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CONSIDERATIONS IN LUNAR LANDMARK SIGHTING AND RECOMMENDED TECHNIQUES

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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CONSIDERATIONS IN LUNAR LANDMARK SIGHTING AND RECOMMENDED TECHNIQUES

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INTRODUCTION

A major consideration in performing navigation functions in lunar orbit is the determination of the optimum tracking techniques with the Apollo CSM-LM. In this internal note, various aspects of tracking that are discussed are: (1) The constraints imposed by limitations of the field of view of the SCT (scanning telescope), (2) possible different maneuvering techniques which might be employed, (3) choice of suitable landmark, (4) choice of an optimum maneuvering and sighting technique.

SUMMARY

The results of this landmark sighting study are: (1) It appears that the optimum technique consists in rotating the CSM at orbital rate, with the SCT shaft axis about 30° ahead of the local vertical. Primary constraints include limitations on the SCT FOV (field of view) and consideration of fuel economy, (2) choice of a set of 25 landmarks to be programmed for automatic acquisition is a function of the envelope of ground tracks and computer programs for their selection. They should be chosen so there is an adequate interval to acquire each after the previous one has disappeared over the horizon, and there is a known relationship to the lunar landing site.

REQUIREMENTS

The requirements to be satisfied by any lunar landmark sighting and selection technique have been developed from considerations of computer errors, consideration of the time required to acquire and track landmarks, and the net effects of geometrical constraints thereon.

Computer errors are minimized when two lines-of-sight (LOS's) on a landmark are perpendicular. Since the error varies as the cosecant of the angle between the LOS's, this angle should be greater than 60 degrees. The computer is capable of accepting up to five marks per landmark. More marks than two can be employed for data smoothing.

Time required for landmark recognition, acquisition and tracking, is presently difficult to define. However, it appears desirable to maximize the duration of landmark LOS dwell within the optics field of view (FOV).

Data in reference 6 indicates that at certain orientations of the CSM-LM, a high level of reflected sunlight may give rise to scattered light in the optics. Therefore, spacecraft attitudes may be limited by the optics scattered light constraint.

Because of the limitations of the RCS propellant, maneuvering should be minimized. In addition, any maneuvers should present a minimum interference with the task of tracking.

Controls are provided at the optics station for both the shaft and trunnion angles of the optics (sextant and scanning telescope), and for rate control of the spacecraft in pitch, roll and yaw. Simultaneous operation of these controls may be difficult, so that it is desirable to limit vehicle maneuver to a constant, stable rate.

The optimum orientation of the vehicle with respect to the target is that which will permit the target to dwell within the FOV of the SCT for the maximum time with no maneuver with respect to the LV system. This would be satisfied by having the roll axis horizontal and the pitch axis perpendicular to the orbit plane.

To maximize the ground tracking period, two CSM orientations are possible: (1) with the roll axis horizontal, the pitch axis along the orbital angular momentum vector, and pitched to place the forward edge of the field of view on the horizon, (2) with the roll axis in the vertical plane containing the orbital angular momentum vector, pitched and rolled to place the shaft axis projection near the ground track and the edge of the field of view on the forward horizon. The first orientation is considered preferable to ease the tracking problem. The LOS should be about 15° from the shaft axis at closest approach to keep shaft rates from becoming excessive.

If maneuvering is to be avoided, the maximum angle between mark LOS's (relative to inertial space) will be about 90° (twice the 38° limit on the readout plus 20° central angle traversed from target at near horizon to nadir, minus about two minutes for acquisition at about 3°/min).

SIGHTING TECHNIQUES

In the light of previous criteria, several proposed techniques have been examined. The techniques considered for LMK tracking may be summarized as follows:

a. Local vertical (LV) tracking - aline the vehicle with the center of the field-of-view along the local vertical and the pitch axis parallel to the orbit polar axis (ω) and rotate at the orbital angular rate. Observe forward section of FOV with SCT. Mark identified LMK as early as possible when observed, then when at nadir, and just prior to exist from FOV (figure 1).

b. Rotation at orbital rate - shaft axis 30° ahead of nadir. Align vehicle with pitch or roll axis along orbit polar axis and shaft axis 30° ahead of nadir, and rotate at orbital rate. Mark at LMK identification and at intervals of about 30° (figure 2).

c. Roll/pitch LMK tracking - position and rotate vehicle as in b. When LMK is identified, pitch the vehicle at the LOS rate with the RCS. Mark at initial sighting, 45° before and after nadir and at nadir, and just prior to disappearance over horizon. After disappearance, maneuver vehicle to original orientation, at minimum rate required to be prepared to acquire next LMK.

d. Roll/pitch LV tracking with average LOS rate tracking-position and rotate vehicle as in b. When LMK is acquired, increase roll/pitch rate to an average LOS rate (0.24°/sec) with minimum impulse control and mark as in c. above while tracking target with shaft and trunnion axes of SCT or SXT. Reorient for next LMK after LMK disappears over horizon.

