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PROJECT APOLLO

ANALYSIS OF TERMINAL PHASE RENDEZVOUS LIGHTING

FLIGHT PROCEDURES BRANCH

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HOUSTON, TEXAS

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ANALYSIS OF TERMINAL PHASE
RENDEZVOUS LIGHTING

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Introduction:

An analysis of the lighting problems associated with terminal phase rendezvous in both earth and lunar orbit has been made to define time limits on the Terminal Phase Initiation (TPI) maneuver. The study is limited to the nominal LM rendezvous from below with CSM rescue from above.

Criteria:

A summary of the assumptions and constraints used in this study are listed in Table I. The lighting problem can generally be separated into LM constraints and CSM rescue constraints. The CSM rescue constraints consist of the following items:

(1) Pre-TPI Tracking - The sun should be at least 15 degrees off the line-of-sight (LOS) from the CSM to the LM (component in the orbital plane) from TPI-35 min. to TPI-15 min. This item provides for a minimum of LM tracking before TPI with some assurance that the sun will not enter the sextant field of view.

(2) Pre-midcourse Tracking - In earth orbit, assuming the LM cannot be seen against the lit earth background at TPI, sunset should occur by TPI+5 min. and sunrise no earlier than the last midcourse correction (M/C). This provision allows midcourse tracking of the LM to begin shortly after TPI and continue up to the midcourse correction. In lunar orbit, assuming the LM is visible through the sextant against the sunlit lunar background at range of 40 NM, the sun must be more than 15 degrees away from the LOS or sunset occur by TPI+5 min.

(3) Braking and LOS Control

a. Sunrise should occur within a range at which the LM is visible out the window against the lit earth or lunar background (approximately 3.5 or 10 NM, respectively). This constraint provides for continuous visibility of the LM between darkness and sunrise, a requirement for pointing during braking and LOS control. In addition, CSM's not equipped with VHF ranging require that sunrise occur at a minimum range of 1 NM for range estimation during braking.

b. The sun should be 30 degrees off the LOS allowing for a ± 20 degree dispersion in the final approach angle, thus preventing sunlight from entering the crewman's eyes during braking and LOS control.

The LM rendezvous lighting constraints are:

(1) Pre-TPI and M/C Tracking - The sun should be at least 30 degrees from the LOS from TPI-10 min. to the last M/C correction to allow visual tracking of the CSM for the purpose of backing up a LM radar failure.

(2) LOS Control and Braking - The sun should be 30 degrees off the LOS allowing for a ± 20 degree dispersion in the final portion of the trajectory preventing sunlight from entering the crewman's eyes during braking and LOS control.

The implications of these constraints on the time of TPI relative to sunset or sunrise can now be discussed.

Discussion - Lunar Orbit

First, examining these constraints in the nominal lunar orbit case in more detail, Figure 1 shows the limits at TPI imposed by CSM pre-TPI tracking. Since the sun moves clockwise on the relative plot, it must be below the horizon at TPI-35 min. or it would sweep through the LOS during the tracking period. Utilizing lunar orbital rate of 3.03 degrees per minute allows the sun's position to be projected from the horizon to the TPI time, which is found to be 106 degrees below the horizon, forming a boundary of sun position on the low side (Boundary AL). The upper boundary is established by placing the sun 15 degrees above the LOS at TPI-15 minutes. Projecting this position to TPI establishes the upper boundary for the sun imposed by this constraint (Boundary BL). Pre-midcourse tracking does not impose any constraints in lunar orbit since the LOS to the LM is 12 degrees below horizon at TPI+5.

Figure 1 also shows the boundary set by Item (3)a. Nominally, a range of 10 NM is reached at TPI+25 min. The limit (Boundary CL) is found by placing the sunline on the horizon at TPI+21.5 min. and rotating back to TPI. It is desirable but far from mandatory that sunrise occur at a range greater than 1 NM. A boundary (DL) defining this condition is located by placing the sunline on the forward horizon at TPI+39.75 min. and rotating it back to TPI.

If sunrise or sunset occurs at ranges less than 1 NM and prior to the completion of braking (TPI+55 min.), the rapid change in visual environment can cause difficulty in LOS control and braking. Boundaries DL/IL and JL/KL define these limits for sunrise and sunset respectively.

Figure 2 shows the nominal inertial LOS motion for both the LM and CSM during terminal phase rendezvous, and illustrates the lighting boundaries defined by braking and LOS control with either vehicle.

