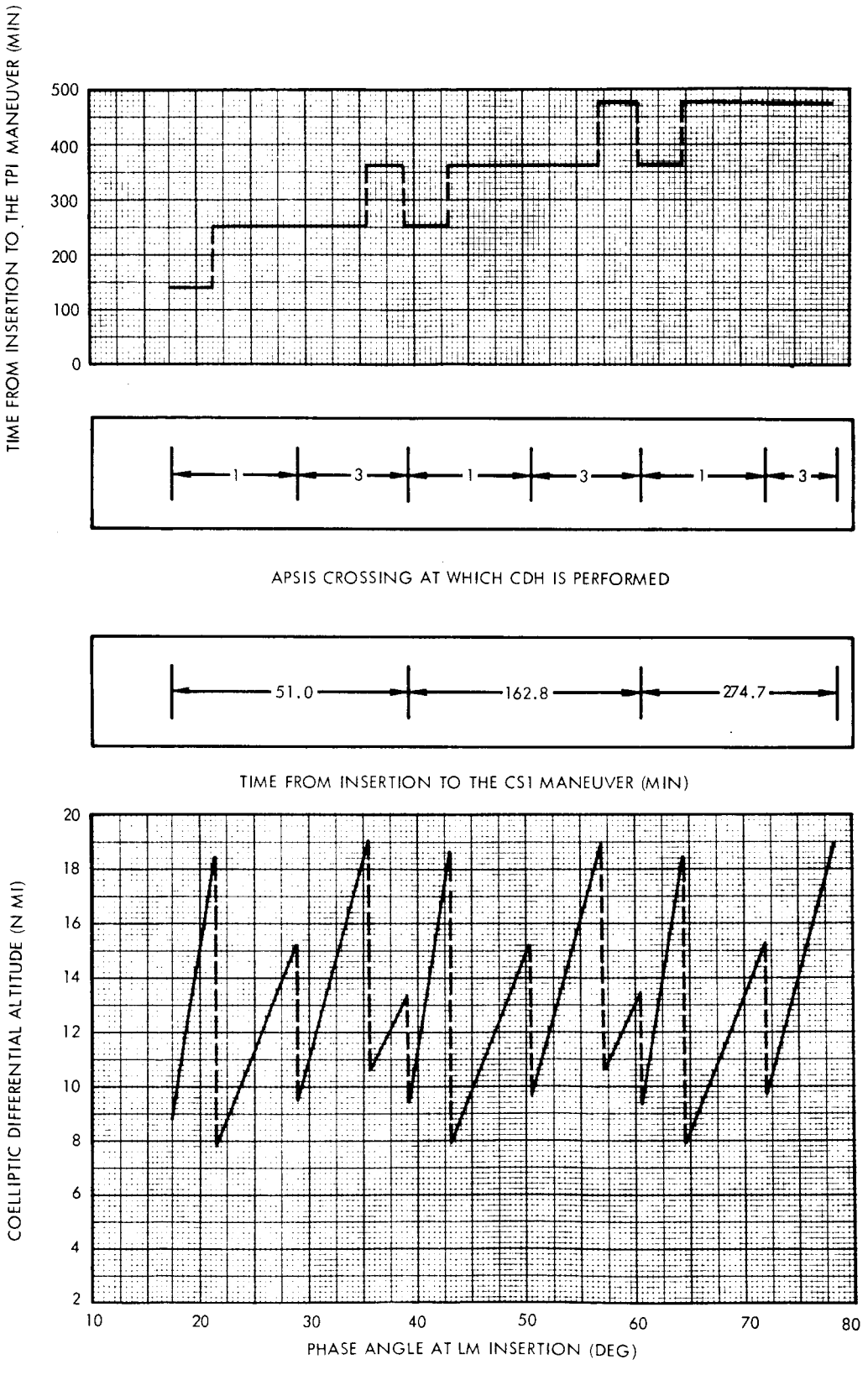


Figure 7. Input Parameters and Resultant Coelliptic Differential Altitude for the CSM-Active Four Impulse Coelliptic Sequence

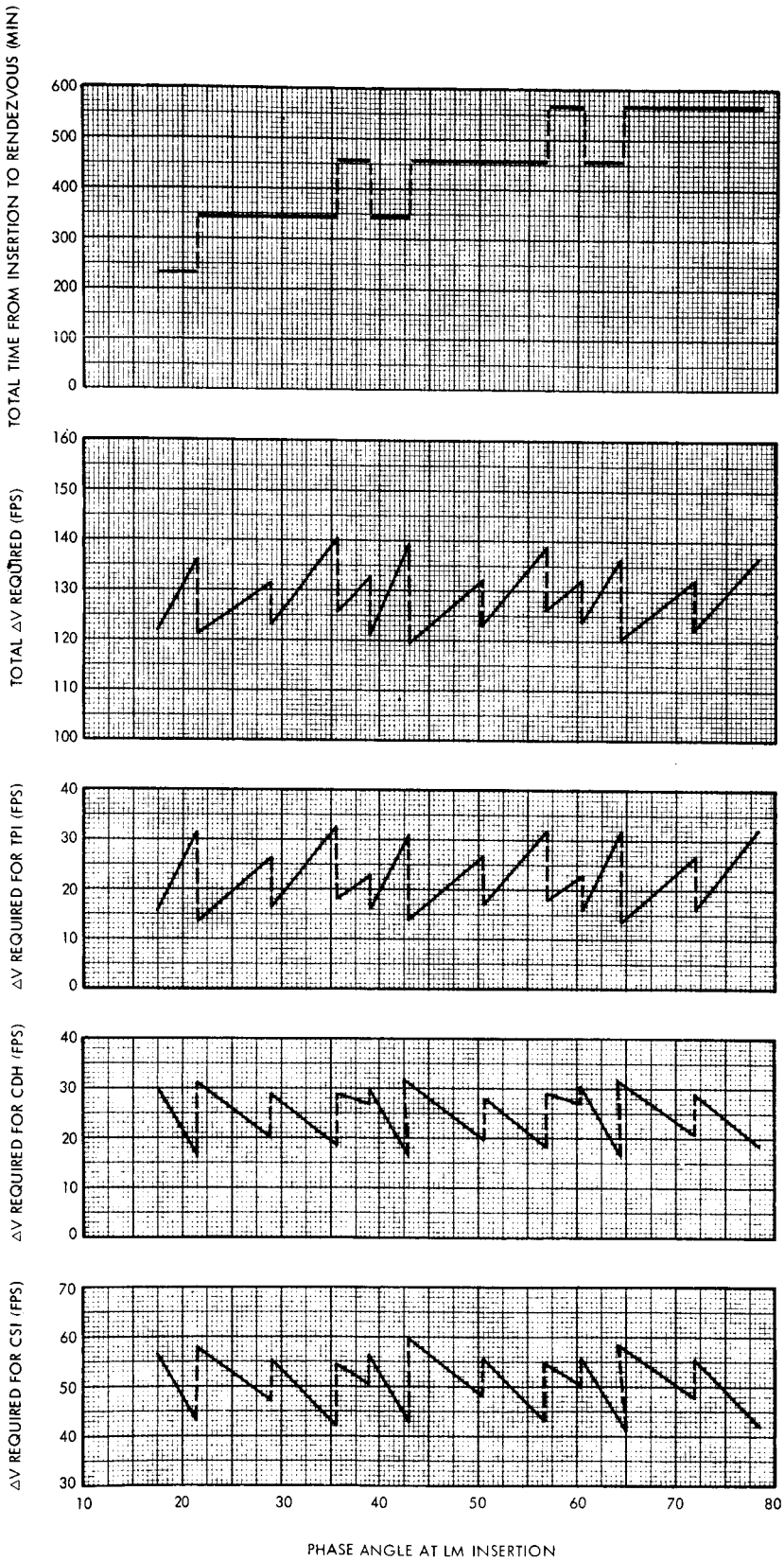


Figure 8. Performance and Time Requirements for the CSM-Active Four Impulse Coelliptic Sequence

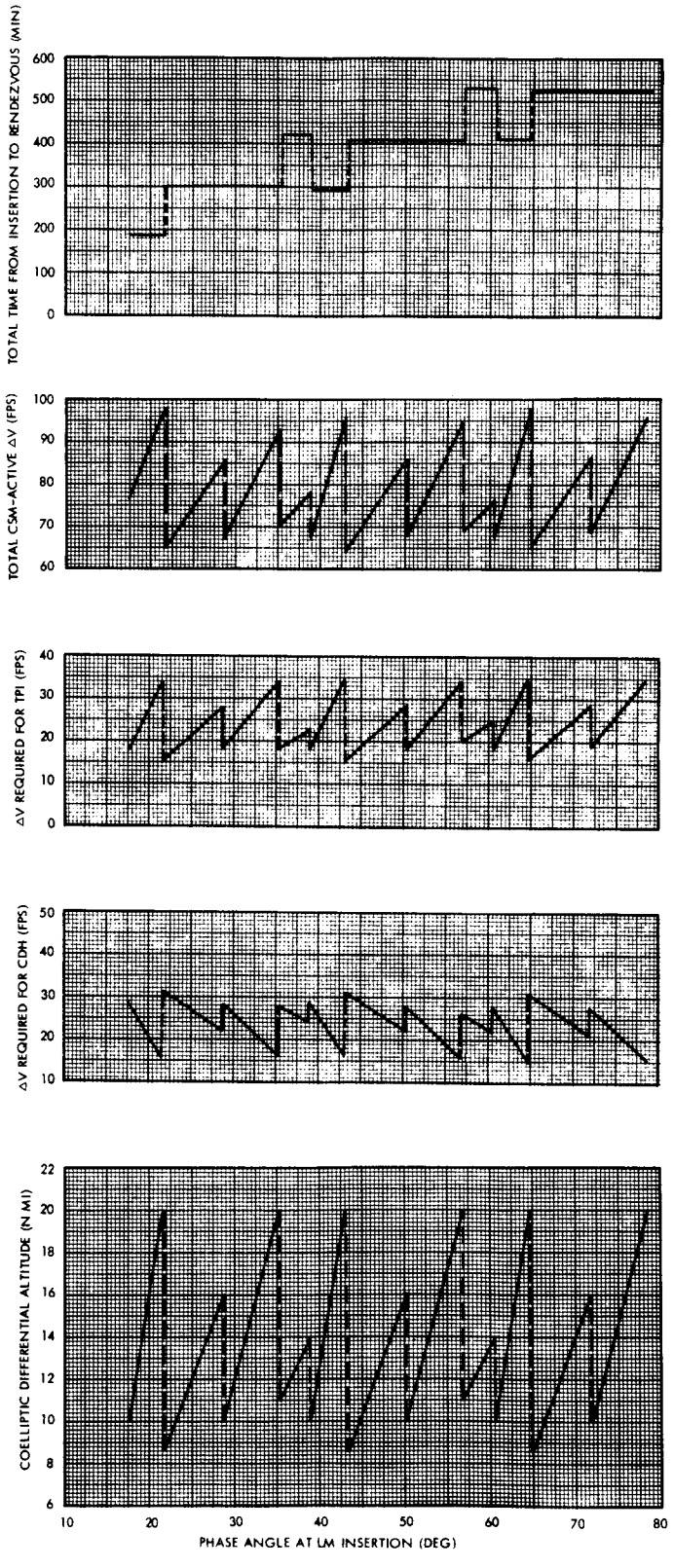
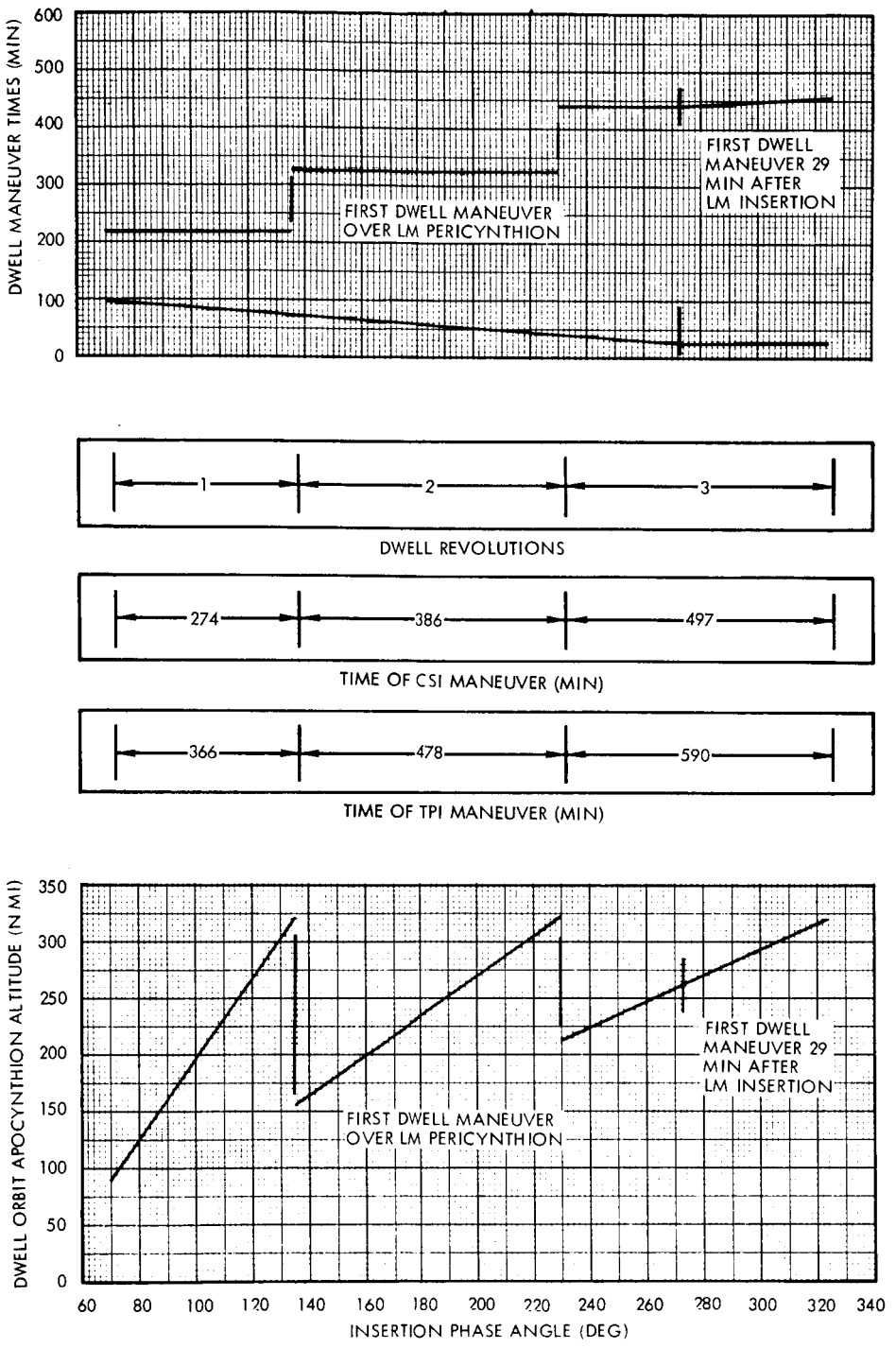
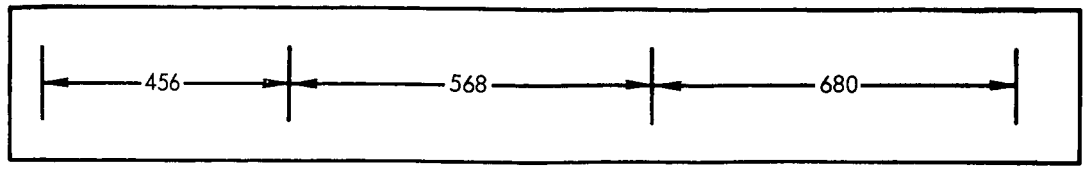


Figure 9. Performance, Time and Coelliptic Differential Altitude for LM-Active CSI, CSM Rescue

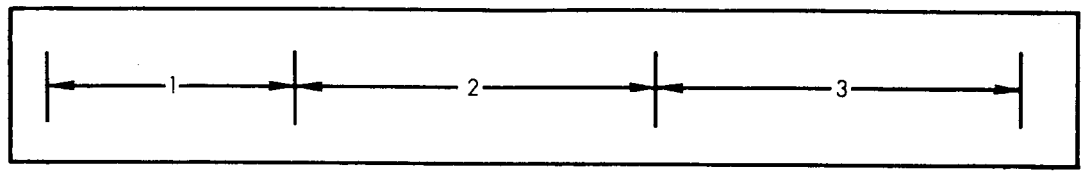


NOTES:
(1) CSI IS PERFORMED 50 MIN AFTER LM PERICYNTHION.
(2) COELLIPTIC DIFFERENTIAL ALTITUDE IS 15 N MI.
(3) TPI IS PERFORMED 90 DEG WEST OF LM PERICYNTHION.