Considering the first method, if local vertical tracking is used with the shaft axis along the nadir at an altitude of 60 n. mi., the vehicle traverses a 40° cone with apex at the LMK and axis along the nadir in about 119 seconds. This might not provide adequate time for acquisition, tracking, and marking. To achieve marks while the line-of-sight rotates through at least 90° may require vehicle rotation because of the limitation of the sextant and telescope fields of view to a 40° cone (approximately). In addition, the early acquisition of the LMK is desired, suggesting a further rotation of the vehicle than required by the geometry. However, if multiple LMK's are tracked per orbit, frequent reorientation of the spacecraft may be required, substantially increasing fuel cost. Therefore, in order to prolong the available viewing time without increasing the required maneuvering, technique b. is suggested. This increases the available viewing time to about eight minutes for LMK on the ground track.

If more time than this is required, the vehicle must be maneuvered to keep the LMK in the FOV of the optics during the time the LMK is above the horizon. The least expensive maneuver is to rotate the vehicle at a constant rate during this time. This method is technique d.

In the following, it is shown that rotating the vehicle at the average LOS rate would allow the LMK to be tracked without further maneuver until it disappears over the aft horizon. The LOS angular rate relative to the local vertical (from reference 2) is:

$$\omega_{LOS} = \left[\frac{r/r_m \cos\theta - 1}{(r/r_m)^2 - 2r/r_m \cos\theta + 1}\right]\omega_o$$

for S/C rotating at orbital rate. The average LOS rate (relative to the local vertical) is:

$$\omega_{LOS_{AV}} = \frac{\sin^{-1}(r_m/r)}{\cos^{-1}(r_m/r)}\,\omega_o$$

This yields an average LOS rate for a 60 n.mi. lunar orbit of 10.5°/minute.

The difference between the average and the true rate is:

$$\omega_{LOS} - \omega_{LOS_{AV}} = \left[\frac{r/r_m \cos\theta - 1}{(r/r_m)^2 - 2r/r_m \cos\theta + 1} - \frac{\sin^{-1}(r_m/r)}{\cos^{-1}(r_m/r)}\right]\omega_o$$

If the vehicle is rotated at the average rate (.24°/sec), the maximum displacement between the optical axis and the LOS (assuming perfect alinement at acquisition on the horizon) will occur when the quantity within the brackets is zero, which, for a 60 n.mi. orbit occurs at $\theta = 5.57°$. The corresponding angle between the LOS and LV is then 58.6, and the angle between the center of the FOV and the local vertical (LV) is 22.1°, giving a maximum difference of 36.5°, which is within the 40° cone. The maximum excursion of the LOS from the center of the FOV may be reduced even further by suitable choice of initial conditions and rates relative to the LV (see figure 3).

In figure 3, the variation of the angle between the LOS and LV is shown as a function of time and the angle between the center of the FOV and the LV for a fixed vehicle rate about a horizontal axis perpendicular to the orbit plane. As may be seen, the maximum angle between the LOS and center of the FOV can be reduced by pointing above the horizon and rotating the vehicle at a larger rate than average. For example, acquiring the target with the center of the FOV about 30° above the horizon and rotating the vehicle at about 4/3 the average rate of the LOS (about .3°/sec) will restrict subsequent excursions of the LOS from the center of the FOV to about 26°.

From the foregoing, it may be concluded that LMK's may be tracked by using a small rate in addition to the orbital rate. The exact value of the desired rate is not too critical, nor is the initial condition at target acquisition.

In the event that RCS fuel limitations preclude the maneuvering required for this technique, the only alternative yielding increased sighting time of the LMK's LOS within the 38° cone within which the CDU's may transmit precise angular data to the computer is to rotate the vehicle at the orbital rate, with the shaft axis of the SCT about 30° ahead of the LV. This will allow the arc under the orbit of the vehicle from 10° in back of the LV to the horizon to be accessible to the SCT. A target on this arc may be tracked for about 510 seconds after it appears over the horizon. If this is done, the desired sighting at an angle of about 45° after passing over the target will be impossible. Rotating of the vehicle about the roll axis has been also considered in the interest of fuel economy.

Since the optics shaft angle is about 33° from the CSM's y-z plane, orienting the vehicle with the X-axis perpendicular to the orbit plane would displace the intersection of the shaft axis projection with the lunar surface about 2.5° of lunar central angle from the orbit plane. Points on the ground track will then cross the field of view in about 400 seconds, and the maximum angle between mark LOS's thereon will be about 70°.

LMK's no more than 2° out of the orbital plane will be trackable with an acceptable loss in tracking time and maximum angle between marks without maneuvering. LMK's with greater displacement will require vehicle maneuver in anticipation of their acquisition. The displacement of the shaft axis (Δ) required from the orbital plane is related to the out of plane angle (A) by the relationship,

$$\mathrm{TAN}\,\Delta = \frac{\mathrm{SIN}\ A}{1.064 - \mathrm{COS}\ A}$$

This is plotted as figure 6.