On the inertial plot, the two horizon lines slope at orbital rate while the sun moves across the plot at a constant angle. The zero inertial angle was selected to be local horizontal at TPI in the direction of orbital travel. The maximum dispersions in the terminal phase trajectory are shown by the dashed lines on either side of the nominal paths. Note that the upper region between rear and forward horizons represents lunar surface background while the lower region between forward and rear horizons represents star background. The LM pre-TPI and M/C tracking constraints are met by placing the sun 30 degrees away from the LOS as shown by Boundaries EL and FL. Boundary EL is located by end of rendezvous visibility, while Boundary FL is critical at TPI-10 minutes. The CSM restriction due to the lunar background during rendezvous required only that the sunrise occur after the rendezvous is complete (Boundary GL) or early enough not to interfere with the final portion of the rendezvous (Boundary HL). It is assumed that the rendezvous is essentially complete by TPI+55 minutes, allowing about 11 minutes for arrival time slip due to braking.

Figure 4 shows all the limits taken from Figures 1 and 2 transferred to a single relative plot. It shows the most desirable sun position at TPI to be in the upper right hand quadrant with a total envelope of 31 minutes or 94 degrees of orbit travel. Although the braking phase is completed at night with this sun position, more severe constraints are avoided. The LM tracking limit (Boundary FL) is probably a constraint to be avoided more so than the CSM braking constraint (Boundary GL). A sun position of 40 degrees above local horizontal results in sunset at TPI+20.6 min. with TPI allowed 11 minutes late or 20 minutes early.

The present sun position is the second preference based on the degree of criticality of the constraints it violates. The loss of sextant (AL to BL) track before TPI does not degrade the TPI solution to a great extent provided a few marks are obtained along with the VHF range data.[1] Sunrise occuring at a range greater than 10 NM (CL to DL) may mean the LM is not visible through the CSM COAS after the second midcourse if TPI is later than nominal.

Discussion - Earth Orbit:

In earth orbit, considering the D Mission trajectory, the lighting limits may be similarly analyzed. Figure 4 shows the limits at TPI imposed by CSM pre-TPI tracking. At TPI-35 minutes, the sunline must be below the LOS to avoid the sun sweeping through the LOS during the tracking period. Since the horizon is depressed only 15.3 degrees for the D Mission, the sun must only be set rather than 15 degrees below the LOS. Utilizing the mean orbital rate of the D Mission (4.06 deg/min) and projecting this limit to the TPI time forms a lower boundary (Boundary AE) of the sun 156.5 degrees below local horizontal. The upper boundary is established by placing the sun 15 degrees above the

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[1]Based on preliminary discussions with MPAD

LOS at TPI-15 minutes. Projecting this position to TPI establishes the upper boundary of the sun imposed by this constraint (Boundary BE).

Pre-midcourse tracking boundaries are located in Figure 4 by placing the sun on the appropriate horizon at TPI+5 and TPI+20 minutes and projecting back to TPI. Thus Boundaries JE and IE are formed.

Figure 4 also shows the limits formed by braking (3a). Nominally, on the D Mission a range of 3.5 miles is reached at TPI+21.5 minutes. The limit (Boundary CE) is found by placing the sunline on the horizon at TPI+21.5 and rotating back to TPI. The other braking limit is imposed by the requirement to be in sunlight in the last mile of the terminal phase. A range of one mile nominally occurs at TPI+28.7 minutes, and again by rotating the sunline back from the horizon an equal amount, the limit (Boundary DE) is established.

Figure 5 establishes the corresponding boundaries due to LOS control for the earth orbit rendezvous case as does Figure 2 for lunar orbit. The logic for positioning Boundaries EE, FE, GE, and HE may be found in the discussion of Figure 2.

Figure 6 is a summary of all limits established in Figures 4 and 5. In the D Mission the region between AE and BE is not critical because the orbital planes are inclined to the ecliptic by more than 15 deg. It can be seen that the remaining envelope CE to DE in which no constraints are violated is only about 7.5 minutes long. Regions HE to GE, DE to JE, and BE to EE are acceptable if the LM can complete the terminal phase (LM radar working and ample RCS fuel).

Conclusions

(1) The optimum lighting for Mission D rendezvous occurs with TPI placed 25 minutes before sunrise. Arrival into daylight should occur at 2.25 NM, resulting in a window of ± 3.7 minutes before any degraded conditions in terminal phase are encountered.

(2) In lunar orbit, the optimum lighting occurs with TPI located about 21 minutes before sunset.

(3) The present lighting for lunar missions with TPI located at midnight is an acceptable second choice.

