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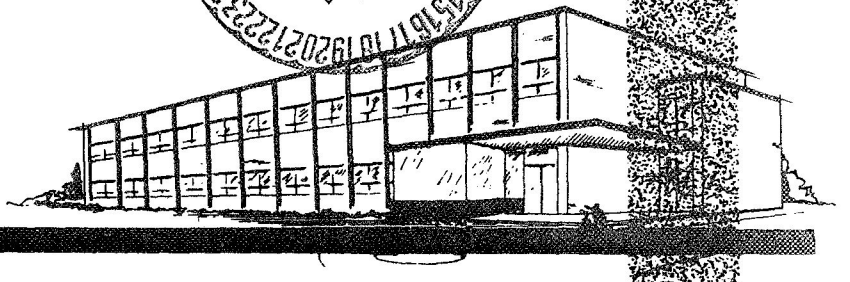

THE Bendix CORPORATION

BENDIX SYSTEMS DIVISION · ANN ARBOR MICHIGAN

N68-20273

LSSM NAVIGATION REQUIREMENTS AND TECHNIQUES

BSR-1239

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1.0 INTRODUCTION

An examination of the LSSM navigation problem, considering the most probable techniques and concepts, was conducted in order to select the minimum system having performance consistent with the LSSM mission objectives. A minimum system should require minimum LSSM vehicle penalties, a minimum development program, and simplicity of operation.

This system selection was accomplished by: (1) defining the minimum navigation requirement of the LSSM mission considering the LSSM mission, the appropriate navigation functions, and the visual sighting distance to the Shelter, and (2) evaluating various possible techniques and concepts in relation to their requirements. These concepts included simply maintaining visual contact with the Shelter, using systems which function in effect by extending the visual homing distance, and using systems which operate beyond the limit of visual homing but assure the capability to navigate to within this limit.

Navigation by an astronaut maintaining visual contact with the Shelter satisfies the functional requirements. However, use of this concept restricts the LSSM mission to operations within the range of visual contact which was determined to be approximately 190 meters.

Navigation by the concepts described for extending the visual homing distance in general constrained the mission operation by requiring that the return route to the Shelter be a retrace of the initial route. One exception to this requirement was the RF homing beacon concept which provides immediate indication of the bearing to the Shelter.

Navigation by concepts described for operating beyond the visual homing distance out to a desired radius of 8 km affords the greatest versatility in mission operations. The navigation data derived by these systems provide a knowledge of LSSM position as well as the basic data required to home on the Shelter.

The most favorable technique for vehicle navigation was found to be simple dead-reckoning. Evaluation of the gyro-odometer dead-reckoning concept indicated that a complete set of navigation data can be obtained by a minimal system without restricting the mission operation.

2.0 LSSM NAVIGATION

2.1 LSSM MISSION [1]

One of the most desirable and logical objectives for post-Apollo missions in the early 1970's is the extended manned exploration of the lunar surface. The initial Apollo missions will be fairly short duration, and will allow for lunar surface exploration only in the immediate vicinity of the LEM vehicle. However, in the Apollo Applications Program (AAP), the basic Apollo hardware may be modified to provide a system which will allow for exploration well beyond walking distance of the landing point on the moon.

One key modification is the evolution of a LEM vehicle into the LEM-Shelter, which will provide the life support for two astronauts for a 14-day mission on the lunar surface. This vehicle will land unmanned and will remain in storage until the time of the manned LEM landing nearby.

In addition to extra life support provisions, the LEM-Shelter may have stowed on it a surface vehicle to be deployed onto the lunar surface for use by the astronauts as a mobility aid. This vehicle has been termed LSSM (Local Scientific Survey Module).

The main purpose of the AAP lunar surface missions will be intensive scientific exploration of significantly larger areas than previously possible. The stay time must be longer and the radius of operations greater than the early Apollo mission. The purpose of the LSSM is to serve as a mobility aid which will increase the radius of operations out to at least 8 km. By driving the LSSM and using a portable life support system (PLSS), a single astronaut will be able to travel up to 13 km/hr between stations on the surface at which scientific experiments will be performed. Also, short sorties on foot may be performed by the astronauts in the vicinity of the Shelter and the LSSM. By means of both types of sorties, the crew of an AAP mission will collect enough data in 14 days to allow a very comprehensive geological and geophysical assessment of the area.