For example, a LMK 5° from the orbital plane appears about 52° from the nadir of the orbiting vehicle. The horizon is 20° out of plane and 70° from the nadir.

The tradeoff's between these various techniques of LMK tracking is summarized in Table I.

SELECTION OF LMK's

It is desirable to develop a general list of lunar LMK's which may be used for precise navigation. These should be precisely located, easily distinguishable and distributed so that any of the expected Apollo lunar orbits will pass within easy tracking distance of two or three of them while illumination is adequate for recognition. Sets of lunar surface maps will be furnished to aid in their recognition.

The factors to be considered in selection of lunar orbit determination landmarks are: (1) The envelopes of expected ground tracks over the moon, (2) the interval desired between LMK's for convenient tracking, (3) the requirements of the LMK selection section of the CM computer program.

Figure 5 indicates the limits of the ground tracks through the selected landing sites, approximated by line segments. In any case, the maximum ground track latitude will be 13° North or South.

For optimum acquisition, tracking and data reduction, consecutive LMK's should be 18° ± 2° apart on the ground track or the same separation in longitude for near-equatorial orbits.

A 15° spacing between LMK's tracked on the same orbit is probably the minimum acceptable, since from the horizon to the nadir is about 20° of central angle on the moon. Looking towards the forward horizon, about 15° of central angle could probably be used for tracking and marking a single LMK if maneuvering is to be avoided. This gives about five minutes of effective tracking time.

Two sets of LMK's have been chosen by LESD for use in the G mission. These sets do not completely satisfy the criteria for longitude and latitude of a general set, but may be altered by a small number of substitutions to satisfy these criteria. A suitable modified set is presented in Table II.

For a nominally equatorial orbit adequate LMK's are available within 2° of the ground track. From the data in reference 5, it appears that for all ground tracks within the extremes of orbital inclination and azimuth of the parking orbit ascending mode, there will be an adequate distribution of available LMK's, with intervals of 16° - 20° of central angle and within one or two degrees of the ground track.

RECOMMENDATIONS

It is recommended that lunar LMK's be tracked by maintaining a constant orientation to the lunar local vertical which places the forward edge of the SCT FOV on the lunar horizon near the projected ground track. This is most readily accomplished by orienting the CSM with the roll axis horizontal, in the orbit plane, and rolled to place the shaft axis projection near the ground track. An alternative is to have the roll axis horizontal and perpendicular to the orbit plane. This would yield a somewhat reduced (about 20 percent less) viewing time (without maneuvering) for LMK's on the ground track, but reduce fuel cost if maneuvering to extend tracking time is required. The projection of the shaft axis should be about 5° - 10° from the LMK LOS to avoid excessive shaft angle rates, which may create some tracking difficulty.

TABLE I.- LANDMARK TRACKING TECHNIQUES

Technique	Major Advantages	Major Disadvantages	Fuel Usage
LV Tracking (center of FOV along LV) ahead of nadir	Low fuel usage, no maneuvering	Minimum target visibility (time 119 sec)	4.8#/orbit (roll-pitch 4.61#/ " (roll) 4.94#/ " (pitch) (ref. 4)
Rotation at orbital rate-shaft axis 30°	Same plus increased target visibility	None, except possible glare problem on sunrise portion of orbit	Probably same as above
Roll LMK tracking (LOS rate after acquisition)	Maximum sighting time 12.3 min. (horizon to horizon)	Higher fuel usage plus continual reorientation	10 lb/orbit approx.
Pitch LMK tracking (LOS rate after acquisition)	Maximum sighting time 12.3 min (horizon to horizon)	Much higher fuel usage and reorientation	Approx. 31 lb/orbit
Roll LV tracking plus average LOS rate over LMK	Maximum sighting time 12.3 min (horizon to horizon)	Higher fuel usage and reorientation	Approx. 9 lb/orbit
Pitch LV tracking plus average LOS rate over LMK	Maximum sighting time 12.3 min (horizon to horizon)	Much higher fuel usage and reorientation	Approx. 9 lb/orbit
Pitch LV tracking plus average LOS rate over LMK	Maximum sighting time 12.3 min (horizon to horizon)	Much higher fuel usage and reorientation	Approx. 27 lb/orbit