TABLE I

Constraints

A. CSM

1. Continuous tracking with sextant from TPI-35 minutes to TPI-15 minutes.

2. Continuous tracking with sextant from TPI+5 minutes to the last M/C correction.

B. LM - Continuous tracking through COAS from TPI-10 minutes to rendezvous.

Assumptions

A. Trajectories

1. Lunar Orbit - CSM 60 NM circular, ΔH = 15 NM, wt = 130 deg.

2. Earth Orbit - CSM 130 NM circular, ΔH = 10 NM, wt = 130 deg.

3. Arrival angle dispersion is $\pm$20 degrees.

4. All orbits are assumed to be in the ecliptic plane except where noted otherwise.

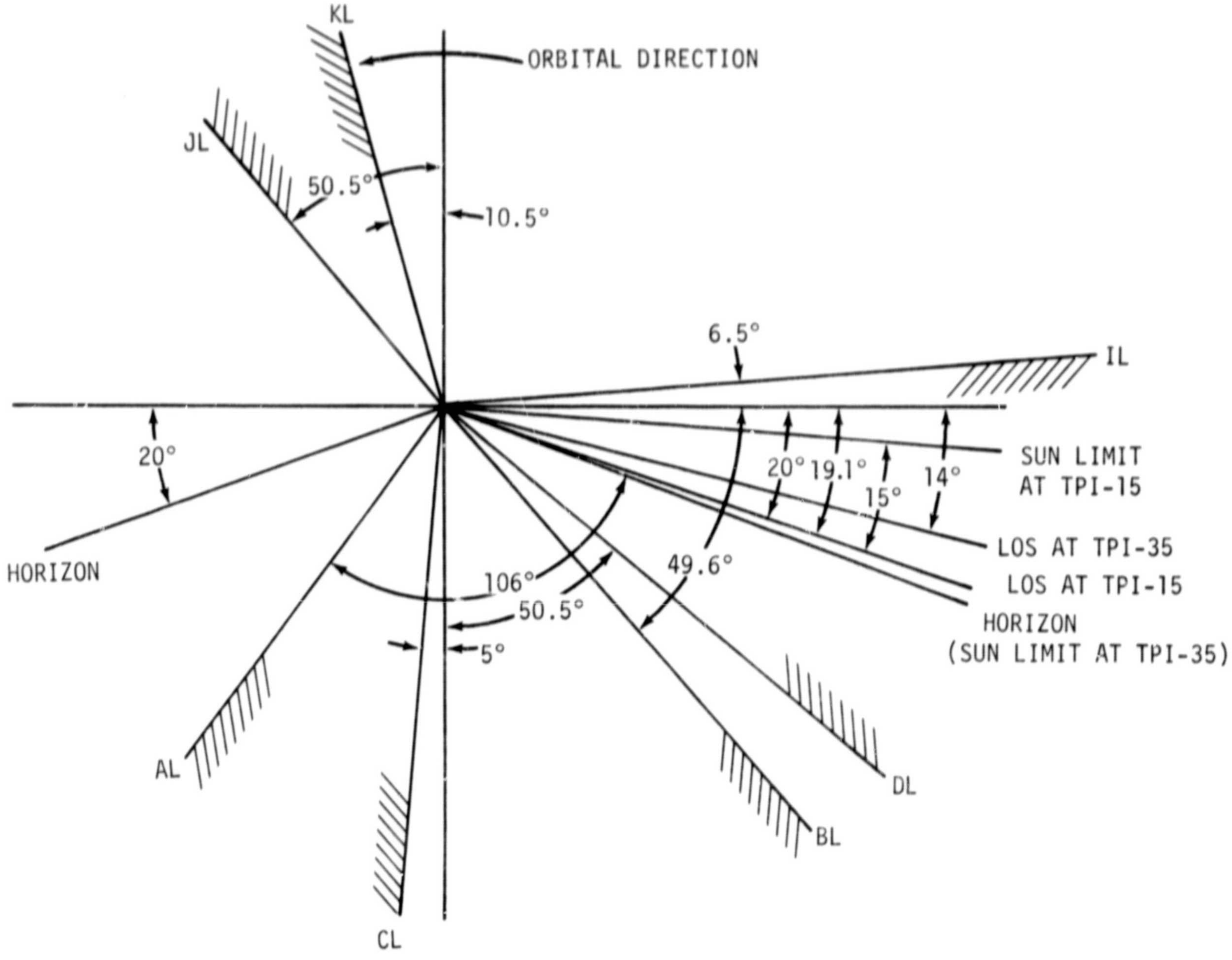
B. Sun-LOS Angle

1. Minimum Sun-LOS angle for COAS viewing is 30 degrees.

2. Minimum Sun-LOS angle for sextant viewing is 15 degrees.

FIGURE 1

Local Horizontal CSM Centered Coordinates, CSM Lighting Constraints Due To Tracking And Visibility-Lunar Orbit