From a review of requirements, traverses and experimental sequences to be performed on the set of missions described in a scientific mission study (Reference 2), it was determined that three principal types of missions would be carried out during LSSM surface traverses: (1) geological/

geophysical reconnaissance sorties, (2) deep refraction seismic surveys, and (3) geological observation including 10-foot drilling operations.

The purpose of the geological/geophysical reconnaissance sorties is to observe widely dispersed interesting features within the maximum radial range (8 km) of the Shelter. The total range per sortie varies from 16 to 26 km straight-line distance and the average range is 20 km.

The purpose of the deep refraction seismic survey sorties is to obtain seismic data to a great depth within the moon's crust.

Typically, a 330 meter spread of 12 geophones spaced at 30-meter intervals is located in a straight line near the Shelter. Shots are emplaced and detonated on a line out from the geophone spread in opposite directions (one sortie in each direction). The radius of operations is 8 km.

The purpose of the geological observation sorties is to obtain core samples at a depth of 10 feet on particularly interesting features. The radius of operations is 5.5 km.

These missions all require some form of navigation activity during their execution for experiment position location and return to the Shelter. Several navigation functions may be involved.

2.2 NAVIGATION FUNCTIONS

Navigation may be required: (a) to locate lunar features and experiment sites, (b) for crew safety while driving the required exploration route, and (c) to determine the return route to the Shelter.

Specifically, the navigation functions for the above purposes are: the provision of position data, the provision of vehicle pitch and roll angles, the provision of return distance to the Shelter information, and provision of bearing angle to the Shelter.

- Position data establishes the location of scientific experiments, terrain features, and terrain samples.

- Pitch and roll angles are for use in operating the vehicle within specific safety limits of maneuverability.

- Return distance to the Shelter is for use in conjunction with the return trip contours such that sortie time and vehicle consumables required for the return travel to Shelter can be determined. This determination is required to assure that the vehicle operator does not extend the sortie beyond the point of return capability.

- Bearing angle allows the vehicle operator to drive the vehicle in a direction leading to the Shelter.

Position data sufficiently accurate for many scientific purposes requires an extensive implementation far beyond that necessary for crew safety. Such equipment must be matched with and considered a part of the scientific instrumentation rather than a part of the navigation system for an LSSM mobility aid.

The fact that the vehicle is operating under very stable conditions (low slopes, slow speed, low vehicle center of gravity) makes pitch and roll angle determination unnecessary. The astronauts should be able to maneuver the vehicle safely under the anticipated conditions.

A knowledge of return distance to the Shelter is of secondary importance. Operational procedures can be adopted which will eliminate this navigation function. For example, elapsed time and distance traveled can be measured and used as adequate indications of the return distance.

The determination of the bearing angle to the Shelter is the primary navigation function. A mission operation which does not include provision of the bearing angle but instead requires a space-suited vehicle operator to search for the Shelter in an unfamiliar environment does not offer the high probability of mission success and the high astronaut confidence that is provided through operation with a navigation system which assures the capability to drive to the location of the Shelter.

For this reason, a fundamental assumption is made with regard to the return to the Shelter:

> The navigation system must provide the bearing angle to the Shelter to a degree of accuracy such that the LSSM vehicle can be navigated within an assured recognition distance of the Shelter.

The assured recognition distance (ARD) is not simply defined as line-of-sight (LOS) distance. The ARD is applicable to a returning vehicle which has not been in constant view of the Shelter, and not only must the Shelter and LSSM be within LOS, but also an astronaut must be able to acquire the Shelter within view and to recognize it. The ARD is a function of the human eye capability, the illumination constants, the optical properties of both the Shelter and the surrounding terrain, visual detection and recognition aids, and the distance of line-of-sight.

If all of the desired LSSM missions could be performed within this ARD, then obviously no navigation aids would be required.

It is of prime importance, therefore, to the specification of possible navigation aid requirements to determine as precisely as possible the extent of this ARD on the lunar surface.

3.0 ASSURED RECOGNITION DISTANCE (ARD)

Assured Recognition Distance (the distance from the Shelter within which the LSSM must be navigated to assure that visual homing can be accomplished) is a function of:

(a) The detection and recognition distance, and

(b) The line-of-sight distance.

There are three steps in establishing the ARD:

1. Determine the minimum detection and recognition distances as a function of the visual properties, i.e., human eye capability, the illumination constants, the optical properties of the Shelter, and the surrounding terrain, etc.