TABLE II.- PROPOSED SET OF LUNAR LANDMARKS

No.	*Source	Longitude	Latitude	Altitude
1	80 III	63° 24' E	2° 15' S	Not Available
2	80 III	58° 14' E	5° 30' S	Not Available
3	80 IV	58° 26' E	6° 35' N	Not Available
4	364-2	52° 19' E	0° 51' N	1736.3 km
5	364-2	38° 42' E	3° 36' N	1737.2
6	364-2	38° 07' E	0° 39' N	1739.0
7	80 III	38° 31' E	2° 18' S	1738.1
8	364-2	38° 20' E	4° 53' S	1737.2
9	80 III	33° 03' E	6° 49' N	1737.5
10	364-2	33° 54' E	2° 24' N	1736.6
11	364-2	23° 42' E	1° 14' N	1734.9
12	80 II	21° 06' E	4° 02' S	1741.1
13	364-2	18° 15' E	1° 40' S	1743.2
14	364-2	12° 33' E	5° 58' N	1743.2
15	364-2	11° 48' E	2° 53' N	1743.2
16	80 II	0° 01' E	4° 30' S	1741.4
17	364-2	1° 20' W	0° 06' N	1737.2
18	38-I	7° 27' W	4° 05' N	1745.8
19	364-2	18° 28' W	2° 45' S	1738.4
20	80 II	20° 16' W	4° 34' S	1733.1
21	364-2	24° 55' W	1° 12' N	1739.1
22	364-2	36° 42' W	2° 49' S	1735.4
23	364-2	42° 16' W	1° 57' N	1735.7
24	364-2	53° 16' W	5° 10' S	1781.1
25	364-2	60° 38' W	0° 52' N	1738.1

* The sources referred to are: Memoranda TH3-68-38 (Table I), TH3-68-364 (Set 2), and TH3-68-80 (Tables II and III).

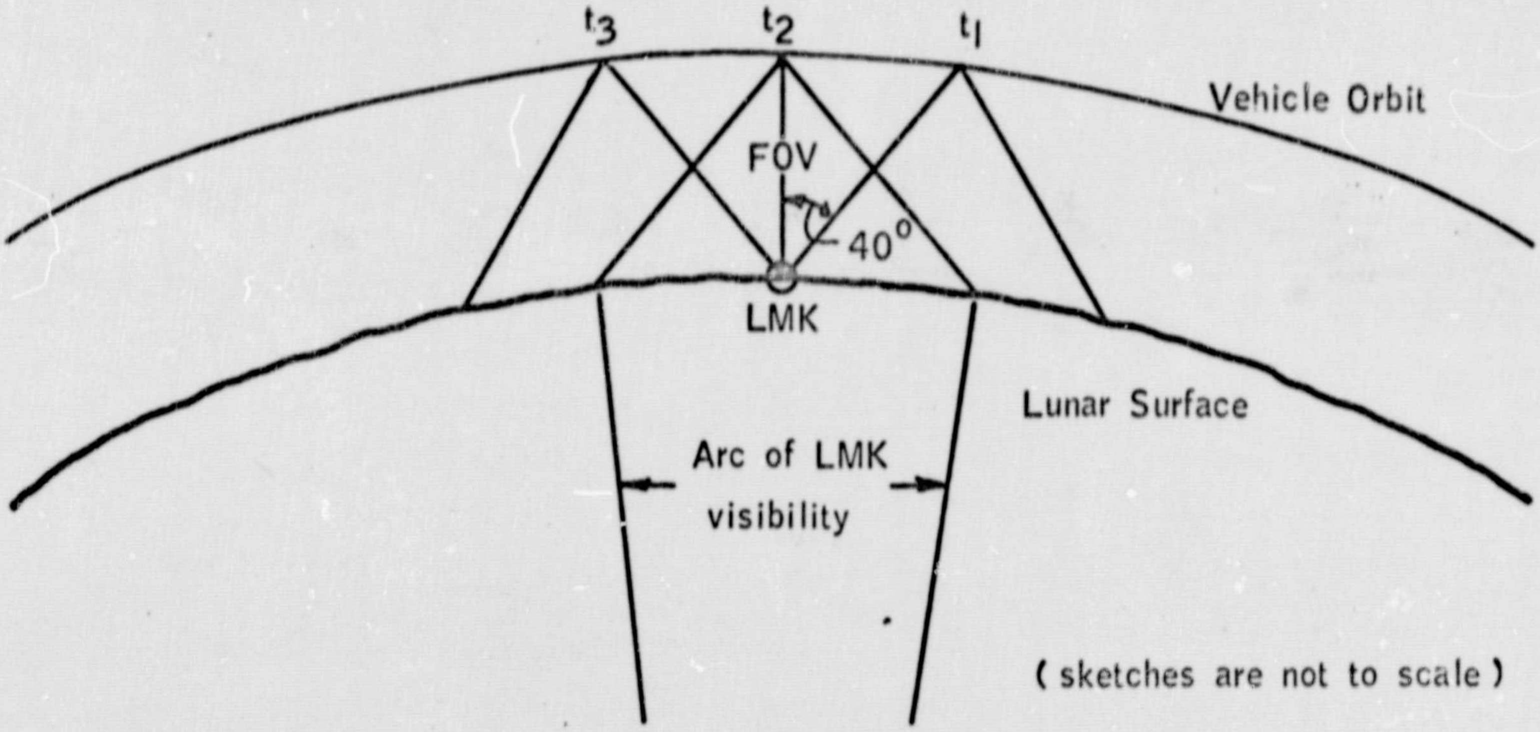

Figure 1.- Local vertical tracking.