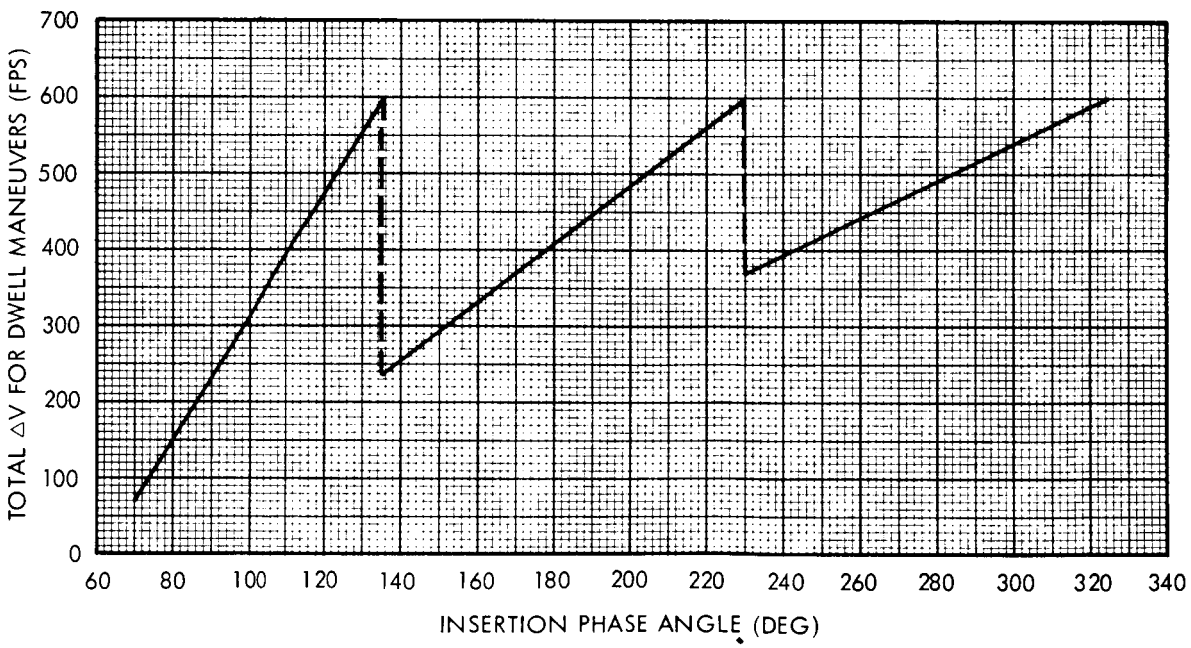
Figure 10. Input Parameters for the CSM High Apocynthion Dwell Followed by LM-Active Coelliptic Sequence



TOTAL
RENDEZVOUS
TIME (MIN)

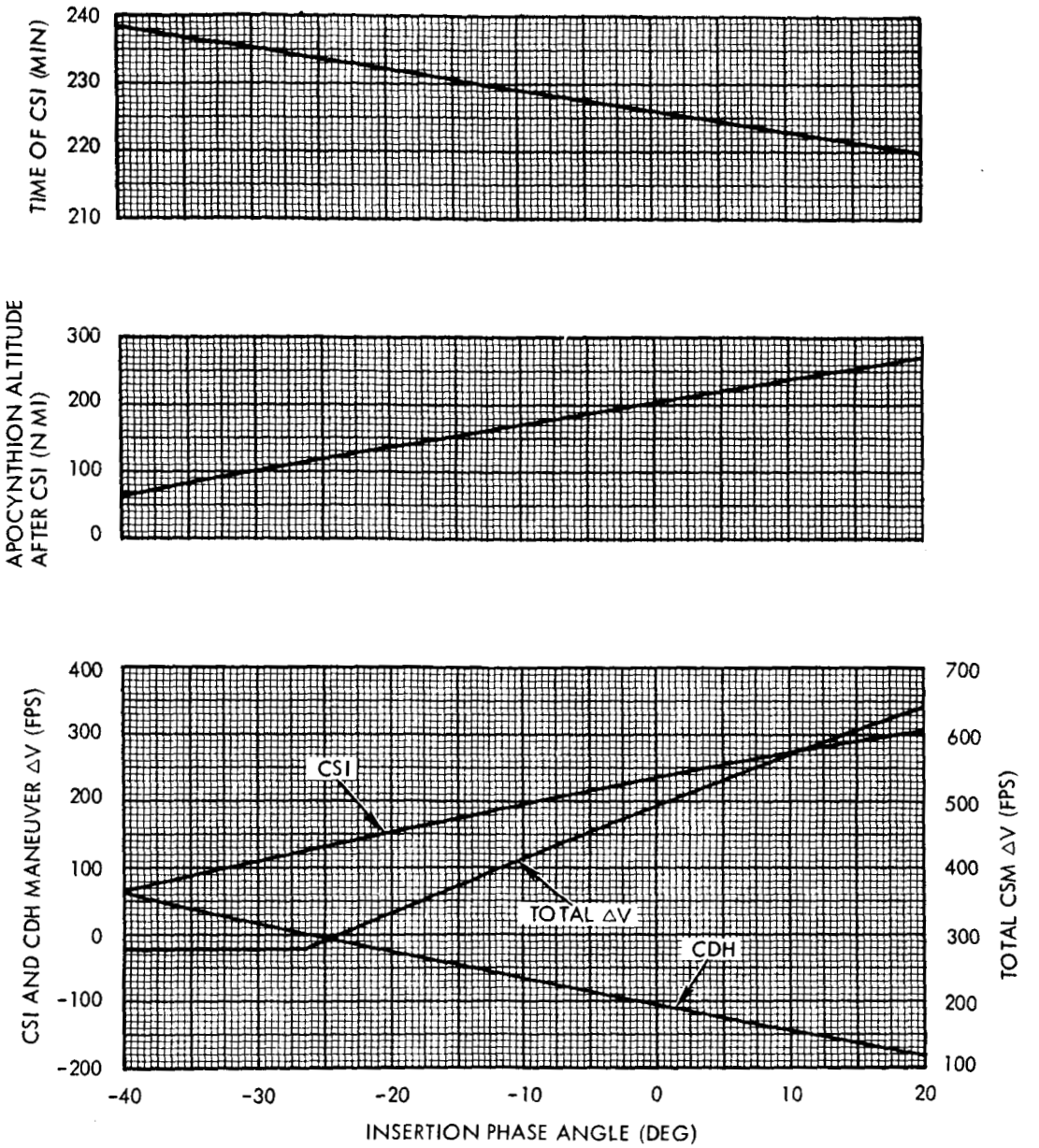


DWELL
REVOLUTIONS



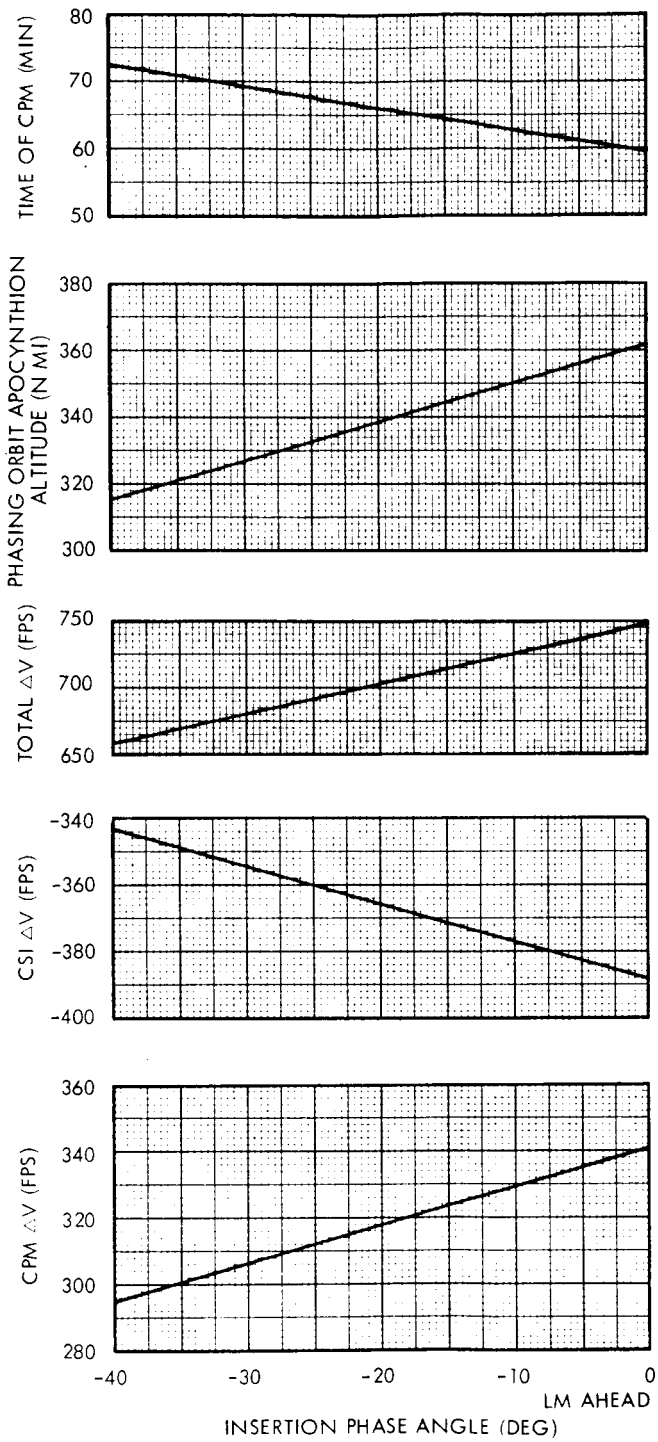
NOTES: 1) LM-ACTIVE RENDEZVOUS REQUIRES 127 FPS
2) CSM RESCUE REQUIRES 131 FPS

Figure 11. Performance and Time Requirements for the CSM High Apocynthion Dwell Followed by LM-Active Coelliptic Sequence



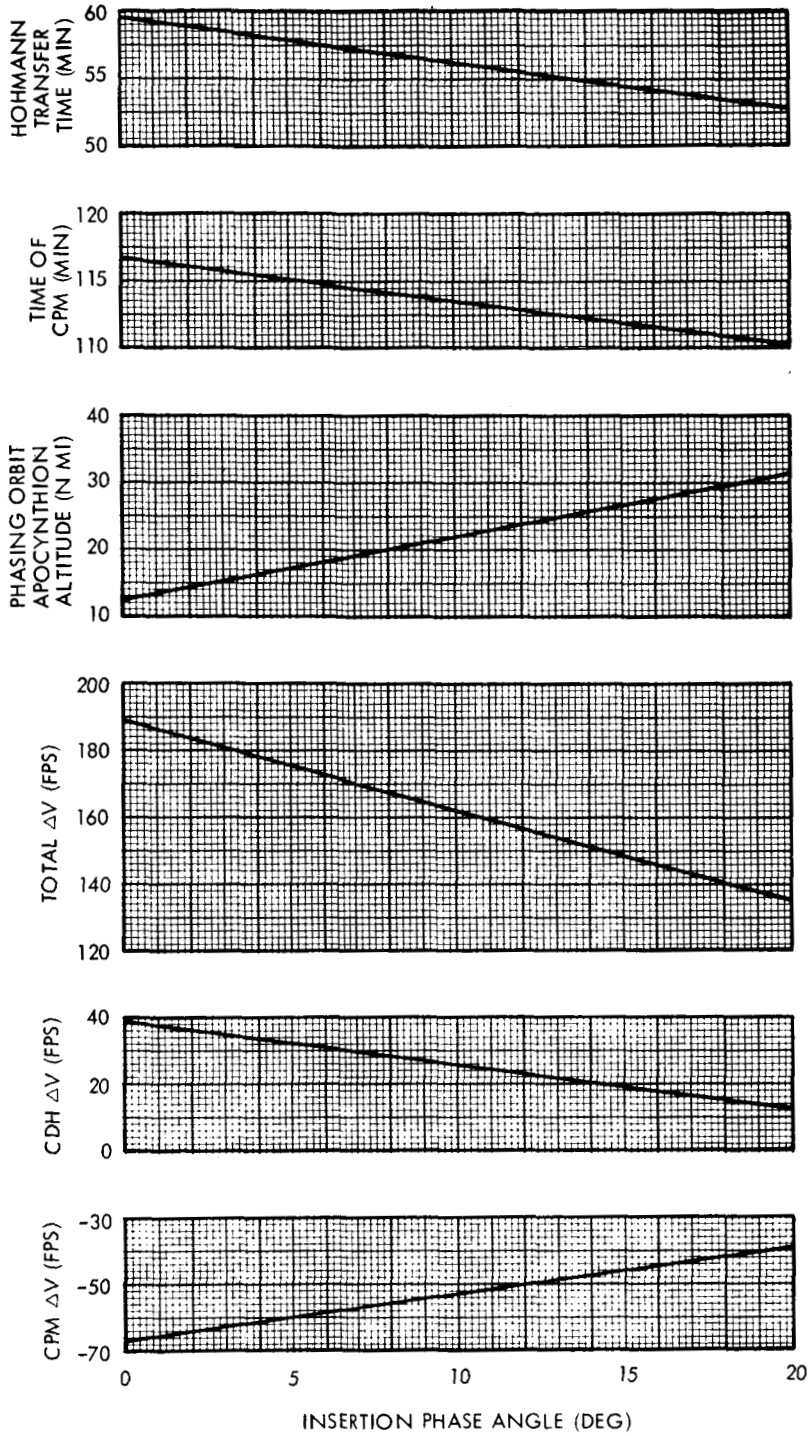
NOTES:
(1) THE LM PERFORMS A 100-FPS HORIZONTAL MANEUVER IMMEDIATELY AFTER INSERTION.
(2) THE CSM INITIATES A HOHMANN TRANSFER TO A 20-N MI CIRCULAR ORBIT 10 MIN AFTER THE LM MANEUVER.
(3) THE CSI MANEUVER IS PERFORMED AT THE SECOND PASSAGE OVER LM PERICYNTHION.
(4) THE CDH MANEUVER IS PERFORMED AT THE SECOND APSIS.
(5) THE COELLIPTIC DIFFERENTIAL ALTITUDE IS 10 N MI.
(6) THE TPI MANEUVER IS PERFORMED 383.1 MIN AFTER INSERTION.