2. Find the LOS distance with regard to:

   a. The lunar curvature

   b. The gross structure terrain features at potential landing sites

   c. The fine structure terrain features of the lunar surface as determined through earth-based measurements and Ranger photographs.

3. Define the ARD as the minimum distance determined in Steps 1 and 2.

3.1 DETECTION AND RECOGNITION

The recognition and contrast problem was investigated in Reference 3. The range of detection (99% probability) was determined for a 5-meter hemisphere (422 ft^2) and a 1-meter hemisphere (16.9 ft^2) under various viewing conditions. The hemispheres were assumed to have an 80% reflectance. This is in agreement with the Shelter absorption of 0.2 given in Reference 4. Visual sighting distance curves are shown in Appendix A. The detection range under worst case observation conditions from these curves is given in Table 3-1. Figure 3-1 describes the observer, target, and illumination source geometry.

TABLE 3-1

Detection Range
(Worst Case Observation Conditions)

	1 meter hemisphere		5 meter hemisphere	
Illum. Cond.	Lunar Day	Lunar Night	Lunar Day	Lunar Night
Viewing Angle	180°	180°	180°	180°
Illum. Angle	90°	30°	90°	30°
Detection Range	5 km	1 km	22 km	4.5 km

Notes:

1. The detection range associated with the above conditions are considered conservative. They are based on a target-to-background contrast of 10 whereas the true contrast ranges from 10 to 100.

2. The lunar night condition assumed maximum earth shine. A minimum earth shine condition reduces the detection ranges by a factor of approximately 2.