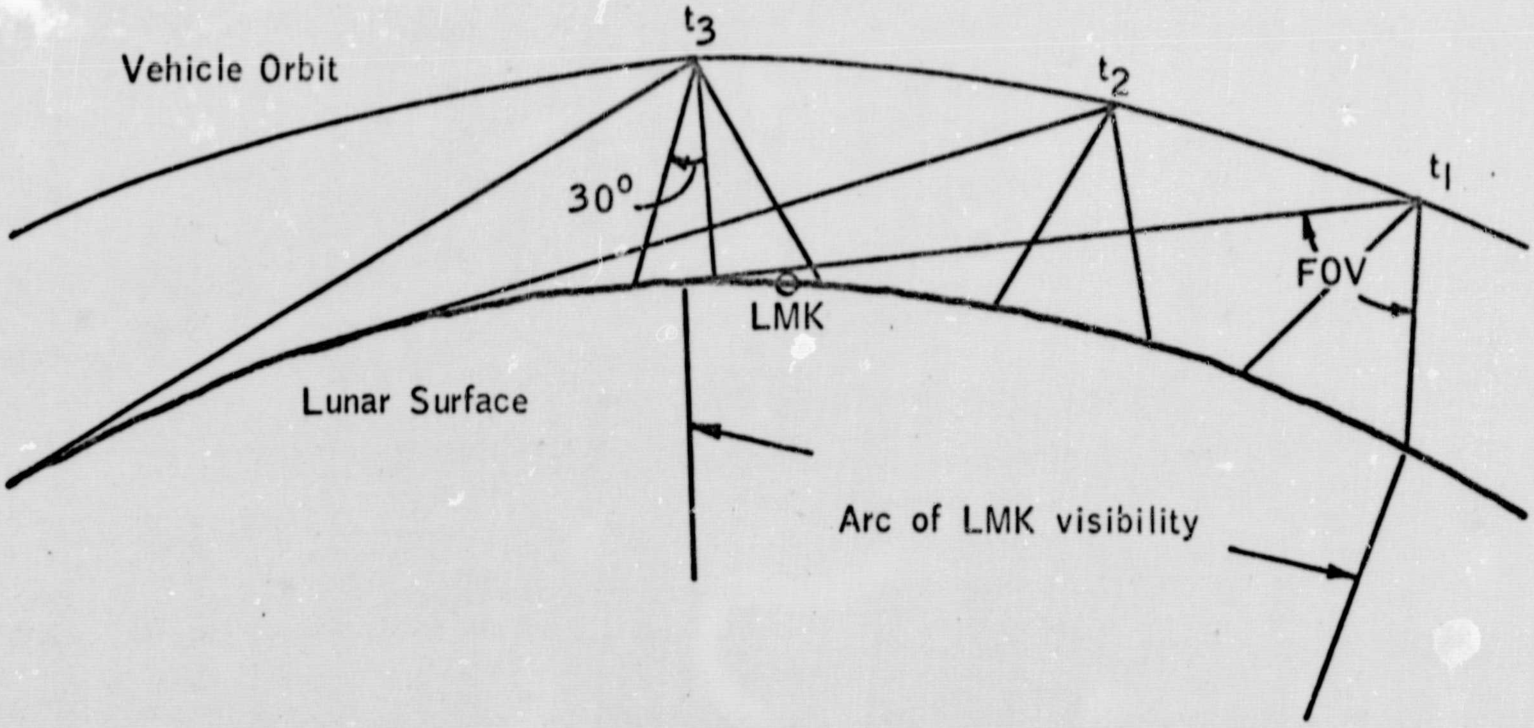

Figure 2.- Orbital rate roll or pitch with center of FOV 30° ahead of local vertical.