Figure 12. Input Parameters and Performance Requirements for CSM-Active Rendezvous Following a Planned LM Thrust at Insertion



NOTES:
1) CSI OCCURS 500 MIN AFTER LM INSERTION
2) TPI OCCURS 587 MIN AFTER LM INSERTION
3) TOTAL RENDEZVOUS TIME IS 677 MIN
4) CDH ΔV = -20 FPS
5) Δh = 15 N MI

Figure 13. Input Parameters and Performance Requirements for the CSM-Active Five Impulse Extended Coelliptic Sequence



NOTES:
1) CSM HOHMANN TRANSFER ORBIT IS 60 N MI/10 N MI
2) HOHMANN TRANSFER ΔV = -69 FPS
3) CSI OCCURS 502 MIN AFTER LM INSERTION
4) CSI ΔV = 14 FPS
5) TPI OCCURS 586 MIN AFTER LM INSERTION
6) TOTAL RENDEZVOUS TIME IS 677 MIN
7) Δh = 10 N MI

Figure 14. Input Parameters and Performance Requirements for the CSM-Active Six Impulse Extended Coelliptic Sequence

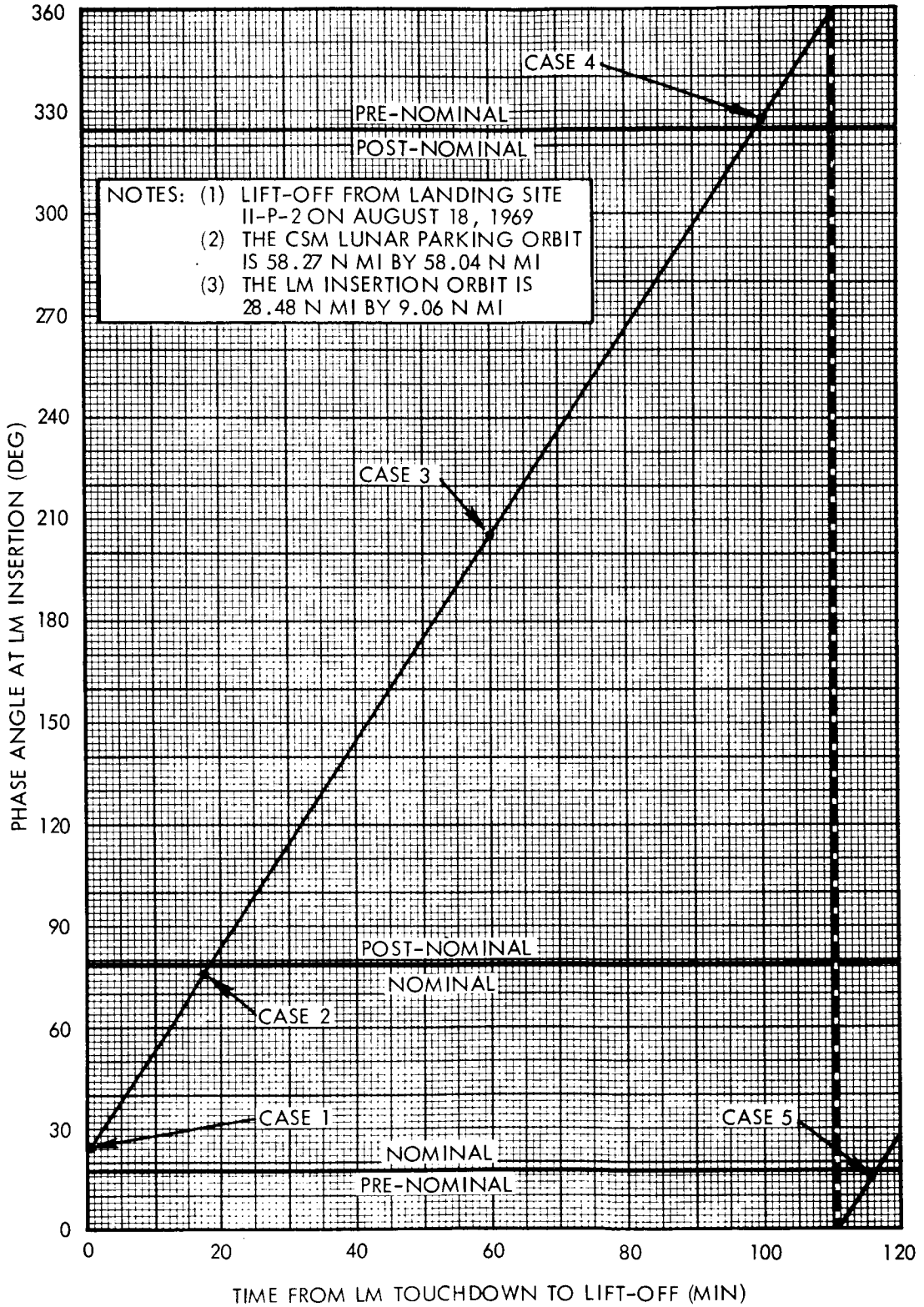


Figure 15. Insertion Phase Angle as a Function of Lift-off Time

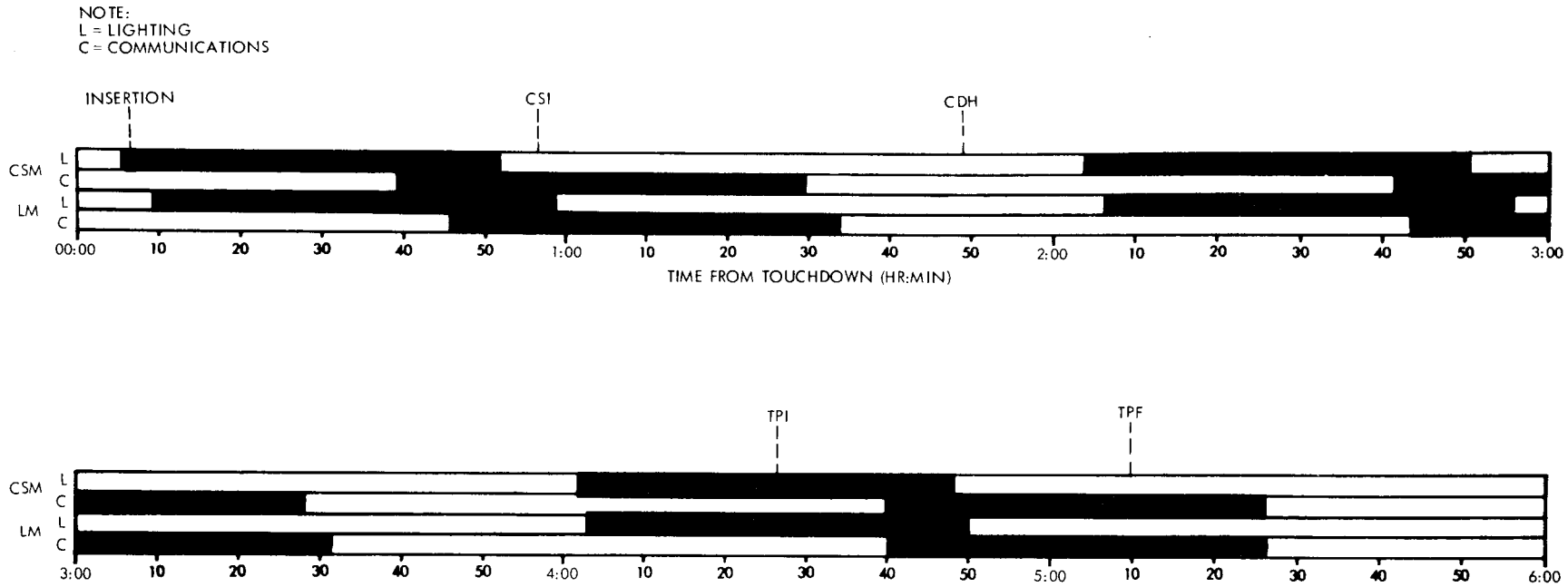


Figure 16. Timeline for Rendezvous Following Lift-off at Touchdown

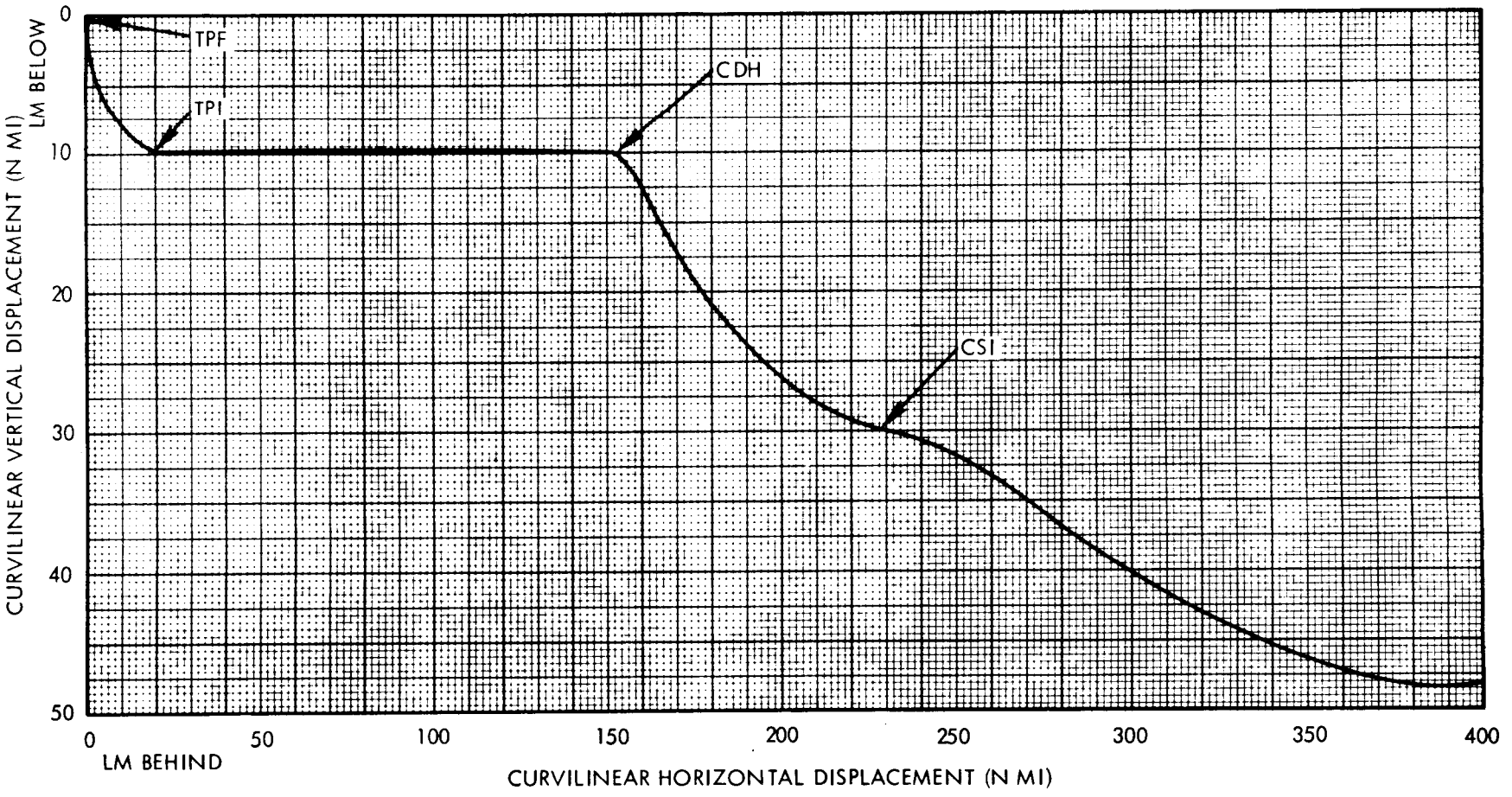


Figure 17. Relative Motion (Curvilinear, CSM-Centered) During Rendezvous Following Lift-off at LM Touchdown

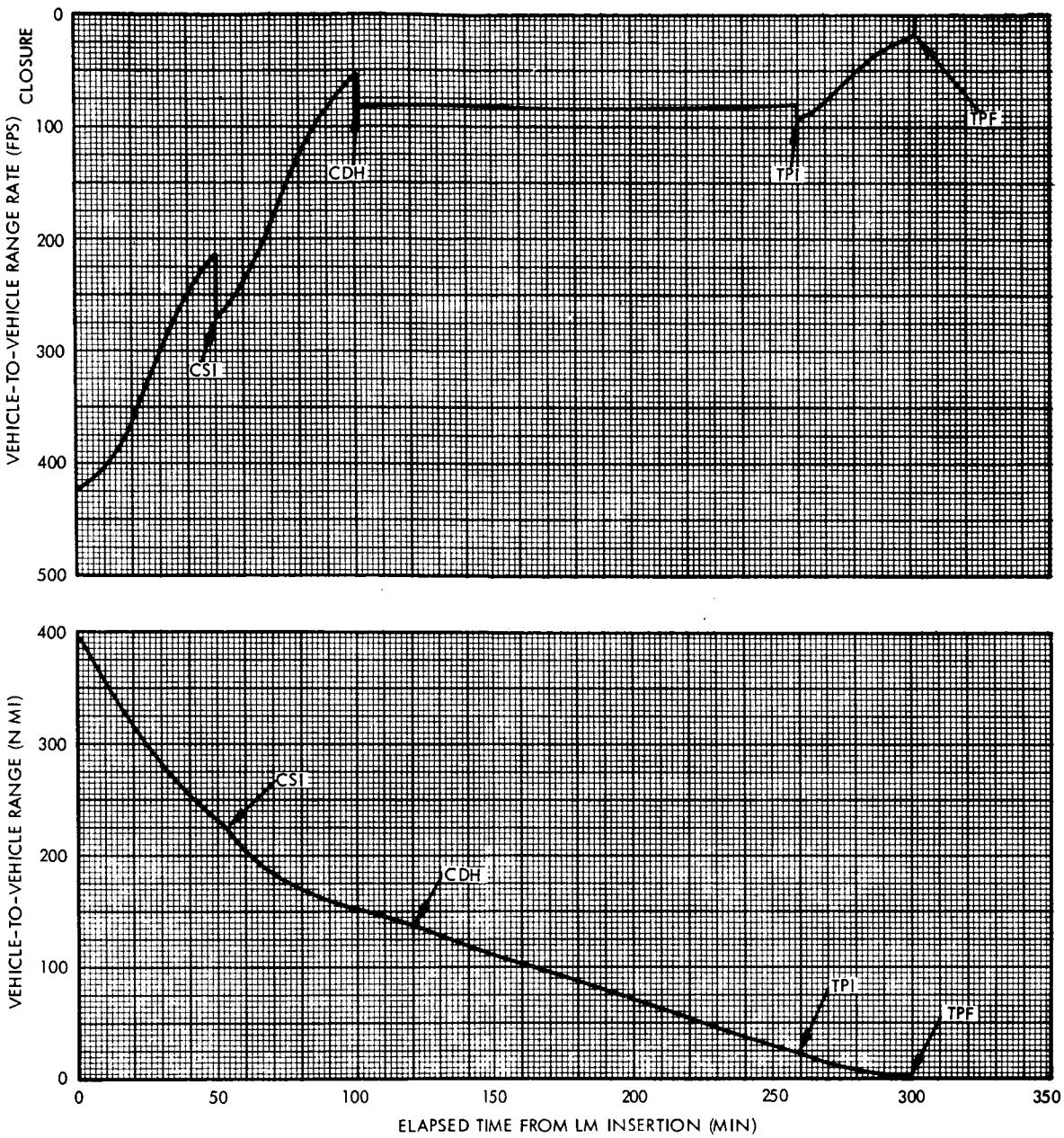


Figure 18. Range and Range Rate During Rendezvous Following Lift-off at LM Touchdown