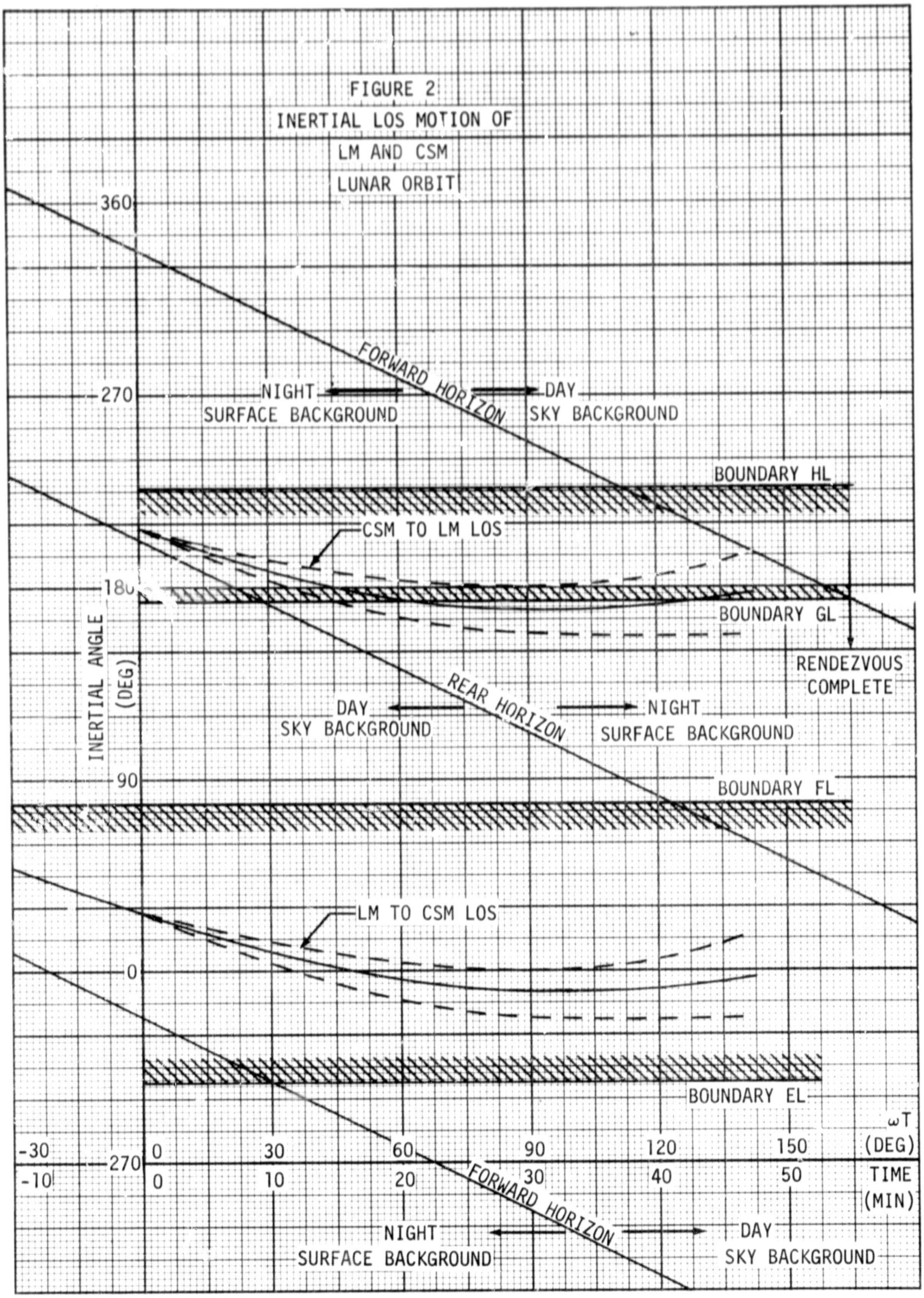