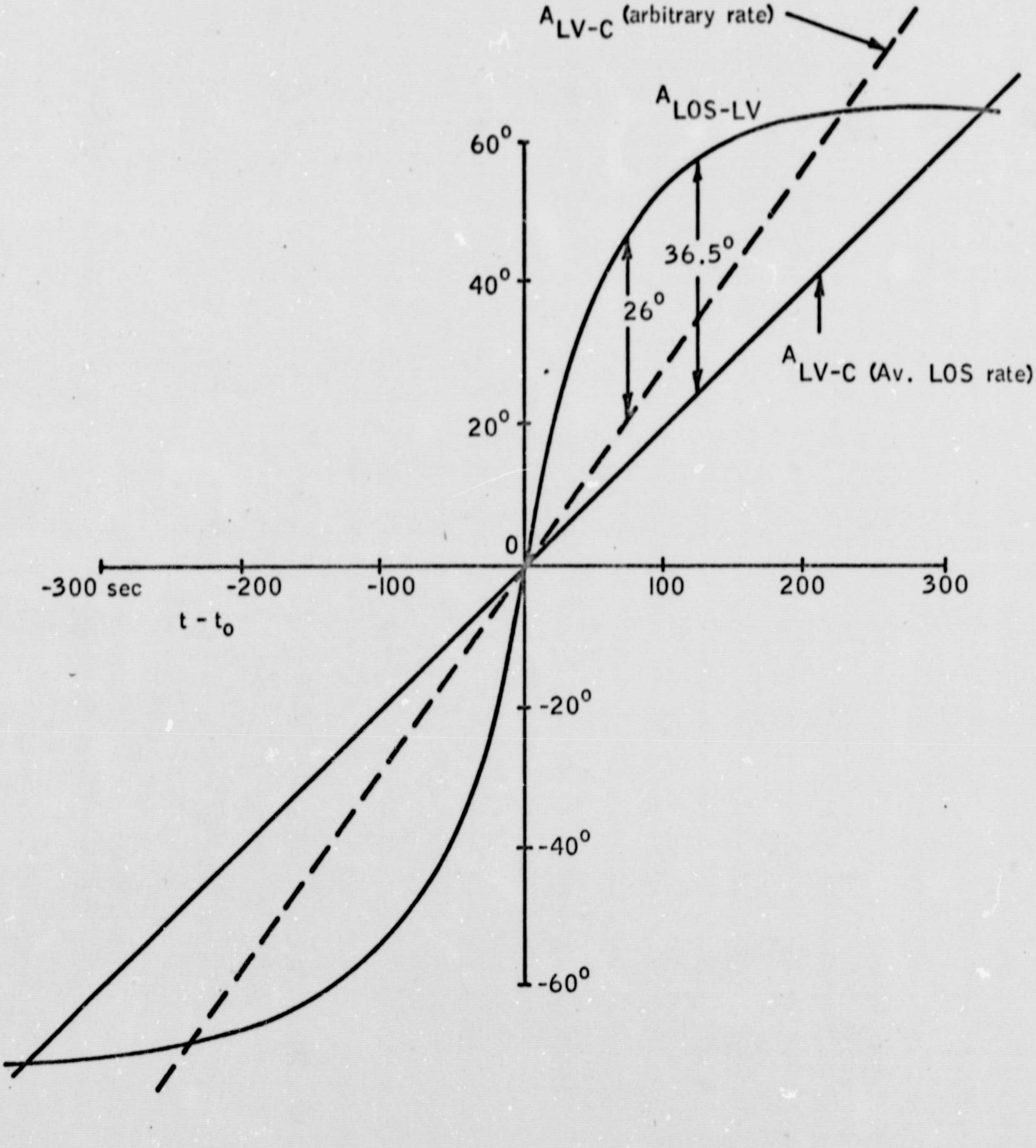

Figure 3.- Relative motion of field-of-view center and LOS to target for 60 n. mi. circular orbit.