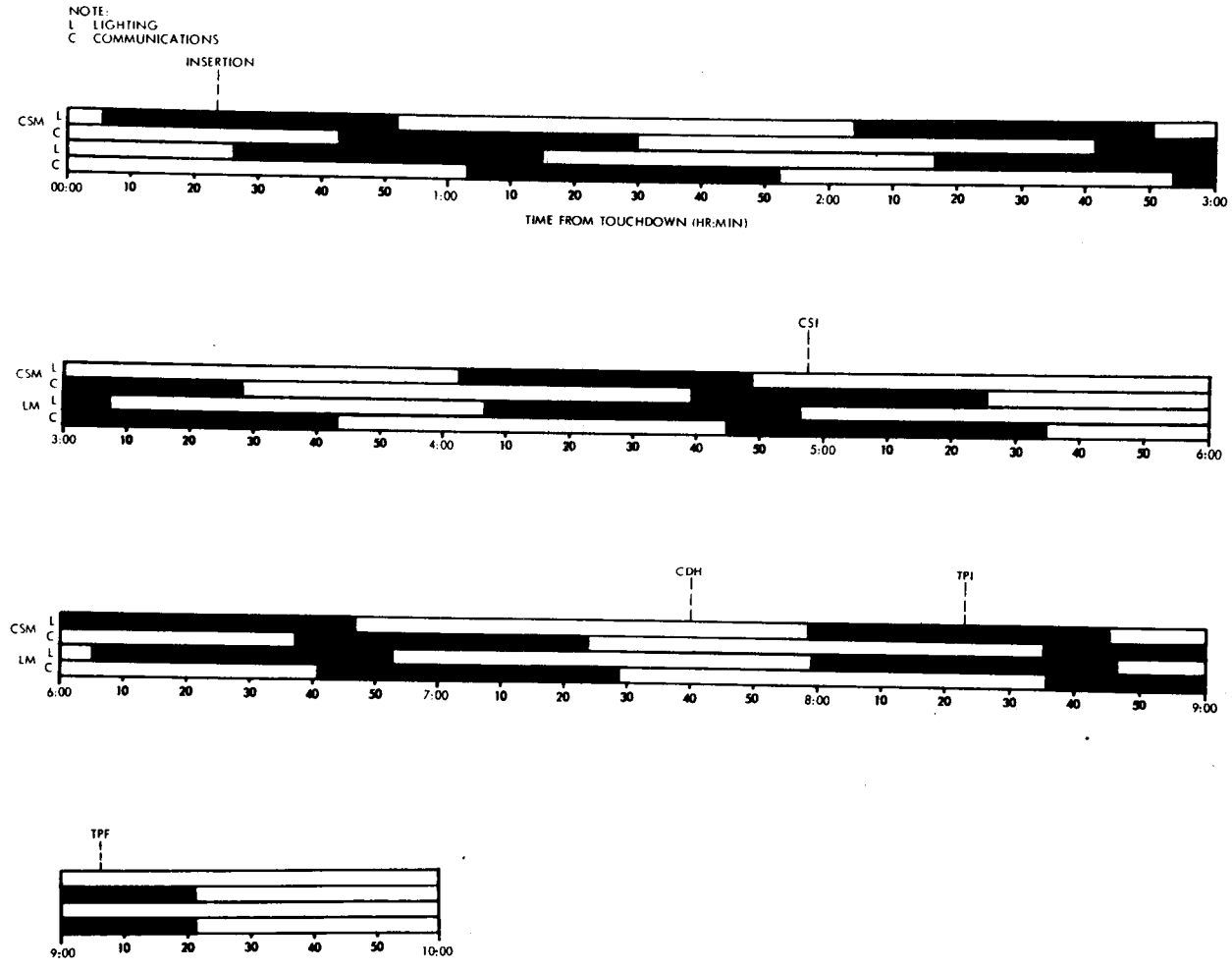


Figure 19. Timeline for Rendezvous Following Lift-off 17 Minutes after LM Touchdown

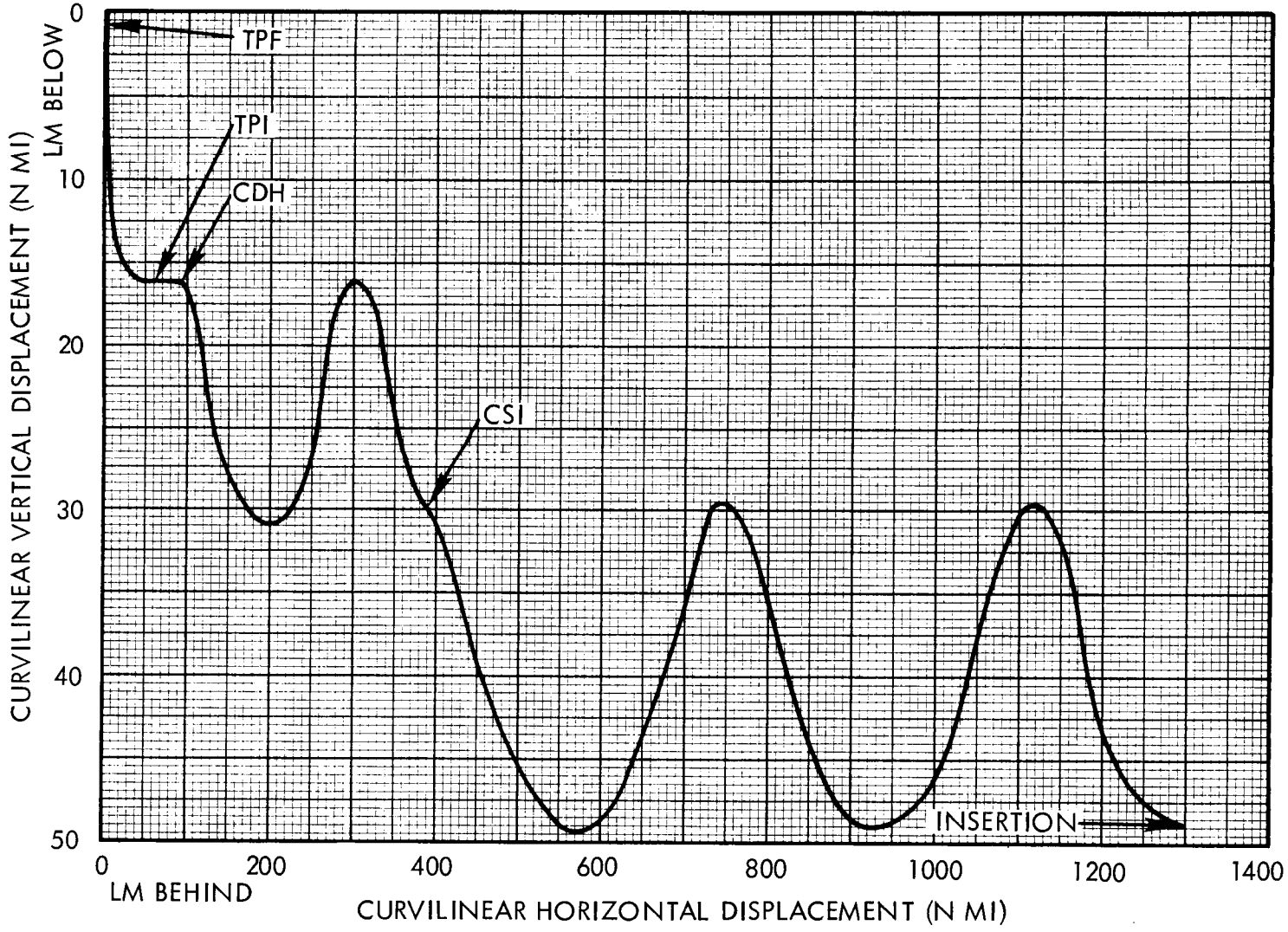


Figure 20. Relative Motion (Curvilinear, CSM-Centered) During Rendezvous Following Lift-off 17 Minutes After LM Touchdown

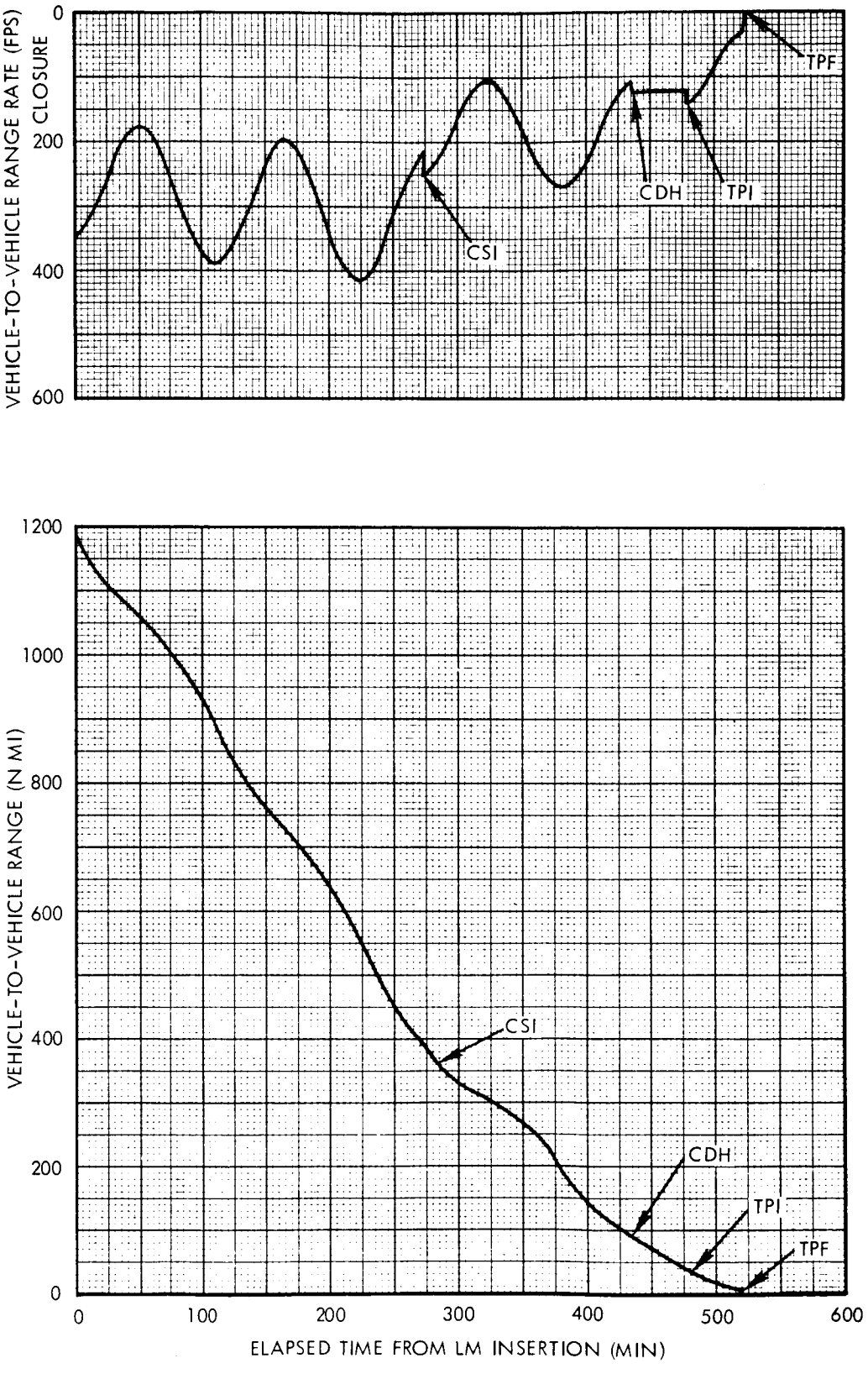


Figure 21. Range and Range Rate During Rendezvous Following Lift-off 17 Minutes After LM Touchdown

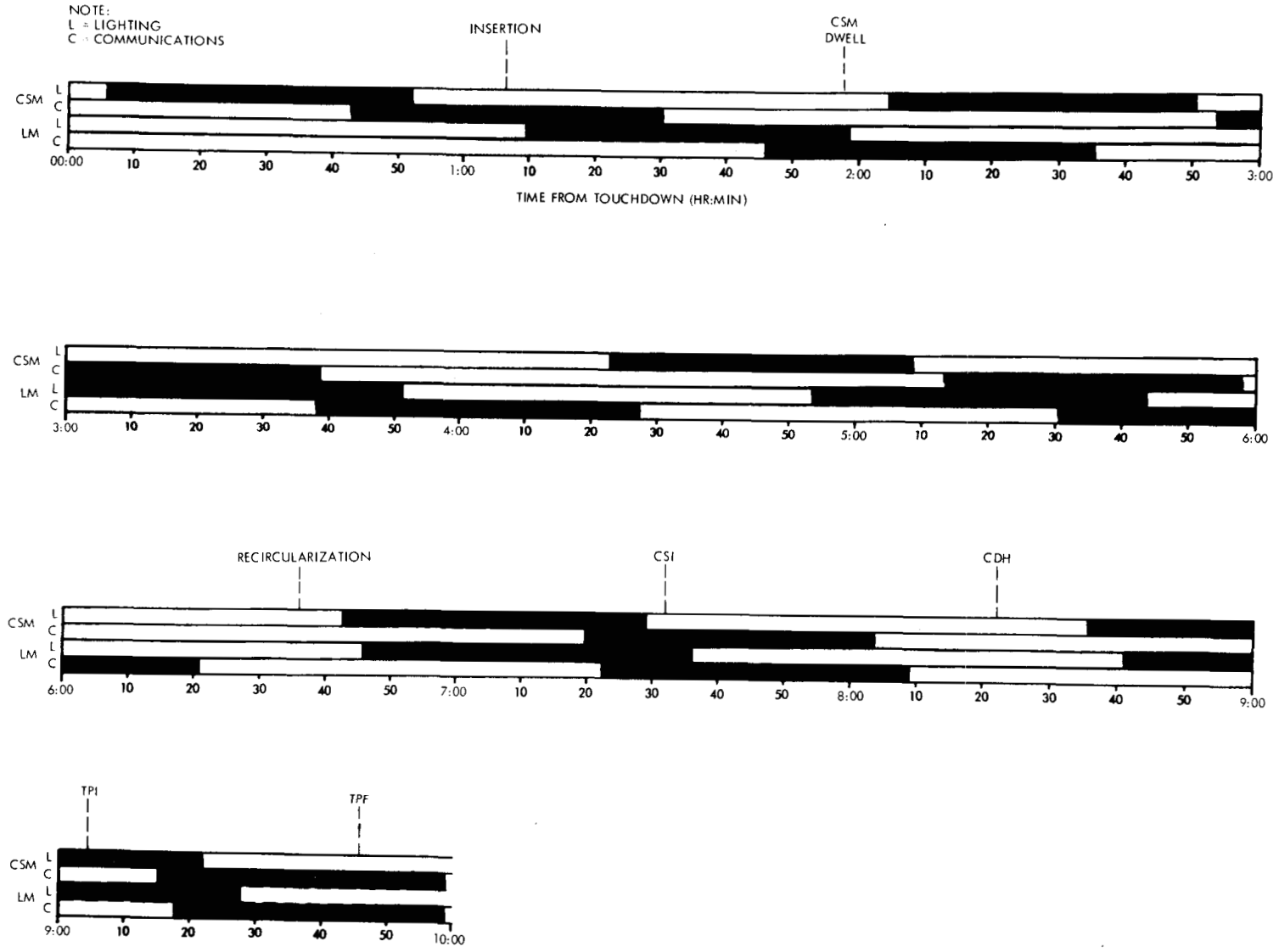


Figure 22. Timeline for Rendezvous Following Lift-off 60 Minutes after LM Touchdown