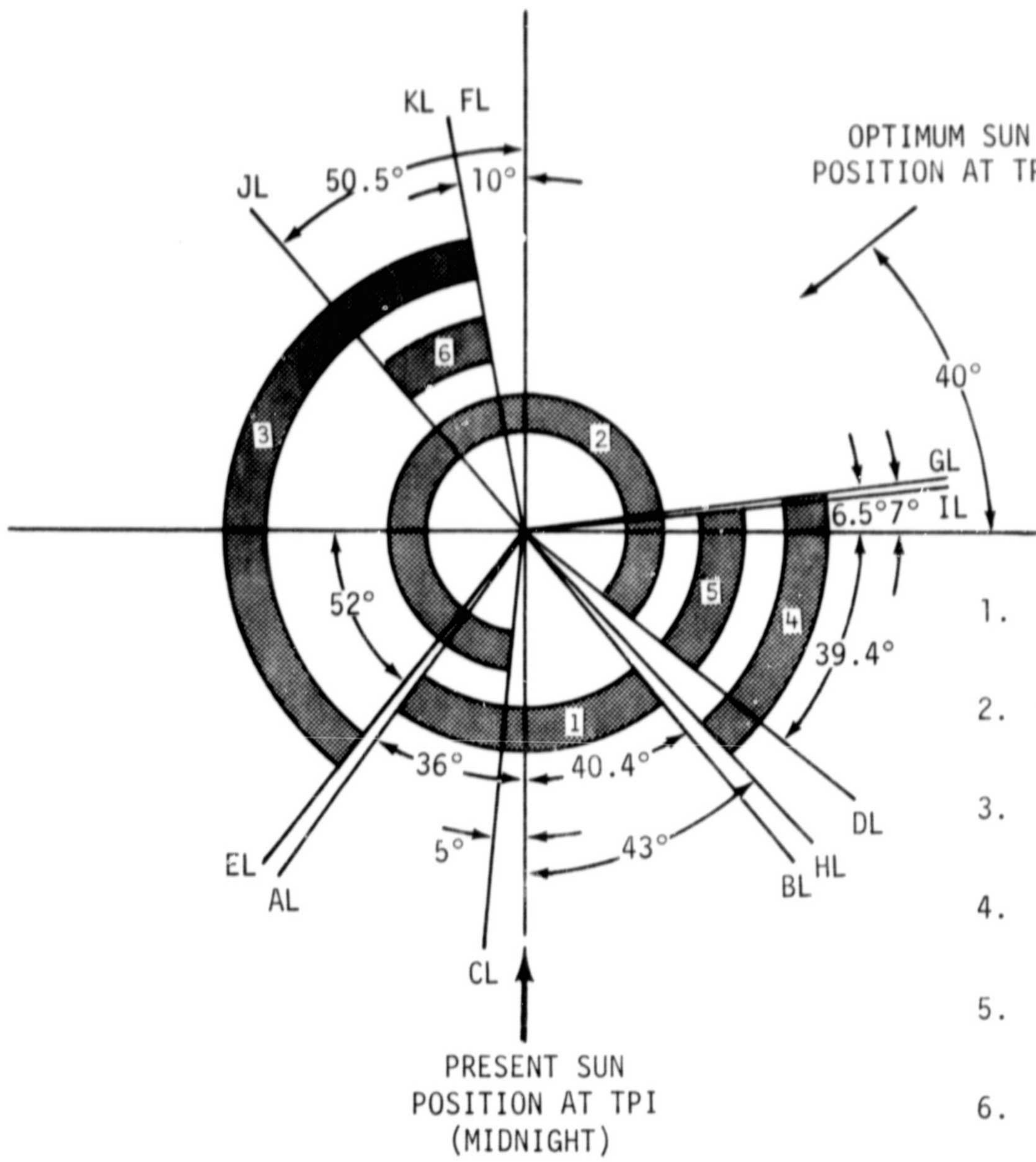