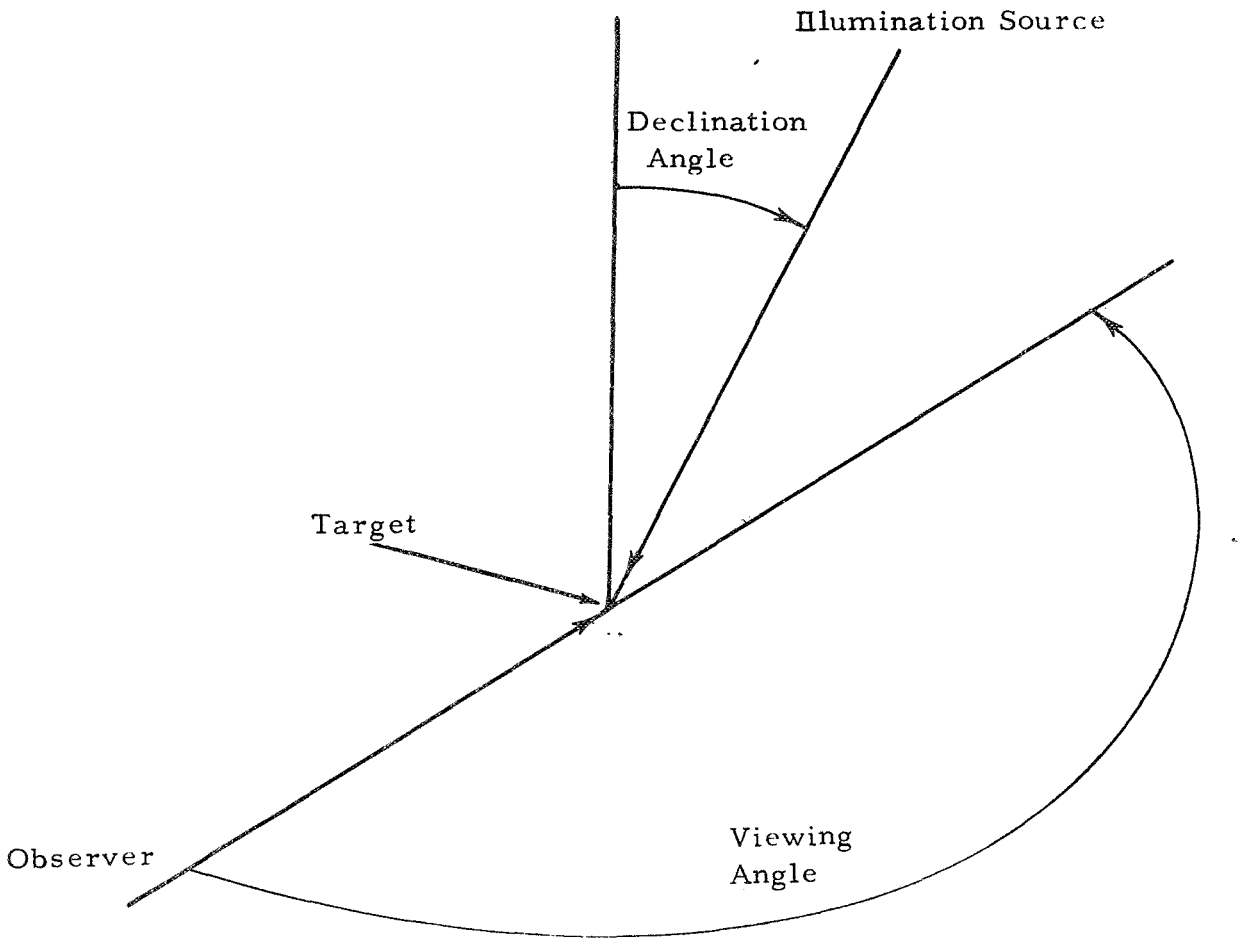

Figure 3-1 Observer, Target, and Illumination Source Geometry

The worst viewing and illumination angle condition detection ranges for a Shelter (assumed to be equivalent to a 150 ft^2 hemisphere) have been interpolated from the above data. The resulting Shelter detection ranges are shown in Table 3-2.

TABLE 3-2

Shelter Detection Range

Illumination Condition	Detection Range
Lunar Day	15 km
Lunar Night (max. earth light)	3.0 km
Lunar Night (min. earth light)	1.5 km

Once an object presumed to be the Shelter has been detected, the operator next must be able to recognize it as the Shelter. The human eye has the capability to resolve an angle of 1 arc min. Assuming that 3 resolution units are required for a comfortable working condition, the target must subtend 3 arc min. This is equivalent to a maximum recognition range of 3.5 km for a Shelter objective.

Thus, the combined detection and recognition distances under the minimum viewing and illumination angle conditions are given in Table 3-3.

TABLE 3-3

Detection and Recognition Range

Illumination Condition	Detection and Recognition Range (km)
Lunar Day	3.5
Lunar Night (max. earth light)	3.0
Lunar Night (min. earth light)	1.5

The detection and recognition ranges presented in the above table are those under the most unfavorable viewing conditions. A more complete analysis would consider not only the probability of detection but also the probability of experiencing the various possible viewing conditions.

By proper mission planning, it may be possible to present a favorable viewing condition during Shelter return without compromising the mission objectives. However, for this preliminary analysis, the minimum condition is accepted.

3.2 LINE-OF-SIGHT

The line-of-sight in the immediate vicinity of the Shelter is defined by the lunar curvature, the irregular terrain obstructions, and the viewing heights of the Shelter and the LSSM vehicles. The irregular terrain obstructions include both surface objects and surface slopes. For simplicity of analysis the irregularities were divided into two classes: gross structure and fine structure. The gross structure refers to the large objects, and their associated slopes, which appear on potential landing site contour maps. The fine structure irregularities refer to the small objects and gentle slopes.

In the following analysis, the viewing heights of the Shelter and LSSM are taken as 5.15 meters (17 ft) and 1.5 meters (5 ft) respectively.

3.2.1 LOS, Lunar Curvature

The LOS distance on a smooth surface spherical moon can be determined as a function of the heights of the objectives by use of the nomograph [5] of Appendix B. For the assumed object heights of 5.15 and 1.5 meters, visual contact can be achieved at a range of 6 km.

3.2.2 LOS, Gross Structure

To determine LOS with respect to large surface objects and their associated slopes, the lunar contour maps of 6 potential LSSM landing sites [2] were examined. The term "large surface objects and their associated slopes" is associated with contour maps which denote contour intervals of 100 meters.

The contour map of the Alphonsus site (located at 13° 30'S, 2° 40W) is shown in Figure 3-2. A shelter landing point dispersion, 800 meter CEP, was assumed about the indicated landing point at the Alphonsus site. The minimum LOS with respect to any landing point contained within the 800 meter CEP was determined as 0.75 km.

Similarly, the LOS, gross structure was determined for the other selected landing sites given in Reference 2 and tabulated in Table 3-4. Maps of these areas are presented in Appendix C.

3.2.3 LOS, Fine Structure

Line-of-sight range is reduced by both surface objects and slopes; however, based on the low frequency of surface protruding objects detected by the Ranger photographs, only "effective slopes" are considered in the following analysis. "Effective slopes" are defined to include both true terrain slopes and those elevation changes resulting from small surface objects.