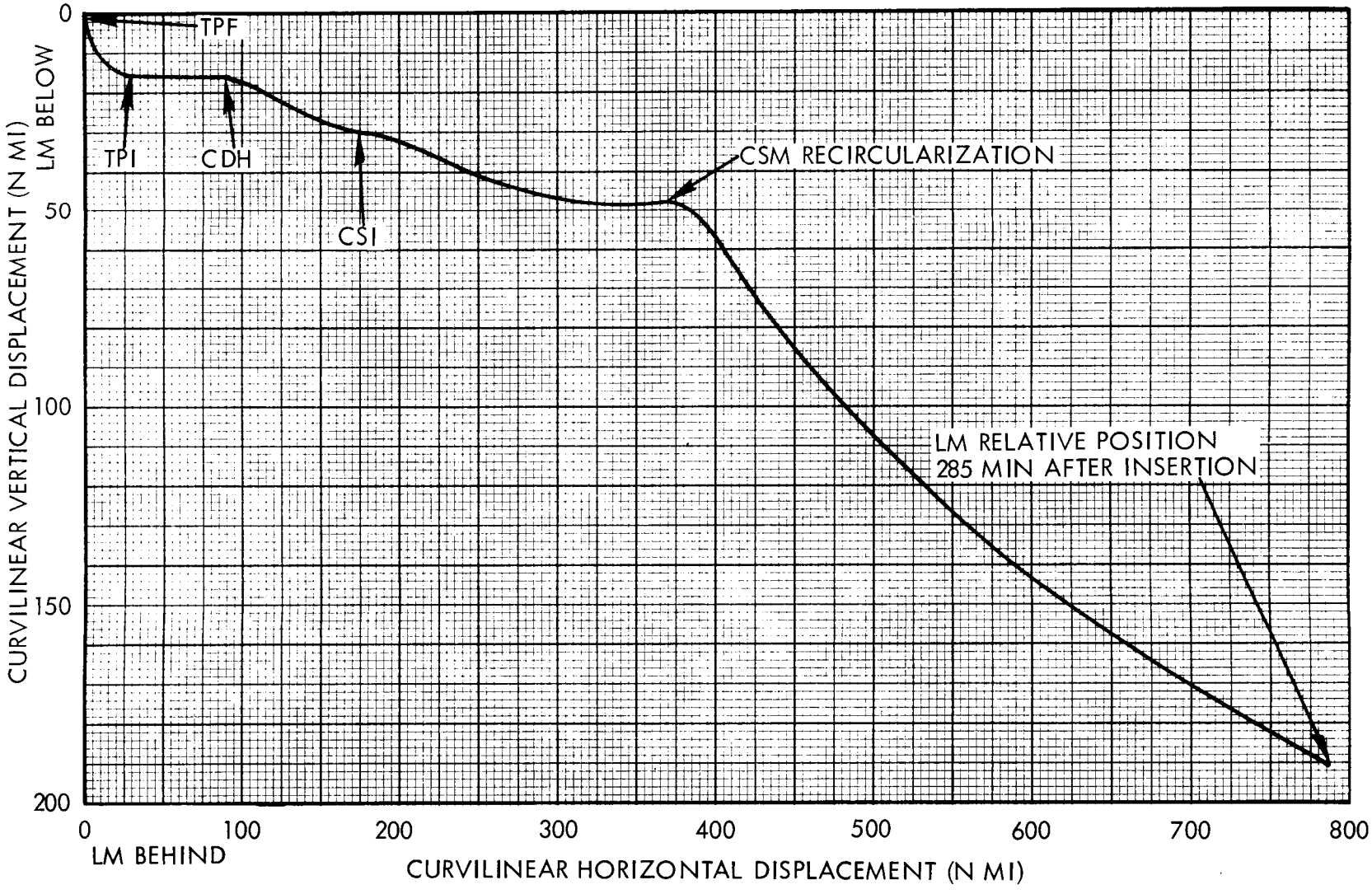


Figure 23. Relative Motion (Curvilinear, CSM-Centered) During Rendezvous Following Lift-off 60 Minutes After LM Touchdown

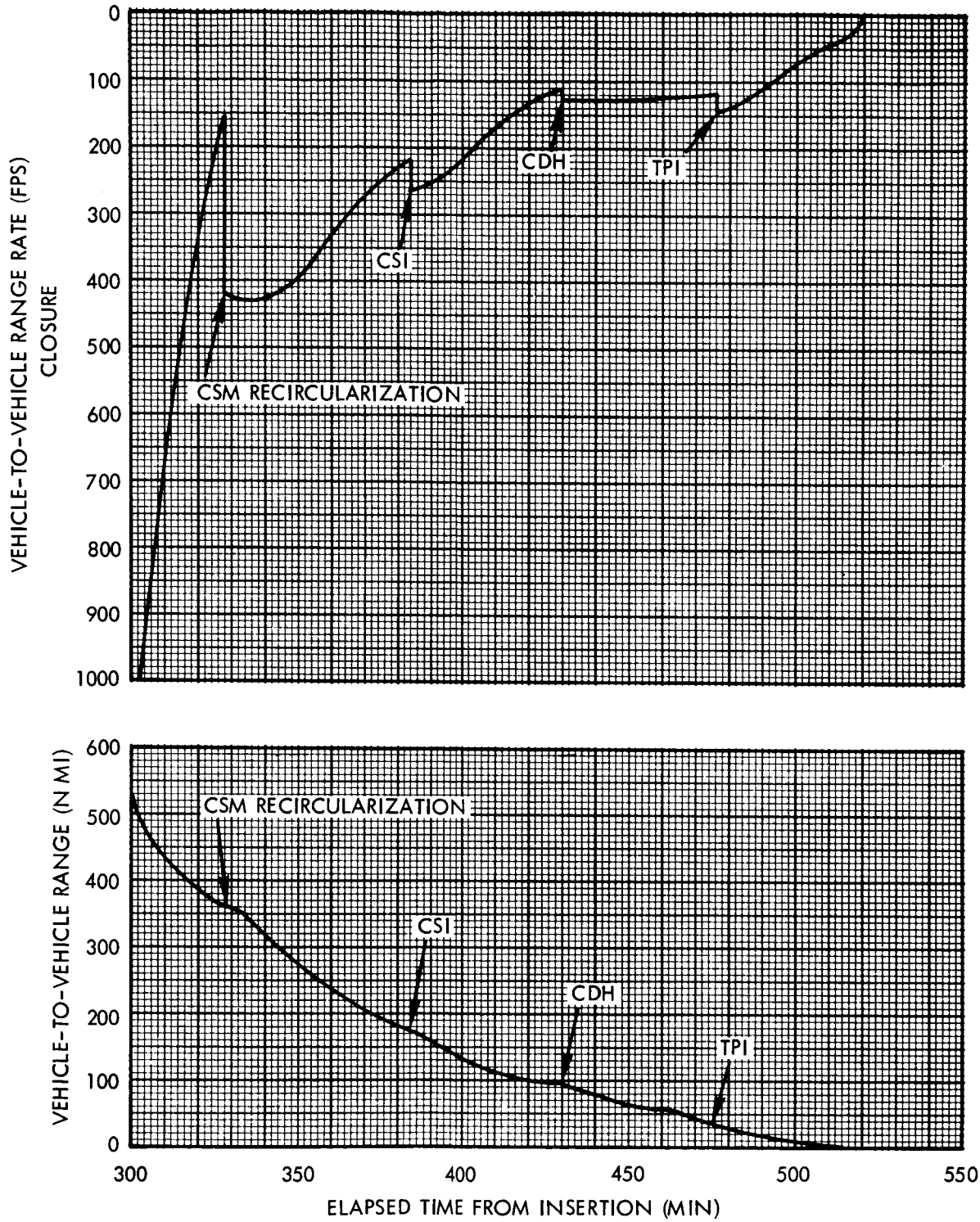


Figure 24. Range and Range Rate During Rendezvous Following Lift-off 60 Minutes After LM Touchdown

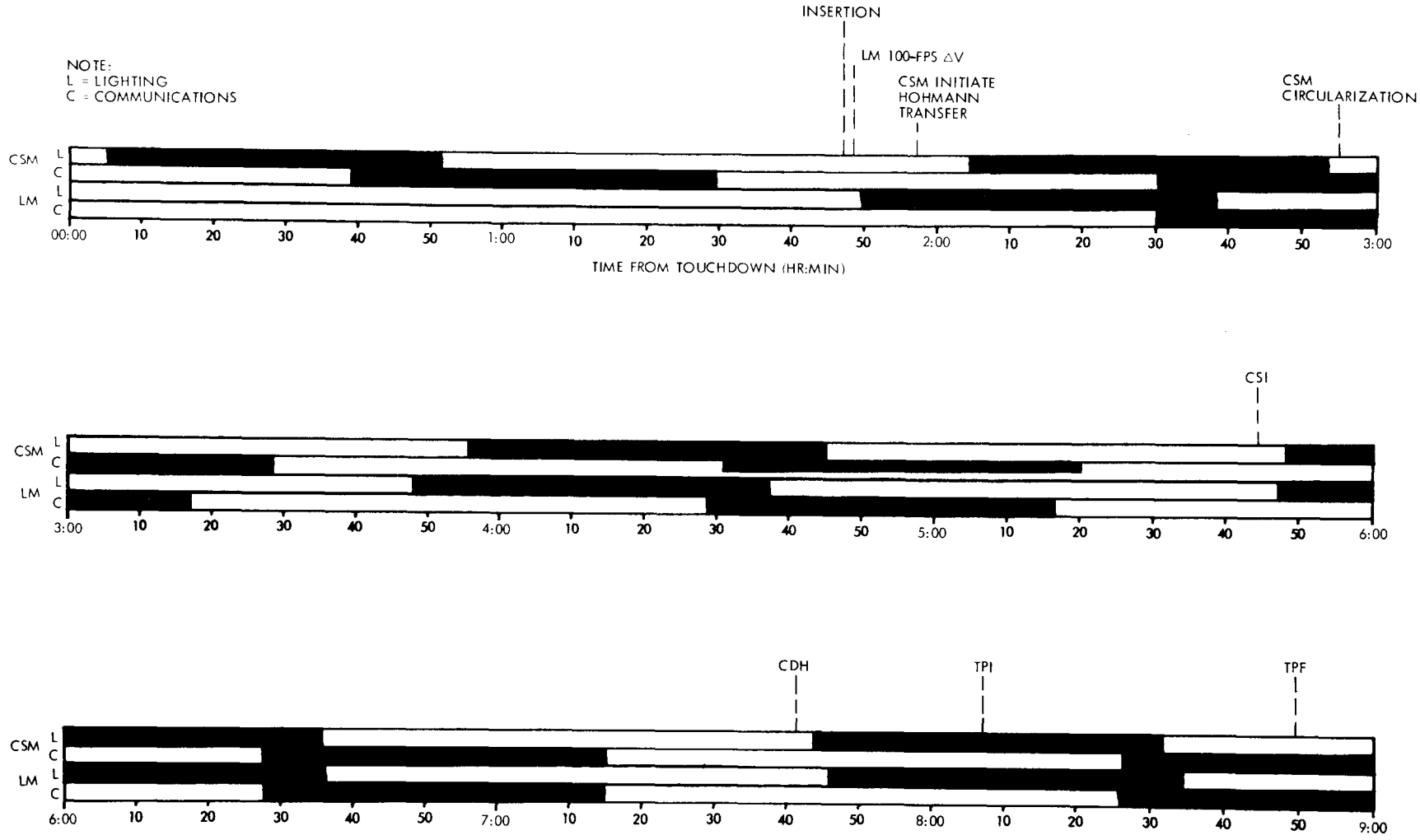


Figure 25. Timeline for Rendezvous Following Lift-off 100 Minutes after LM Touchdown

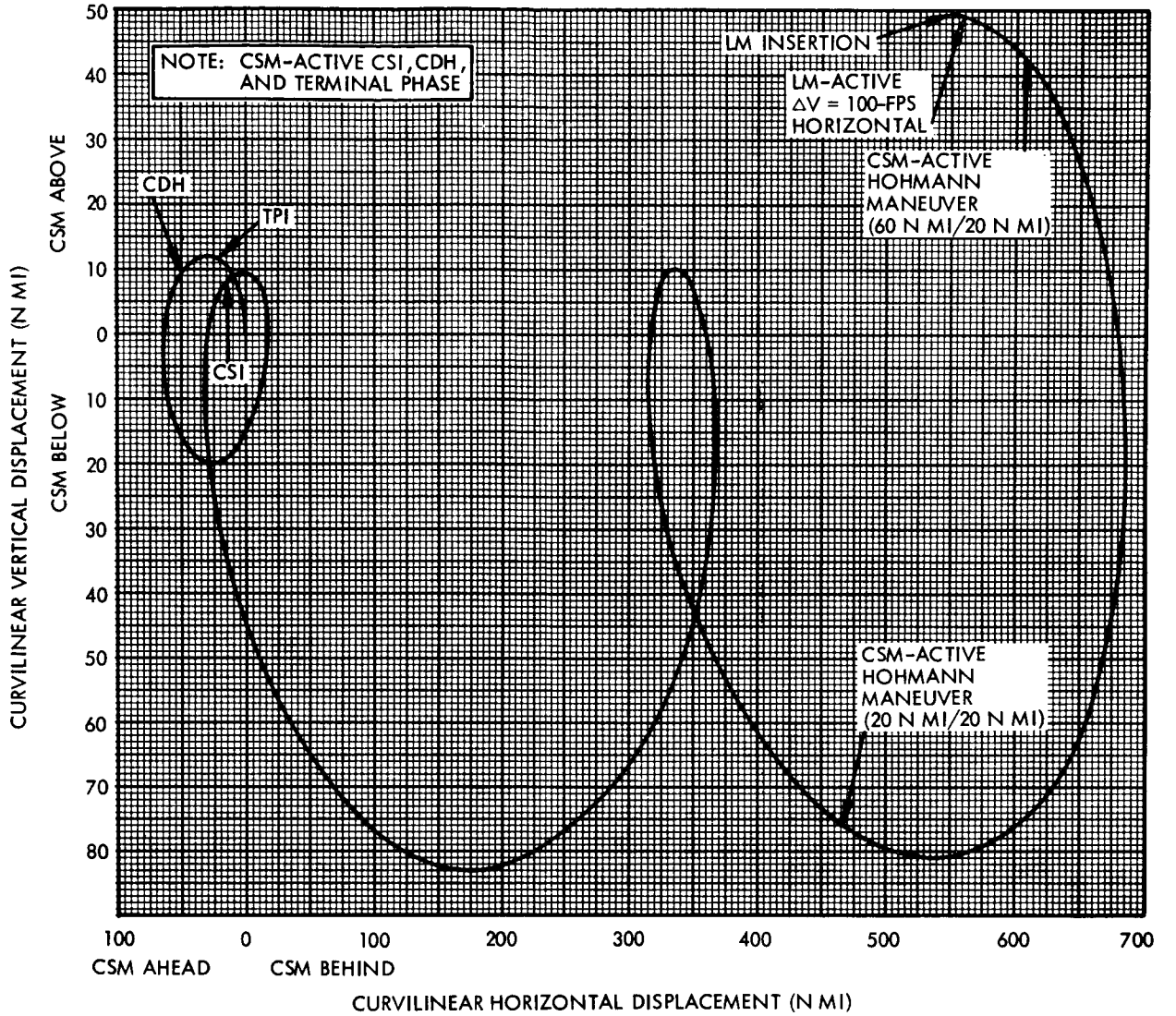


Figure 26. Relative Motion (Curvilinear, LM-Centered) During Rendezvous Following Lift-off 100 Minutes After LM Touchdown