FIGURE 2
INERTIAL LOS MOTION OF
LM AND CSM
LUNAR ORBIT
360
270
180
90
0
-270
INERTIAL ANGLE
(DEG)
FORWARD HORIZON
NIGHT
SURFACE BACKGROUND
DAY
SKY BACKGROUND
BOUNDARY HL
CSM TO LM LOS
BOUNDARY GL
RENDEZVOUS
COMPLETE
REAR HORIZON
DAY
SKY BACKGROUND
NIGHT
SURFACE BACKGROUND
BOUNDARY FL
LM TO CSM LOS
BOUNDARY EL
ωT
(DEG)
-30
0
30
60
90
120
150
TIME
(MIN)
-10
0
10
20
30
40
50
FORWARD HORIZON
NIGHT
SURFACE BACKGROUND
DAY
SKY BACKGROUND

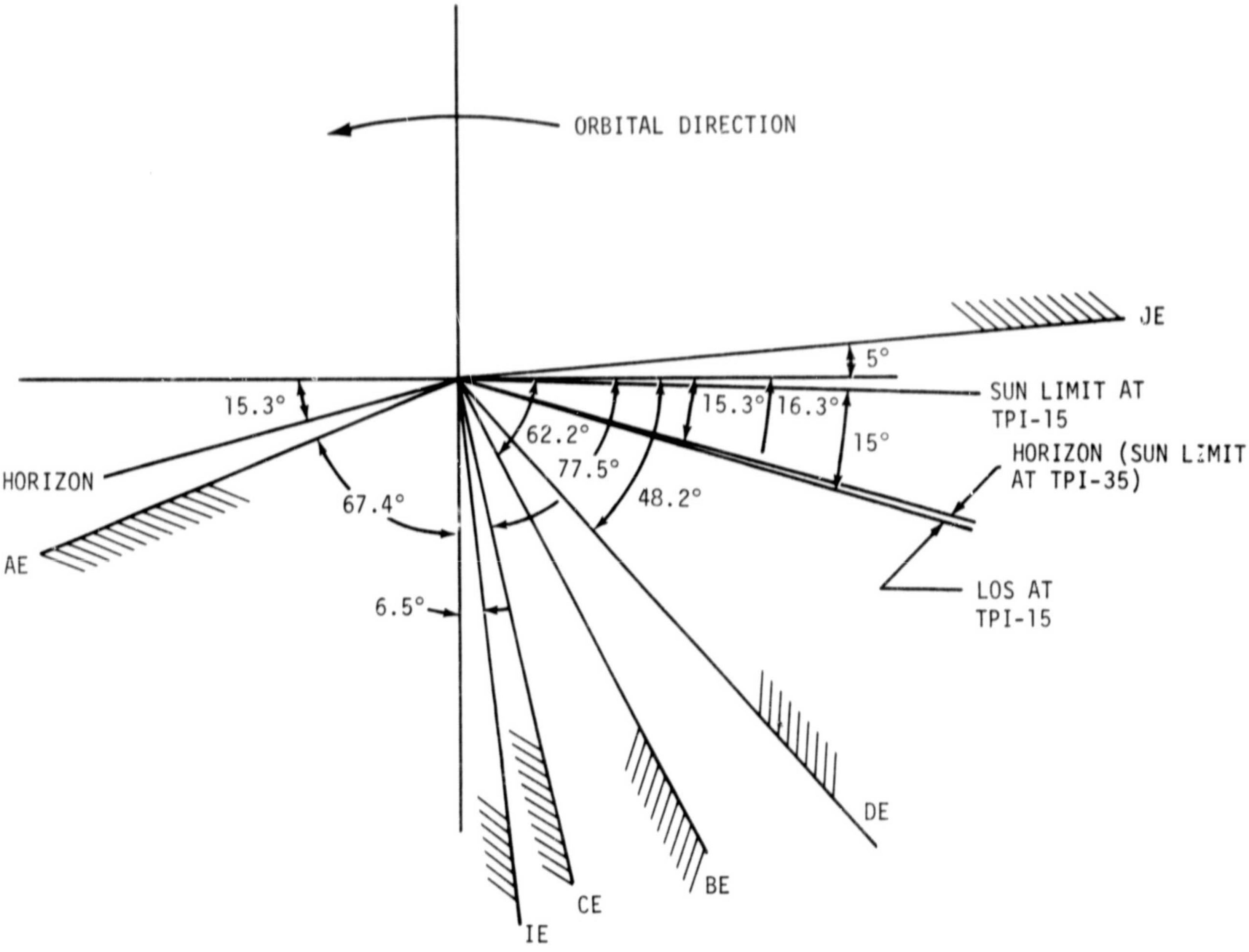
FIGURE 3
SUMMARY OF LIGHTING
CONSTRAINTS AND OPTIMUM
SUN POSITION AT TPI
LUNAR ORBIT



1. AL to BL-Sun Within 15° of LOS From CSM to LM Between TPI-35 and TPI-15.
2. CL to DL-Sunrise Occurs At Ranges Greater Than 10NM or Occurs Within a Range of 1NM
3. EL to FL-Sun Within 30° of LOS From LM to CSM from TPI-10 To Rendezvous
4. GL to HL-Sun Within 30° of LOS From CSM to LM during LOS Control and Braking
5. DL to IL-Sunrise Occurs Between 1 NM and Completion Of Braking
6. JL to KL-Sunset Occurs Between 1 NM and Completion Of Braking