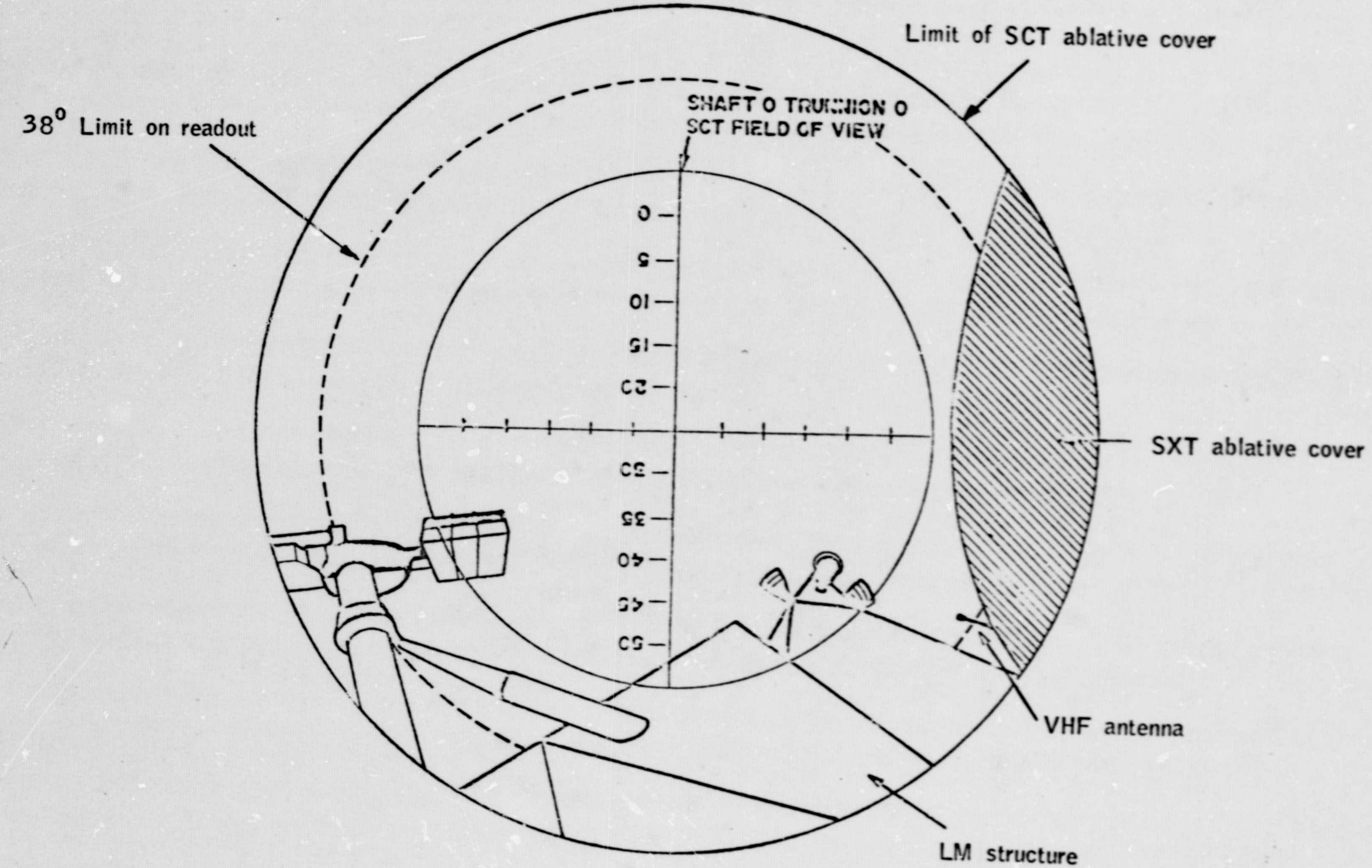

Figure 4.- Apollo Command Module scanning telescope field of view constraints.