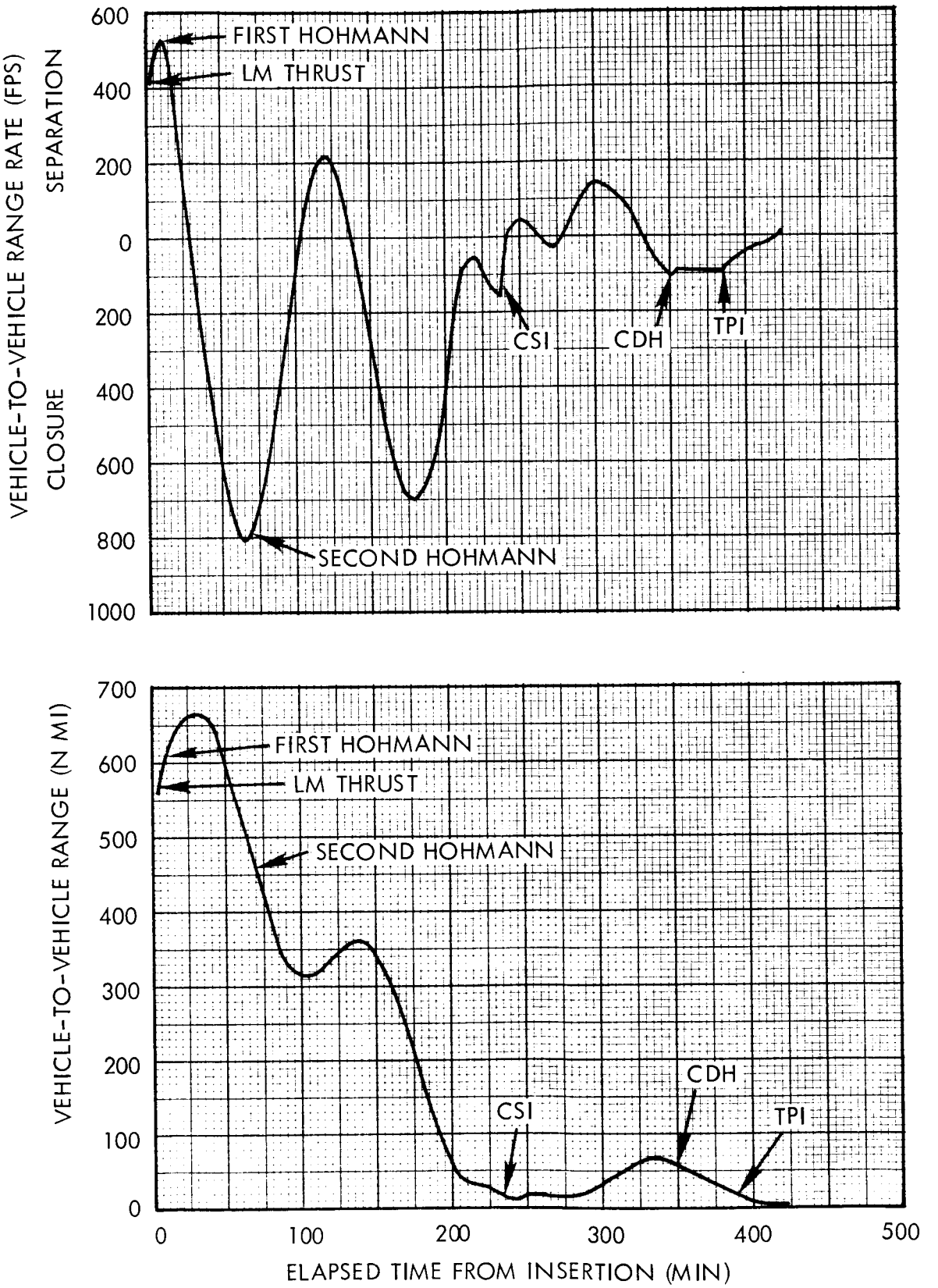


Figure 27. Range and Range Rate During Rendezvous Following Lift-off 100 Minutes After LM Touchdown

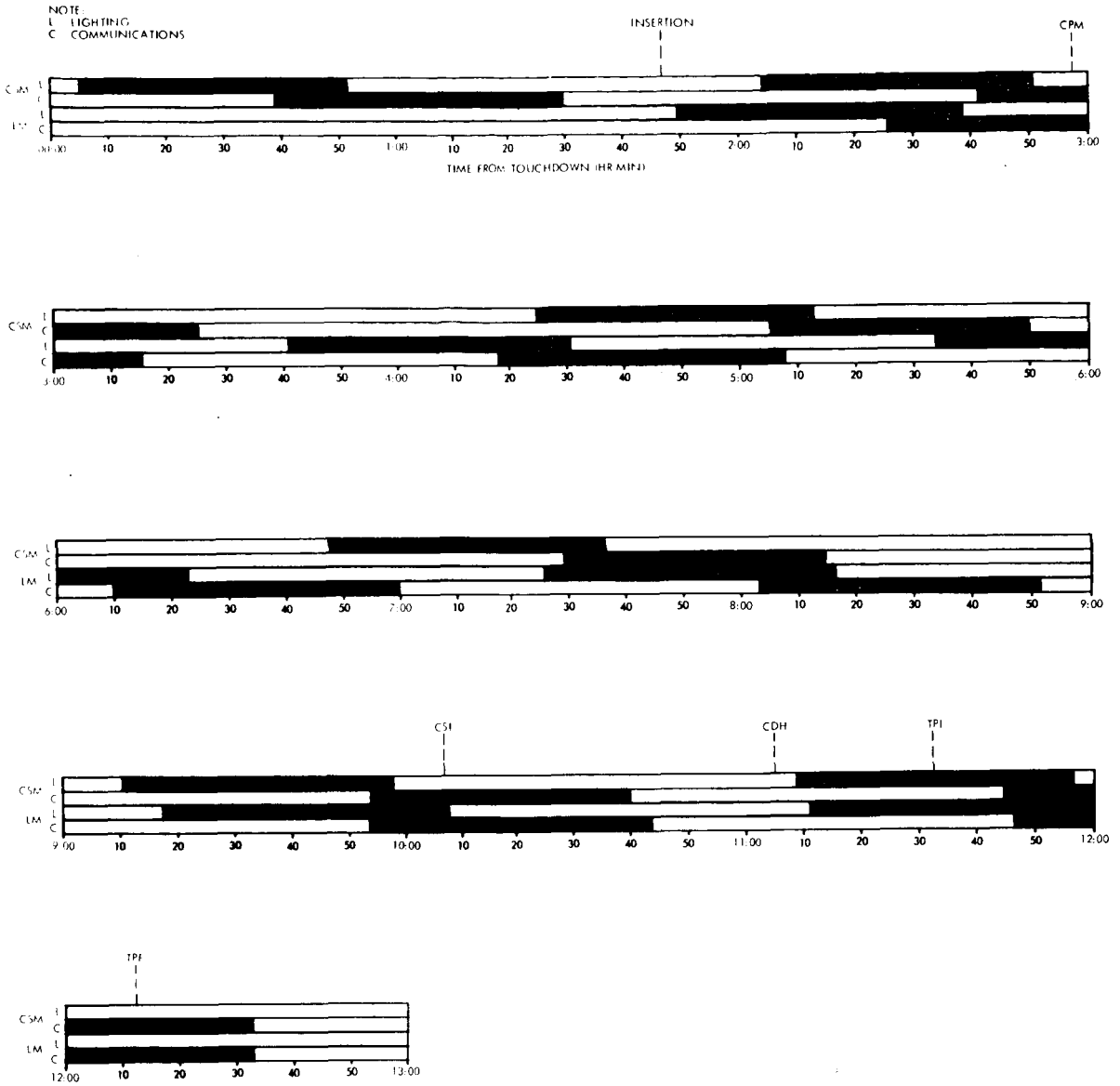


Figure 28. Timeline for CSM Rescue Following Lift-off 100 Minutes after LM Touchdown

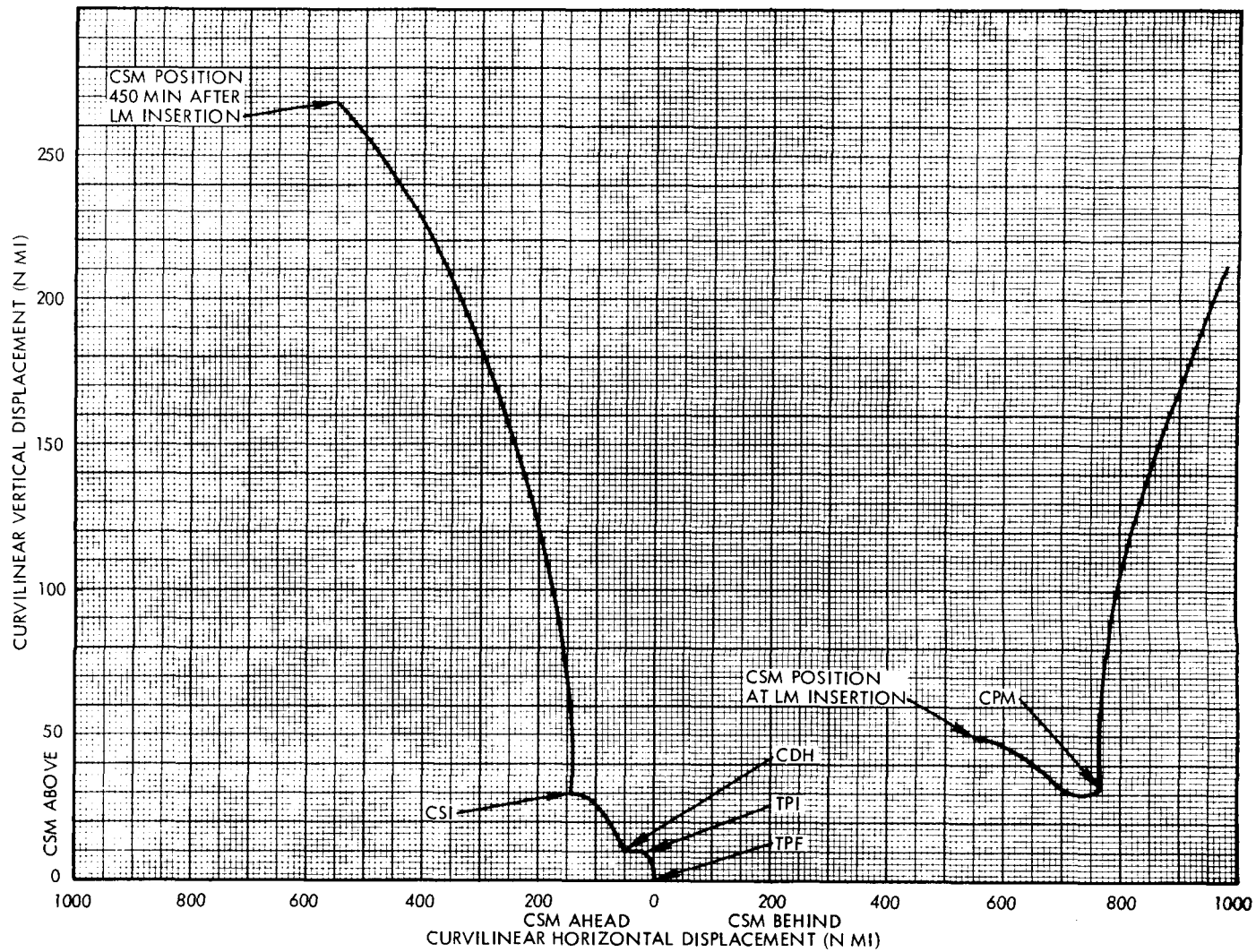


Figure 29. Relative Motion (Curvilinear, LM-Centered) During CSM Rescue Following Lift-off 100 Minutes After LM Touchdown

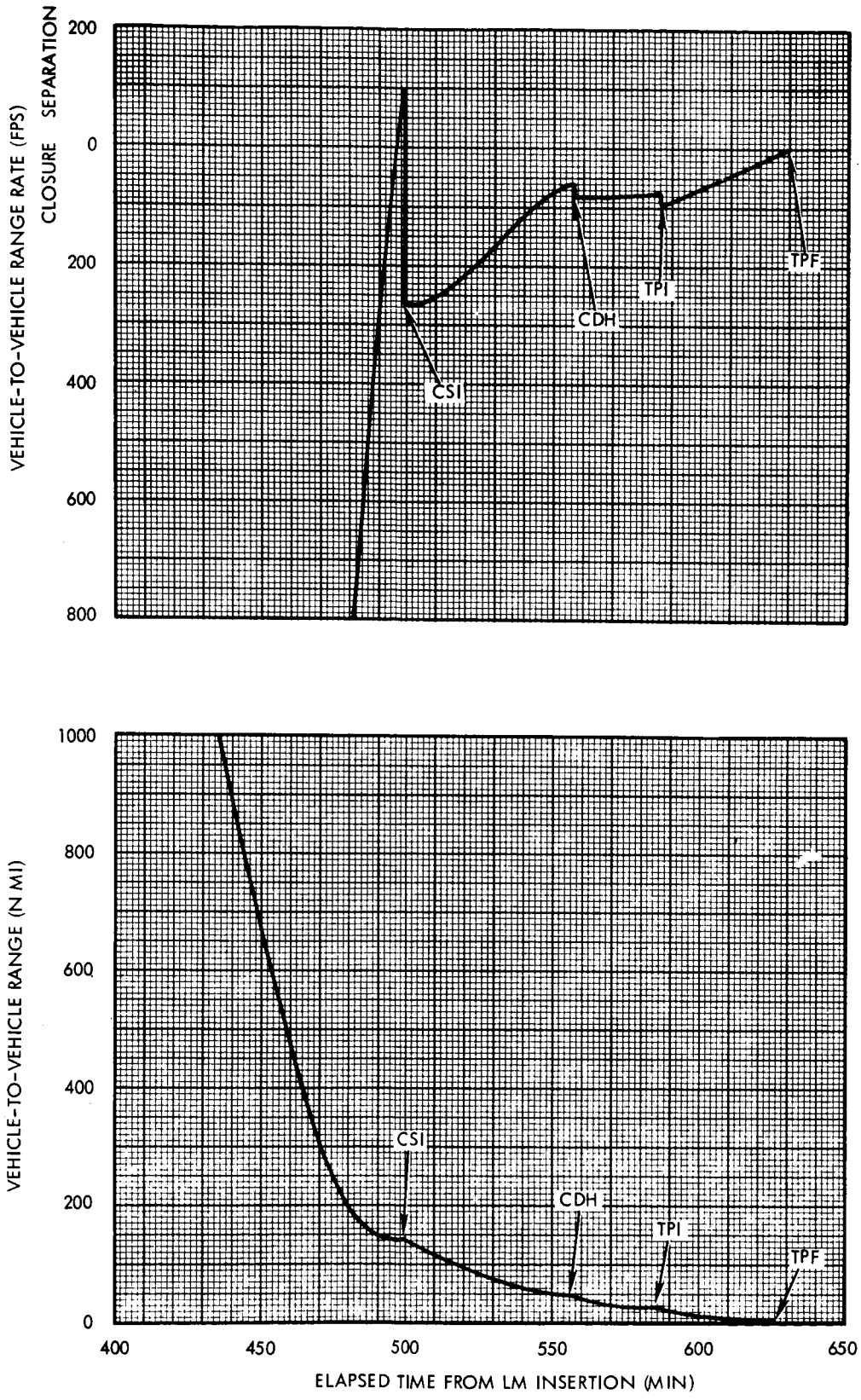


Figure 30. Range and Range Rate During CSM Rescue Following Lift-off 100 Minutes After LM Touchdown