The method of determination of LOS distance as constrained by the fine structure of the lunar terrain may perhaps best be described in terms of a series of procedural steps. These steps are outlined in the flow diagram of Figure 3-3. Steps A through C define the parameters of a hypothetical object which will limit the LOS. Steps D through G define the parameter associated with particular lunar objects. The combination of these data, Step H, results in a limiting value of LOS. These steps, explained below, will be applied to the LSSM-Shelter LOS determination using currently available lunar data.

Step A

Determine the object height which will obstruct LOS. The object may be a sharply sloped protuberance or a peak of a gentle slope. As shown in Step A, of Figure 3-3, the spherical curvature of the lunar surface is not included. This assumption is valid for short distances.

Step B

Relate the object height of Step A to a family of effective slope magnitudes and lengths.

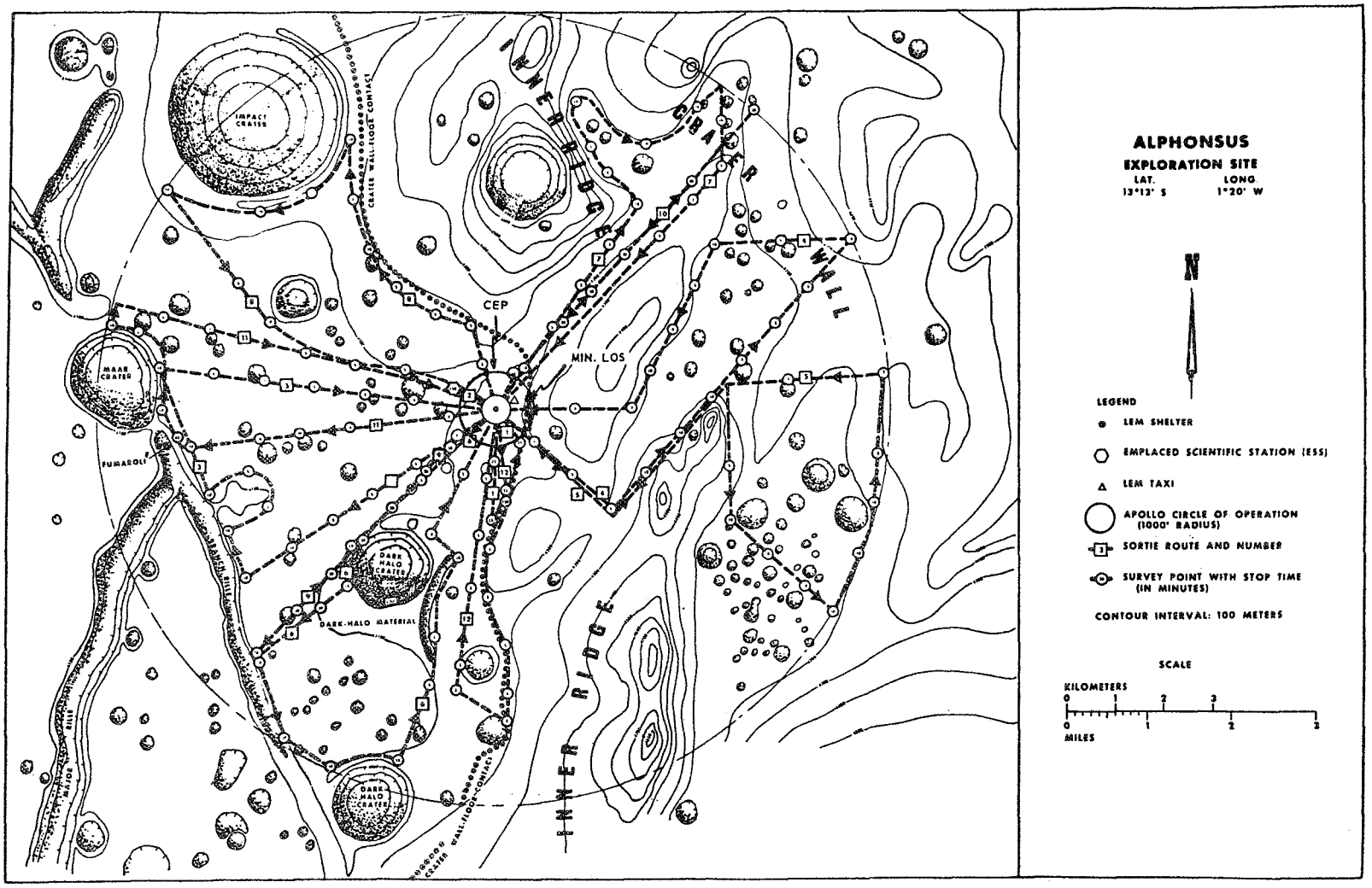

Figure 3-2 Alphonsus - LSSM Traverse Map

TABLE 3-4

Minimum LOS, Gross Structure for Potential LSSM Landing Sites

Site	Minimum LOS (km)
Alphonsus	0.75
Hyginus Rille	0.75
Capella M	0.75
Moltke B	4.0
Farside	1.1

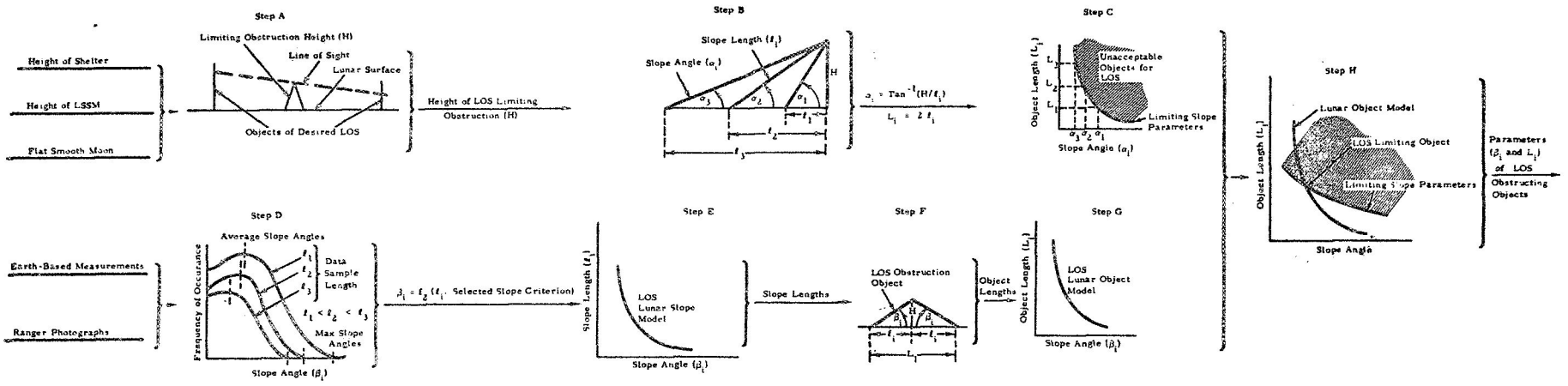

Figure 3-3 Fine Structure LOS Determination Flow Diagram

Step C

Express the object length vs. slope angle relationship. (Object Length, L_i, is assumed to be 2 times the slope length derived in Step B.) The surface objects which are identified with the shaded portion of the figure in Step C represent objects which block LOS; i.e., the effective object height is too great for LOS to exist if: (1) for a given slope magnitude α_2, the slope length is increased ($L > L_2$), or (2) for a given slope length L_2, the slope magnitude is increased ($\alpha > \alpha_2$).

Step D

Apply the available lunar surface data which defines the slope frequency, slope length, and slope angle. From this data, a selected slope criterion is defined. The slope data for the remaining analysis is based on the selection of a maximum slope angle associated with a specific slope length, or average slope angle associated with a specific slope length, or slope distribution associated with the range of applicable slope lengths. The first of these criteria is used in the subsequent analysis.

Step E

Derive a LOS Lunar Slope Model which relates slope angle to slope length for the specified criterion of Step D.

Step F

Assume the condition of equal magnitude slopes oriented such that they form an effective object of height H with length, $L_i = 2\ell_i$.

Step G

Determine a LOS Lunar Object Model which relates slope angle to object length for the specified criterion.

Step H

Superimpose the two derived slope relations (from Step C and Step G). The portion of the object model data which lies above

the limiting slope parameter data (the shaded portion of the figure of Step C) describes lunar terrain which will obstruct the LOS.

A more complete analysis of the LOS, fine structure would require:

(a) A consideration of the distribution of terrain object location between the two LOS objects. This effect should be considered due to the fact that a taller terrain object is acceptable if it is located near the taller LOS object (Shelter) rather than near the shorter LOS object (LSSM).