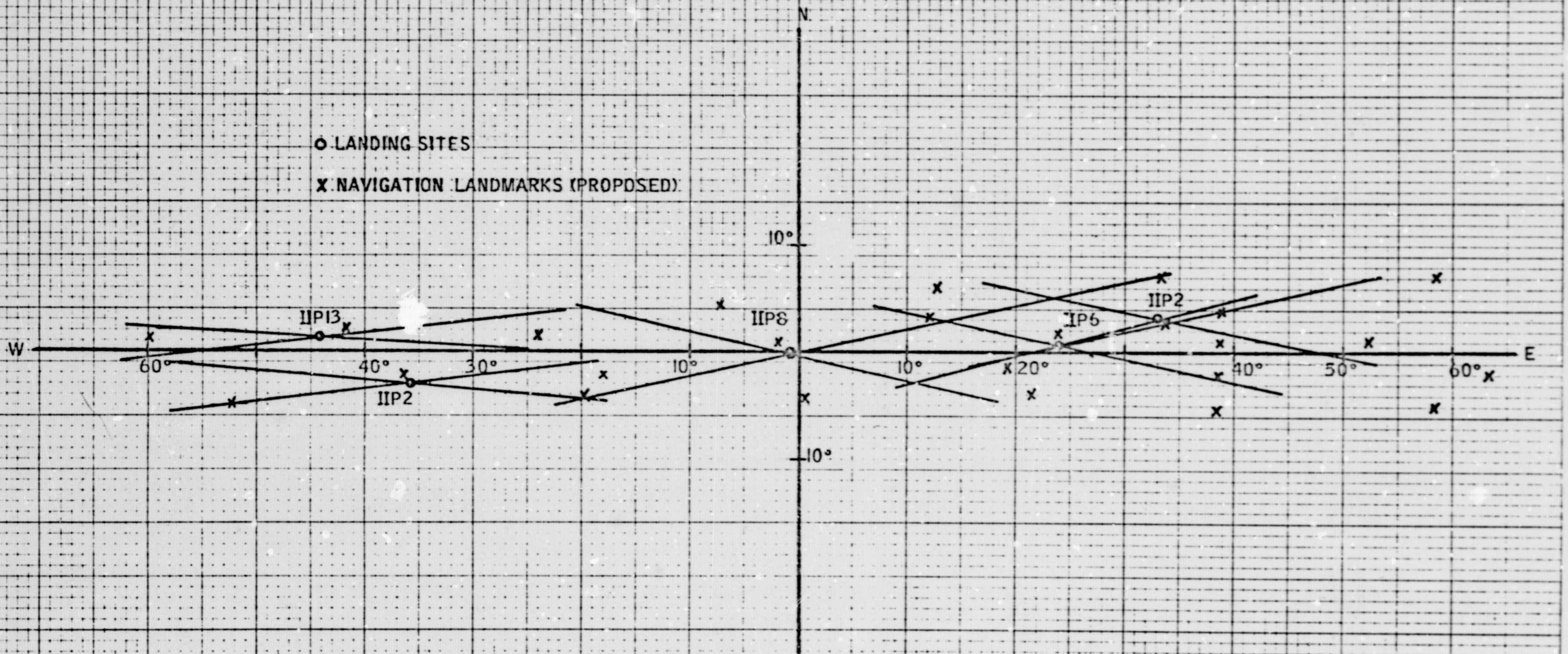

FIGURE 5.- PROPOSED LANDMARKS, LANDING SITES, AND LIMITING AZIMUTHS OF APPROACH

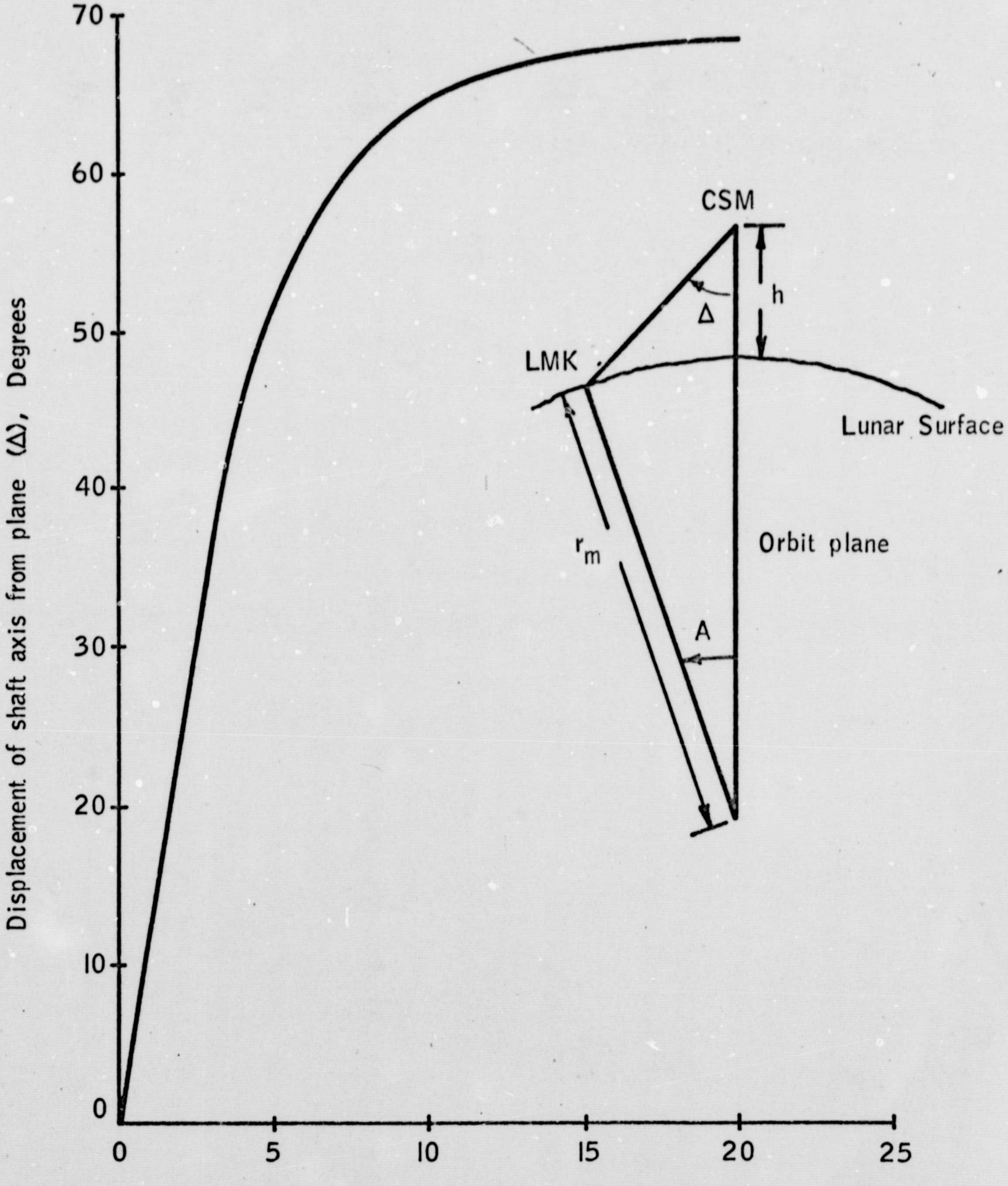

Figure 6.- Maneuver angle for out-of plane targets.

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2. MSC IN 66-EG-46, "A Study of Lunar Orbit Navigation and Landing Accuracy", by Rudolph L. Saldana, et al.

3. MSC Memorandum TH3-68-280, "Lunar landmarks for use in the determination of the lunar parking orbit", by P. R. Bell.

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5. MSC Memorandum TH3-68-238, "Locations of lunar landmarks for orbital navigation", by P. R. Bell.

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