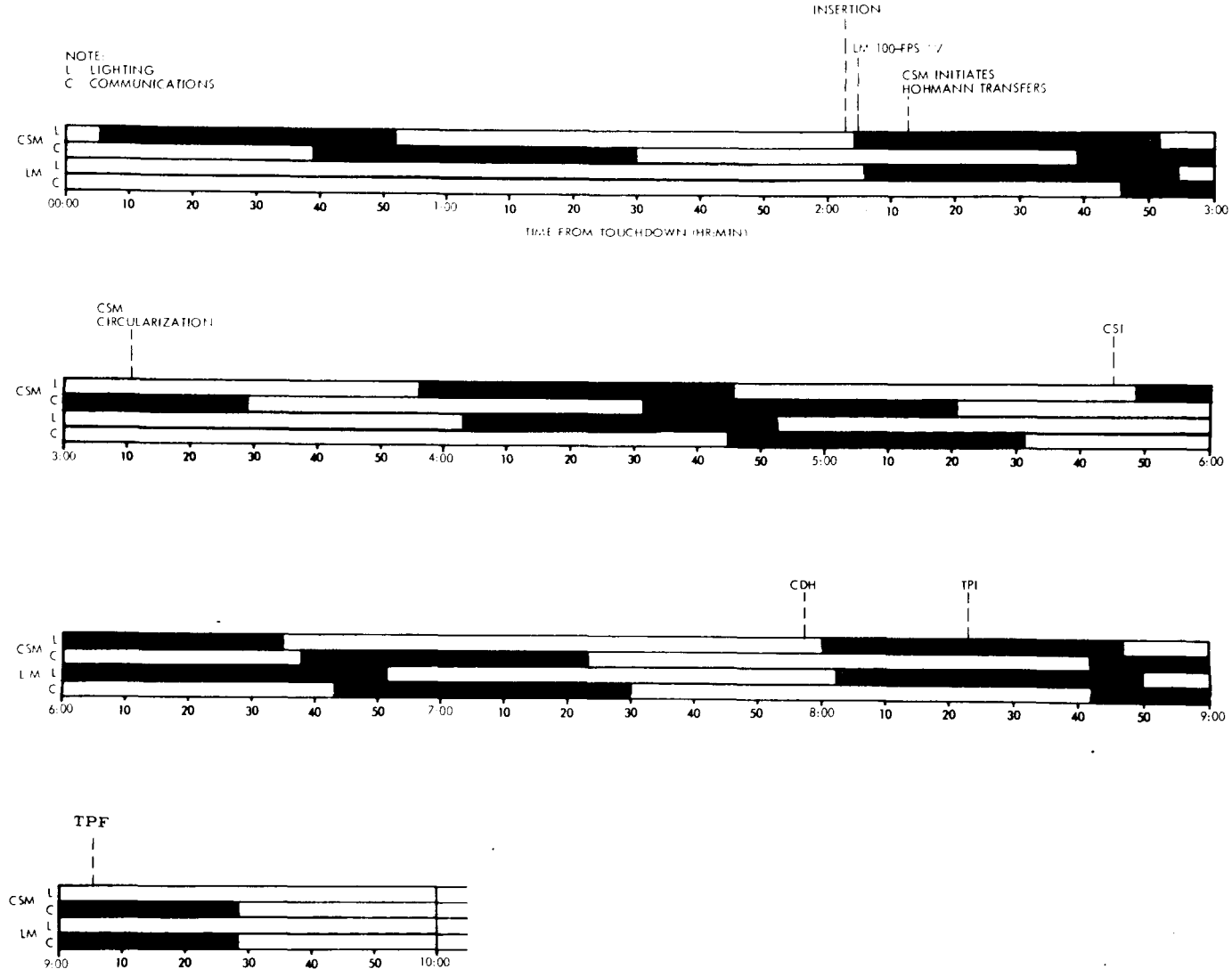


Figure 31. Timeline for Rendezvous Following Lift-off 116 Minutes after LM Touchdown

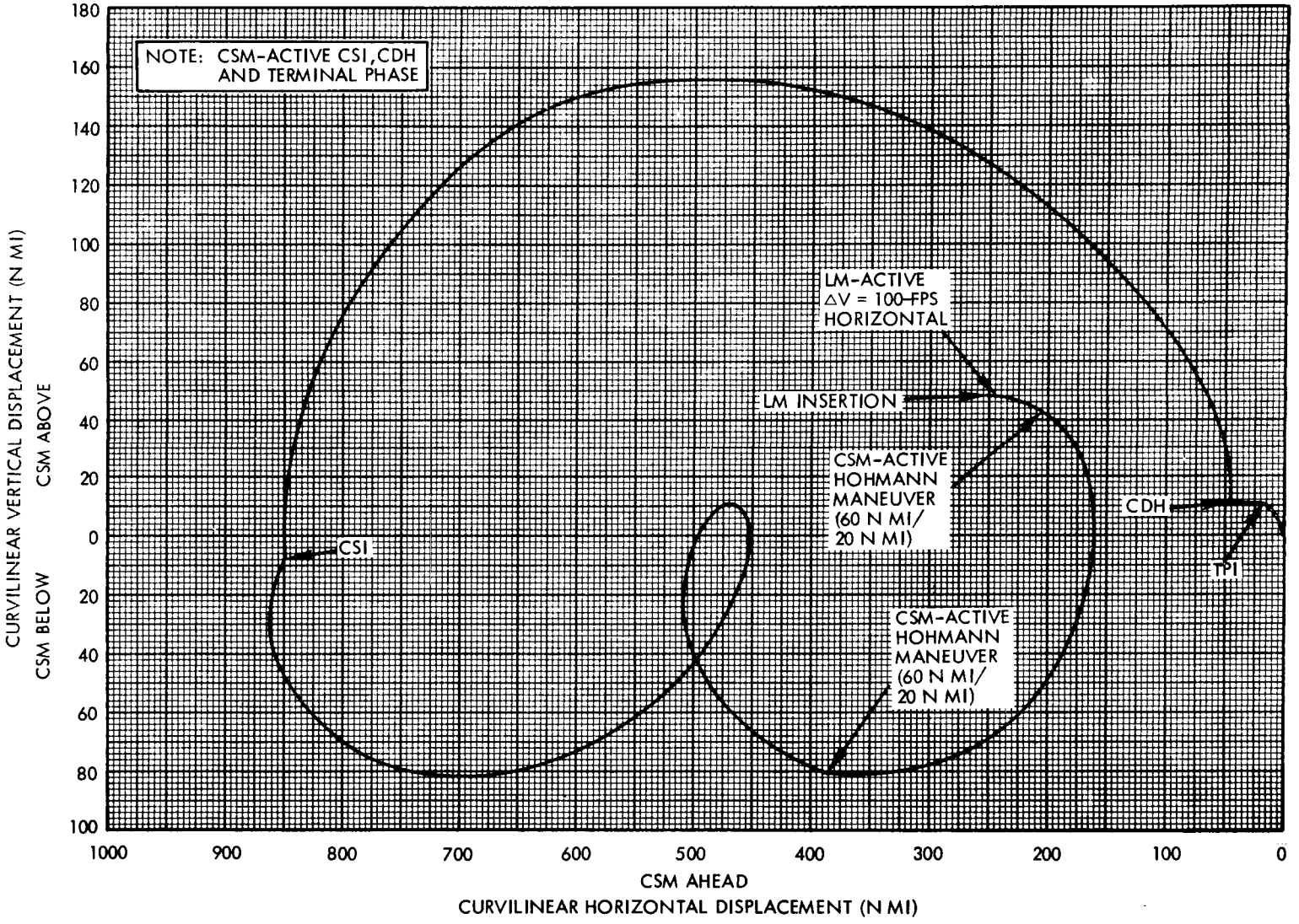


Figure 32. Relative Motion (Curvilinear, LM-Centered) During Rendezvous Following Lift-off 116 Minutes After LM Touchdown

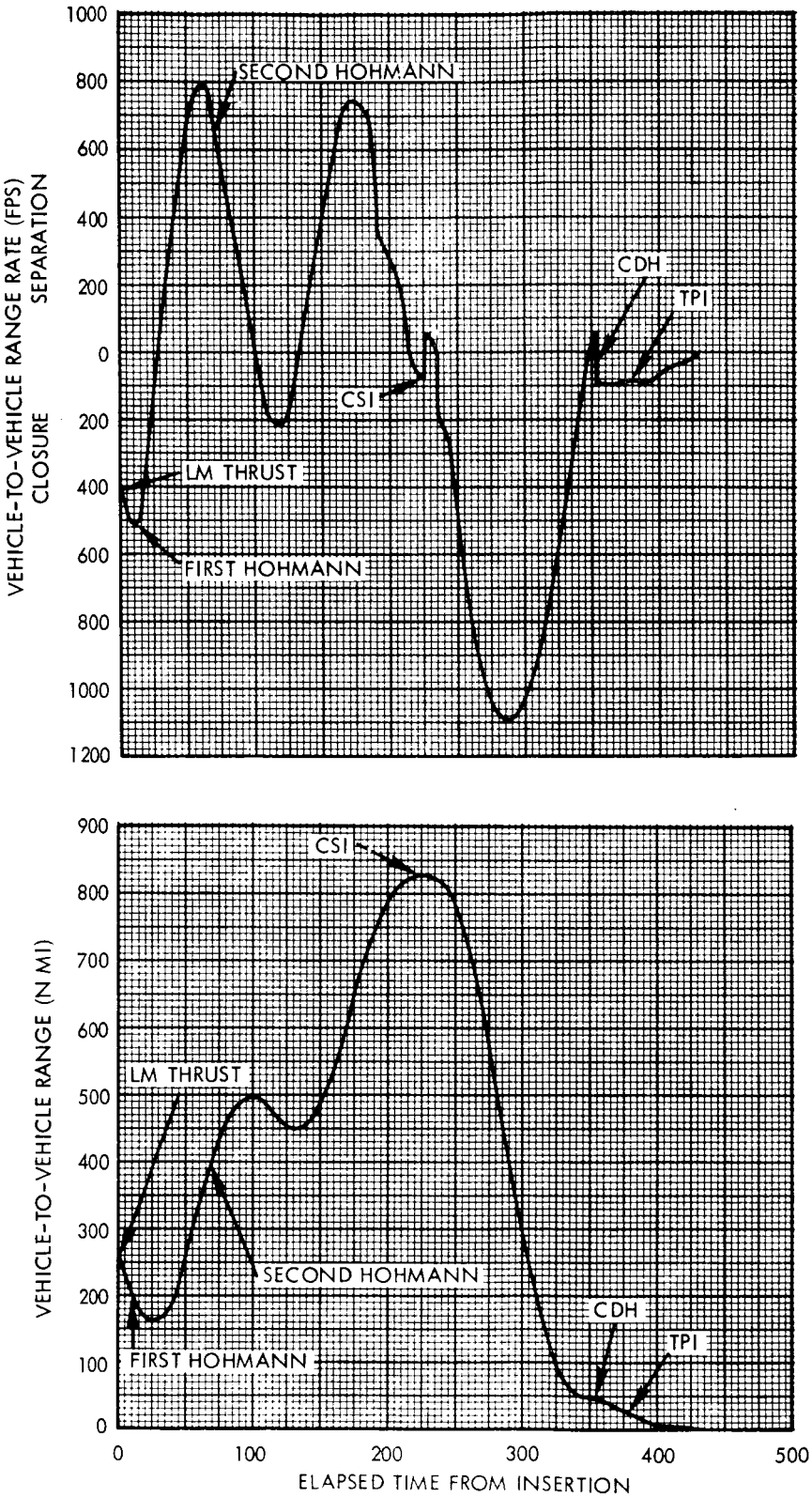


Figure 33. Range and Range Rate During Rendezvous Following Lift-off 116 Minutes After LM Touchdown

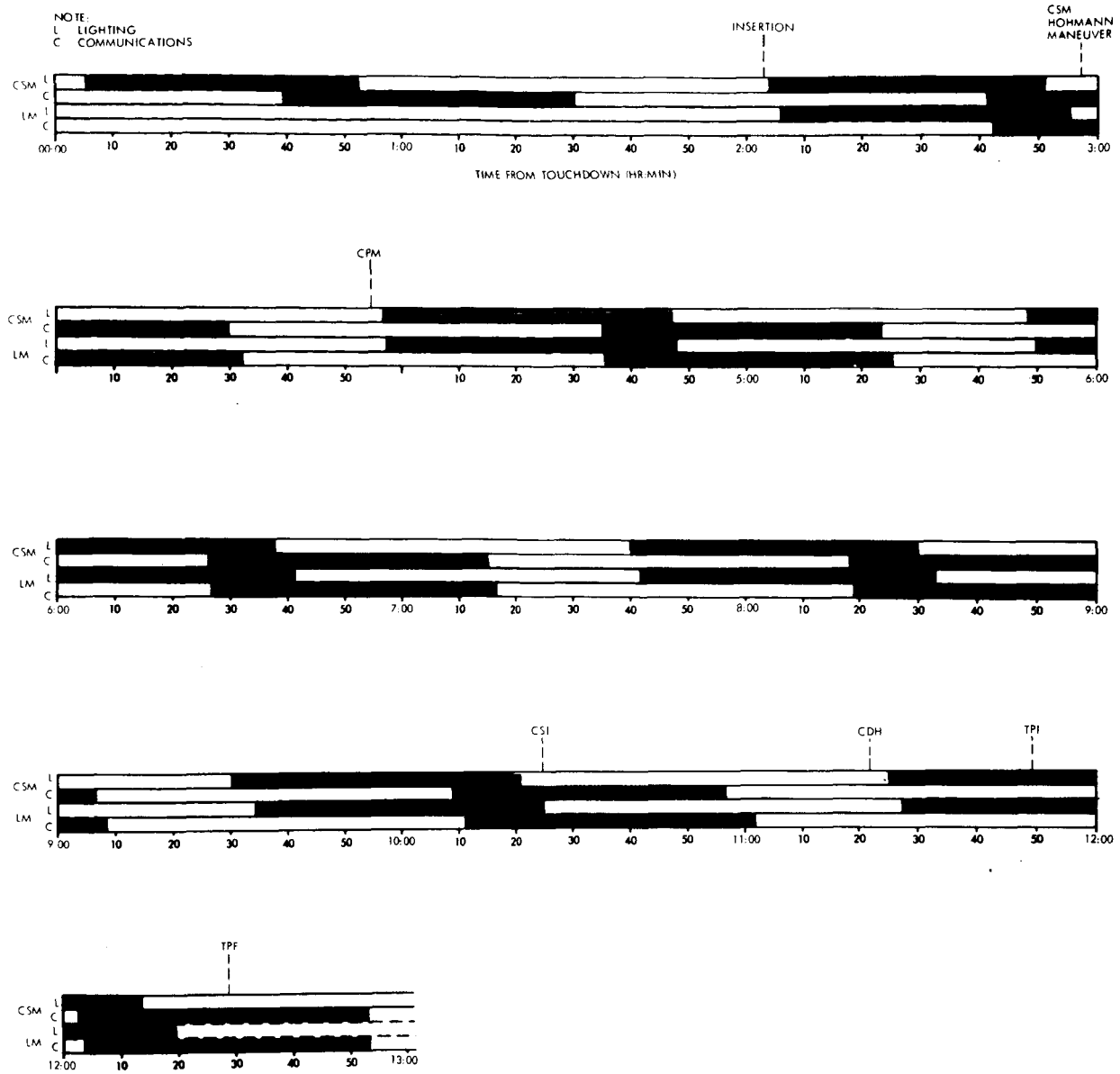


Figure 34. Timeline for CSM Rescue Following Lift-off 116 Minutes after LM Touchdown