FIGURE 4

Local Horizontal CSM Centered Coordinates
Sun Constraints For CSM Optical Tracking
And Visibility - Earth Orbit



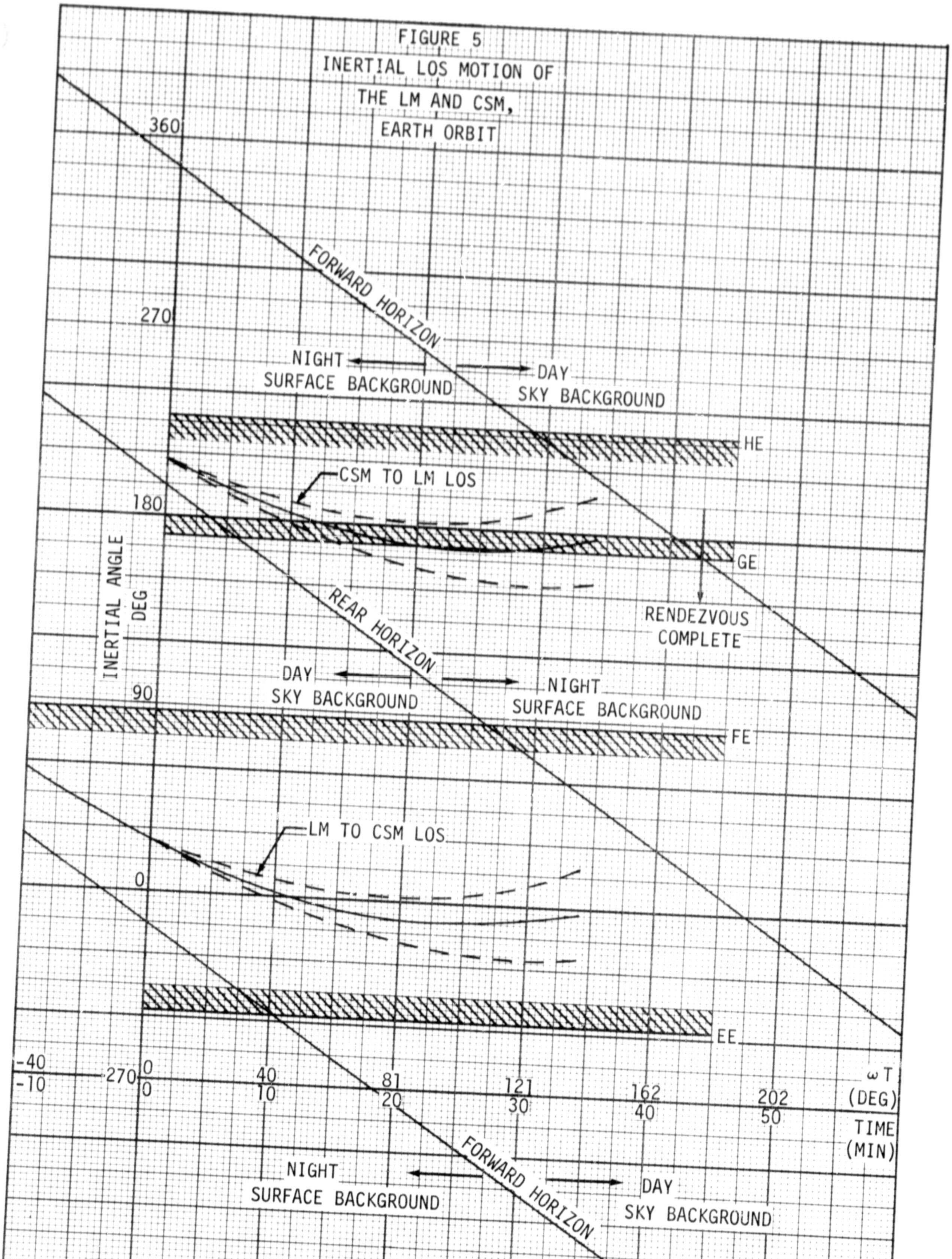
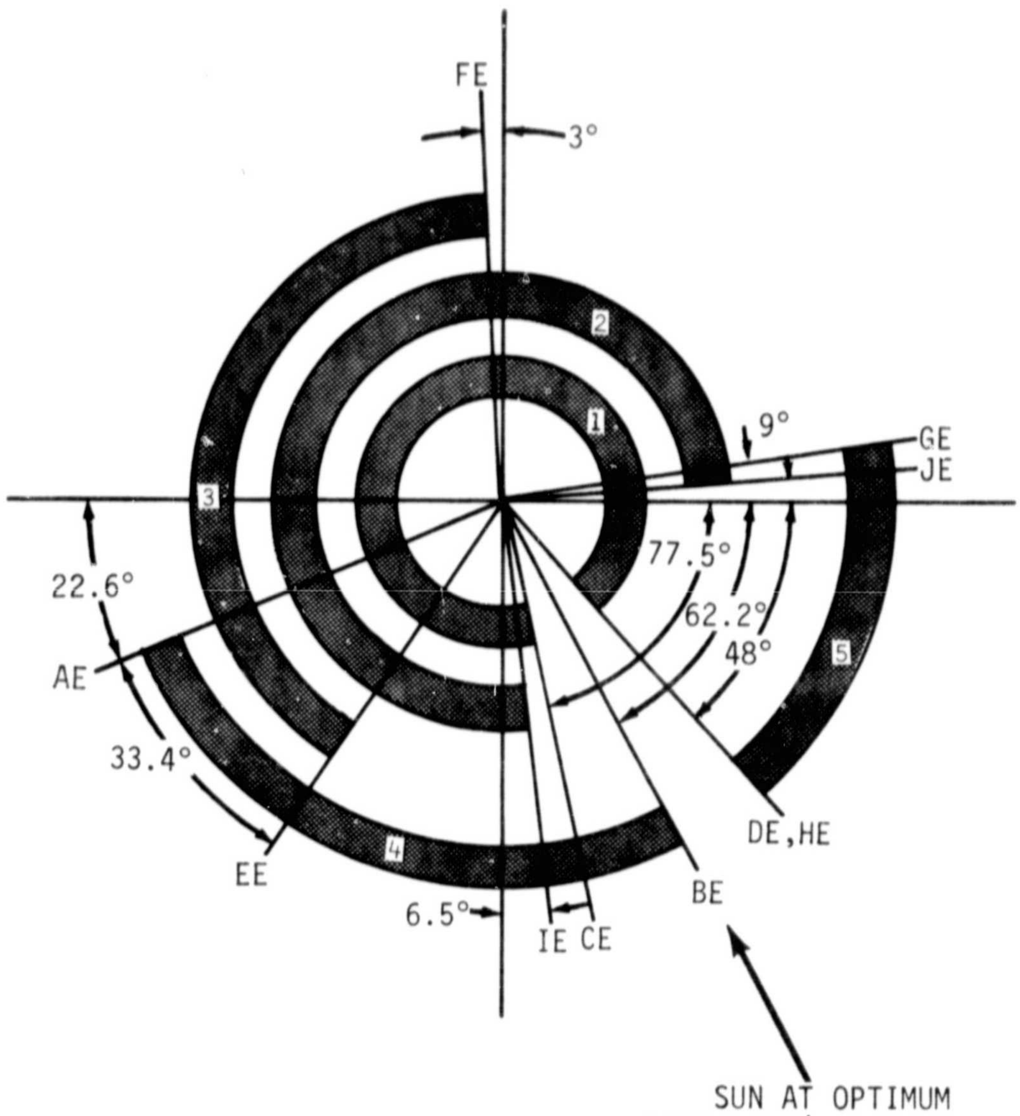