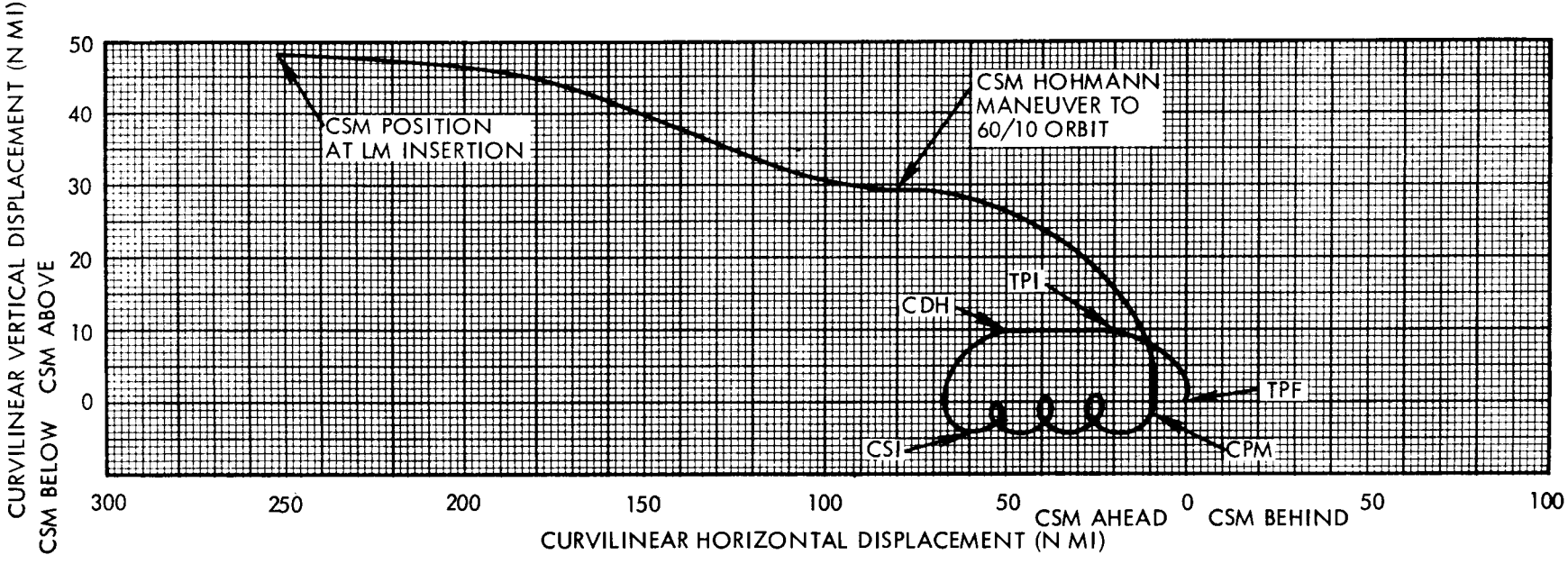


Figure 35. Relative Motion (Curvilinear, LM-Centered) During CSM Rescue Following Lift-off 116 Minutes After LM Touchdown

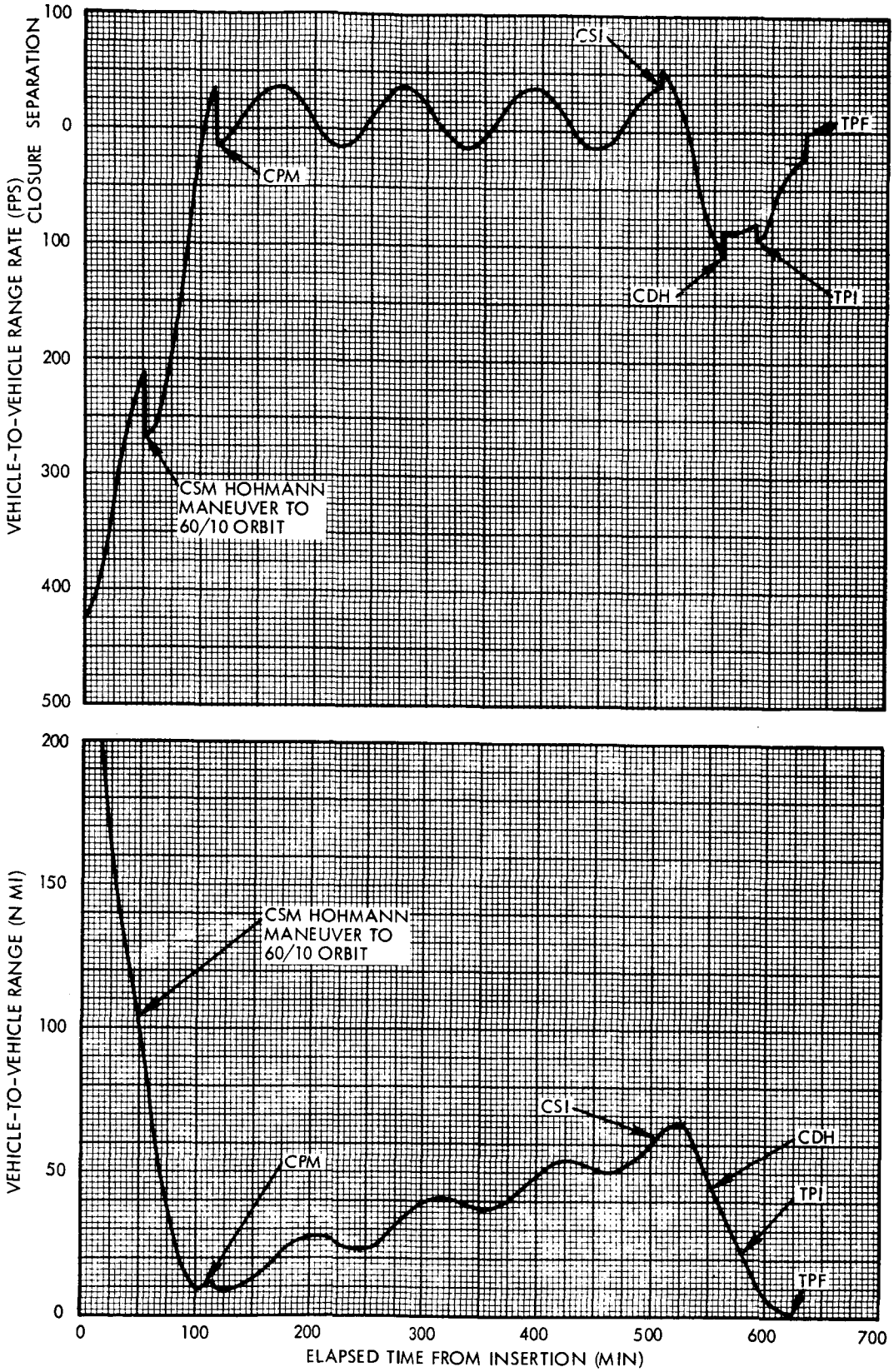


Figure 36. Range and Range Rate During CSM Rescue Following Lift-off 116 Minutes After LM Touchdown

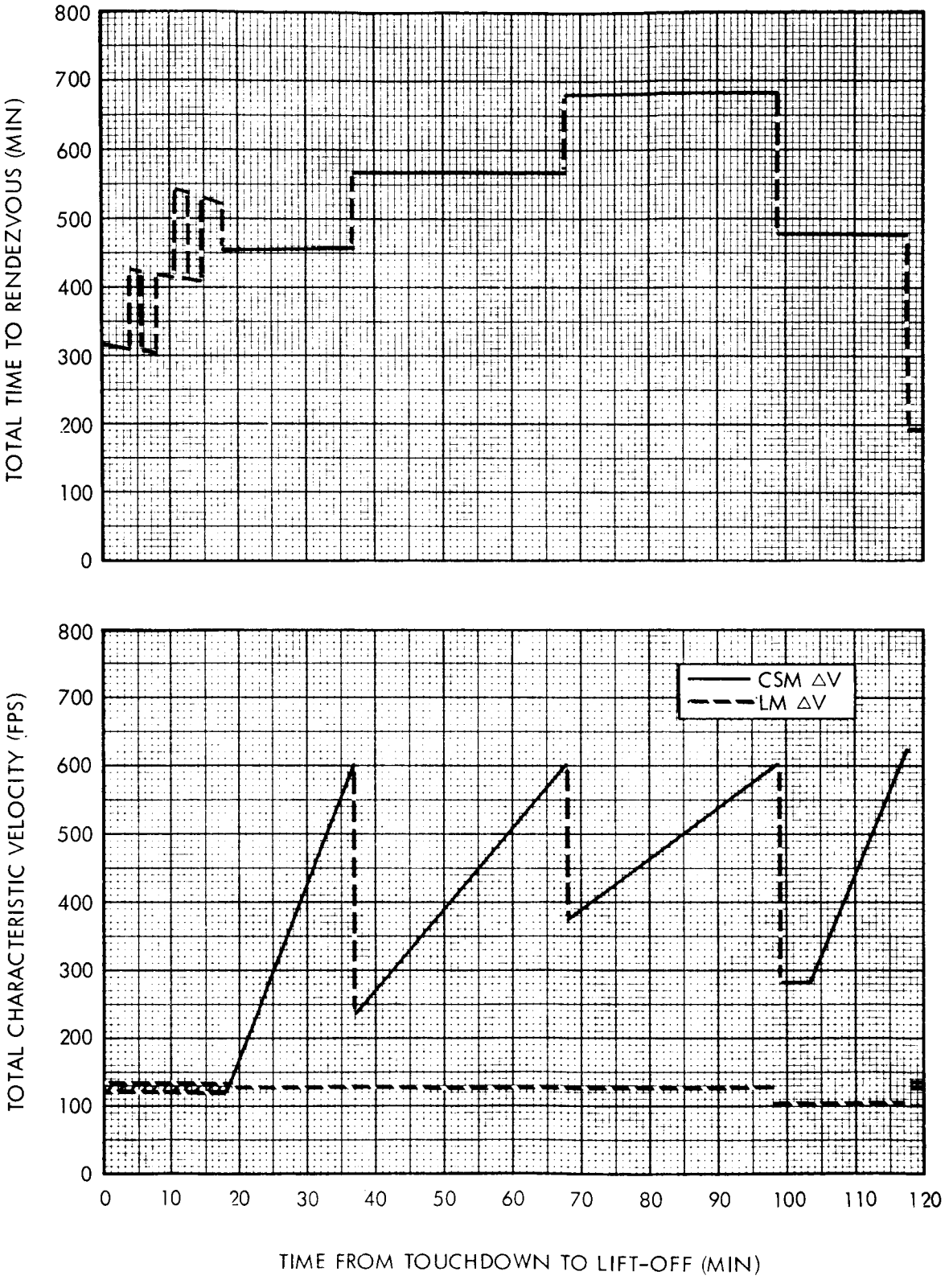


Figure 37. Performance and Time Requirements for Rendezvous Following Anytime LM Lift-off.

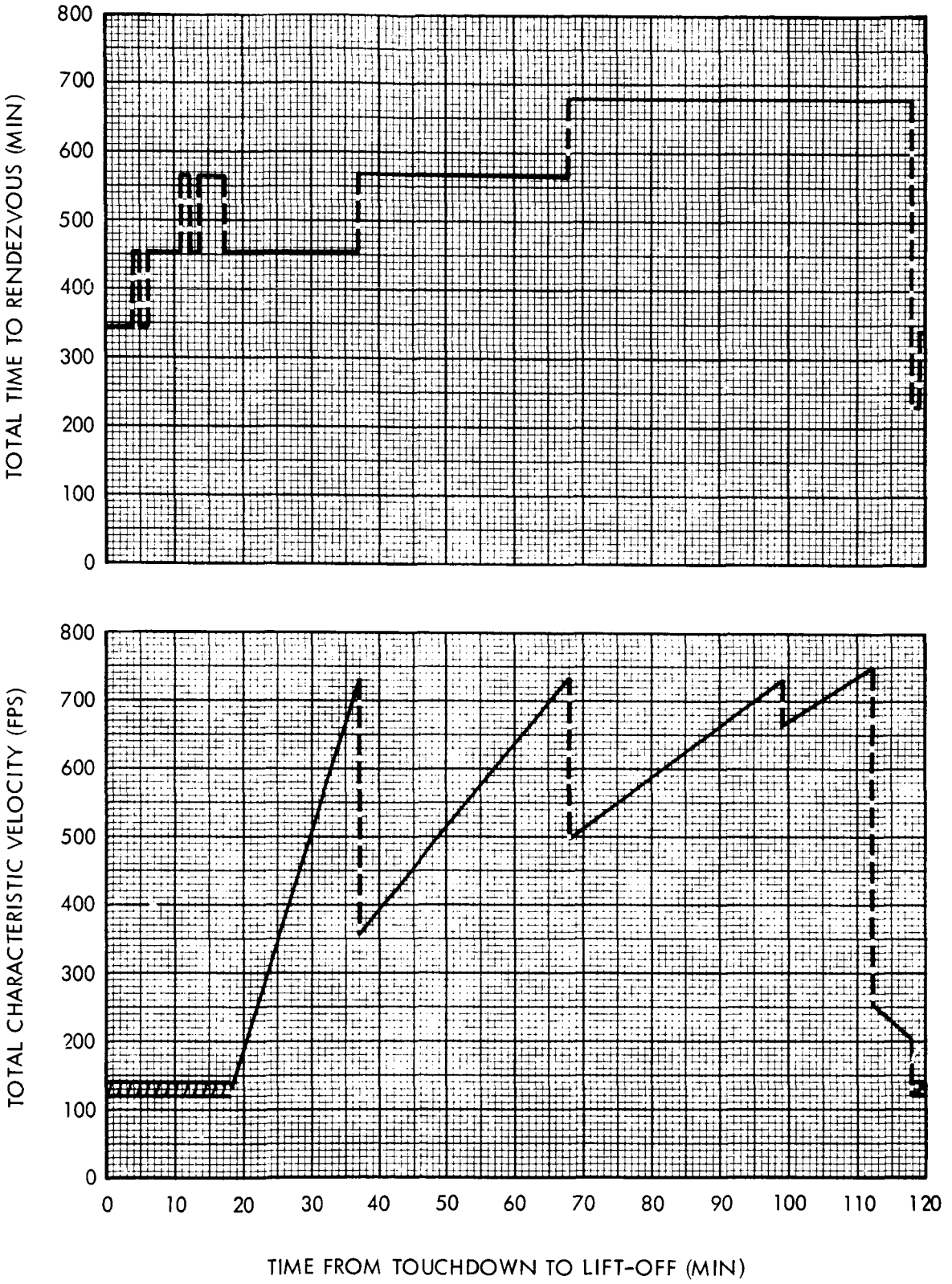


Figure 38. Performance and Time Requirements for CSM Rescue Following Anytime LM Lift-off

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1. Lloyd, E., Diamond, R. M., et al., "Parametric Analysis of Lunar Orbit Phase Abort and Rescue Techniques," MSC IN 68-FM-185, 31 July 1968.

2. Diamond, R. M., "Evaluation of CSM Rescue for the Lunar Mission Using the Mirror Image Coelliptic Sequence with Maneuver Timing and Velocity Biases," TRW Letter 3421.7-169, 17 October 1968.

3. Tindall, H. W., Jr., "G Rendezvous Mission Techniques," MSC Memorandum 68-PA-T-202A, 23 September 1968.

4. "Task Agreement for the Development of Lunar Orbit Phase Abort and Rescue Procedures, Task MSC/TRW A-159, Amendment No. 2," 17 September 1968.