FIGURE 5
INERTIAL LOS MOTION OF
THE LM AND CSM,
EARTH ORBIT
360
270
180
90
0
-270
-40
-10
INERTIAL ANGLE DEG
FORWARD HORIZON
NIGHT
SURFACE BACKGROUND
DAY
SKY BACKGROUND
HE
CSM TO LM LOS
GE
RENDEZVOUS COMPLETE
REAR HORIZON
DAY
SKY BACKGROUND
NIGHT
SURFACE BACKGROUND
FE
LM TO CSM LOS
EE
0
0
40
10
81
20
121
30
162
40
202
50
ωT (DEG)
TIME (MIN)
NIGHT
SURFACE BACKGROUND
FORWARD HORIZON
DAY
SKY BACKGROUND

FIGURE 6
SUMMARY OF LIGHTING
CONSTRAINTS AND OPTIMUM
SUN POSITION AT TPI
EARTH ORBIT



1. CE to DE Sunrise Occurs Outside Of Range Between 3.5 NM And 1 NM
2. IE to JE Sunlit Earth Background Between TPI+5 Min And TPI+20 Min.
3. EE to FE Sun Within 30° of LOS From LM to CSM From TPI-10 to Rendezvous.
4. AE to BE Sun Within 15° of LOS From CSM to LM between TPI-35 to TPI-15.
5. GE to HE Sun Within 30° of LOS From CSM to LM During LOS Control and Braking..