(b) A consideration of all slopes rather than selecting a maximum or median criterion as discussed in Step D. All slopes would be included in the analysis of the probability of slope occurrence.

(c) A consideration of the probability of various slope combinations rather than assuming two slopes of equal magnitude occur back to back as described in Step F.

This statistical approach for both the LOS obstruction object definition and the Lunar Model Object definition would establish the probability of LOS obstruction for any slope conditions. Since this is a problem of considerable magnitude, the simplified approach described in the above steps was used in the following analysis to determine the most restrictive condition.

STEPS A, B, AND C

The minimum LOS obstruction height is associated with the condition where the obstruction is adjacent to the shorter of the two LOS objects, i.e., the LSSM vehicle. The maximum LOS obstruction height is associated with the condition where it is adjacent to the taller of the two LOS objects, i.e., the Shelter. This is shown in Figure 3-4.

For simplicity, rather than investigating the probability of object location, the two identified extreme conditions were examined.

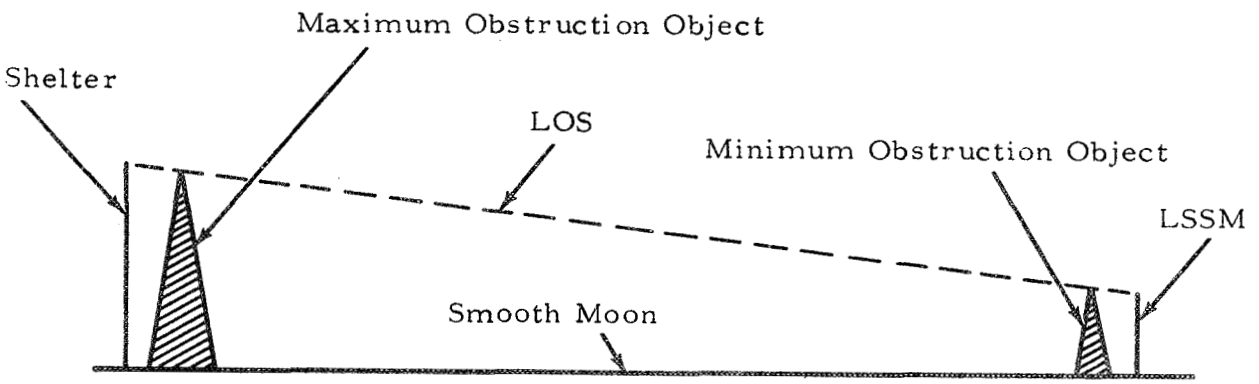

Figure 3-4 Maximum and Minimum Objects of Obstruction

The length of the obstruction slope (ℓ_i) is defined as a function of the slope angle (α_i) and the obstruction height (H) as:

$$\ell_i = H/\alpha_i$$

The object length (L_i) is assumed to be twice the length of the slope. Parametric curves of object length, as a function of H and α_i, are shown in Figure 3-5 for the values:

H = Shelter Height = 17 ft,
and H = LSSM Height = 5 ft.

STEP D

Several models of the lunar terrain have been proposed during the recent years: data used in the following analysis was derived from Ranger 7 photographs [6]. This data was extracted from the photographic data by sampling the contours at 1, 3, 5, and 10 meter intervals. Figures 3-6, 3-7, 3-8, and 3-9 illustrate the cumulative per cent of traverse distance as a function of slope length for the various sampling intervals, e.g., for a one-meter sample interval (Figure 3-8), slopes greater than 8° occur along 20% of a typical traverse.

The LOS terrain parameters of slope angle and slope length can be interpreted from Figures 3-6 through 3-9. For example, from Figure 3-6, the maximum slope angle associated with a one-meter slope length is 28°; the average slope associated with a one-meter slope length is 4.99°.

STEP E

The slope criterion assumed for the following analysis is a maximum or extreme limiting condition. That is, the maximum slope for any given slope length is considered when determining the resultant height of the effective surface object.

The maximum slopes associated with each sample spacing or slope length taken from the data presented in Step D are shown in Figure 3-10. To extend the data to slopes of greater length, one additional data point [7] was obtained from the USGS, Branch of Astrogeology, at Flagstaff, Arizona. As expected, a short sampling spacing (or slope length) yields terrain segments of "high slope".

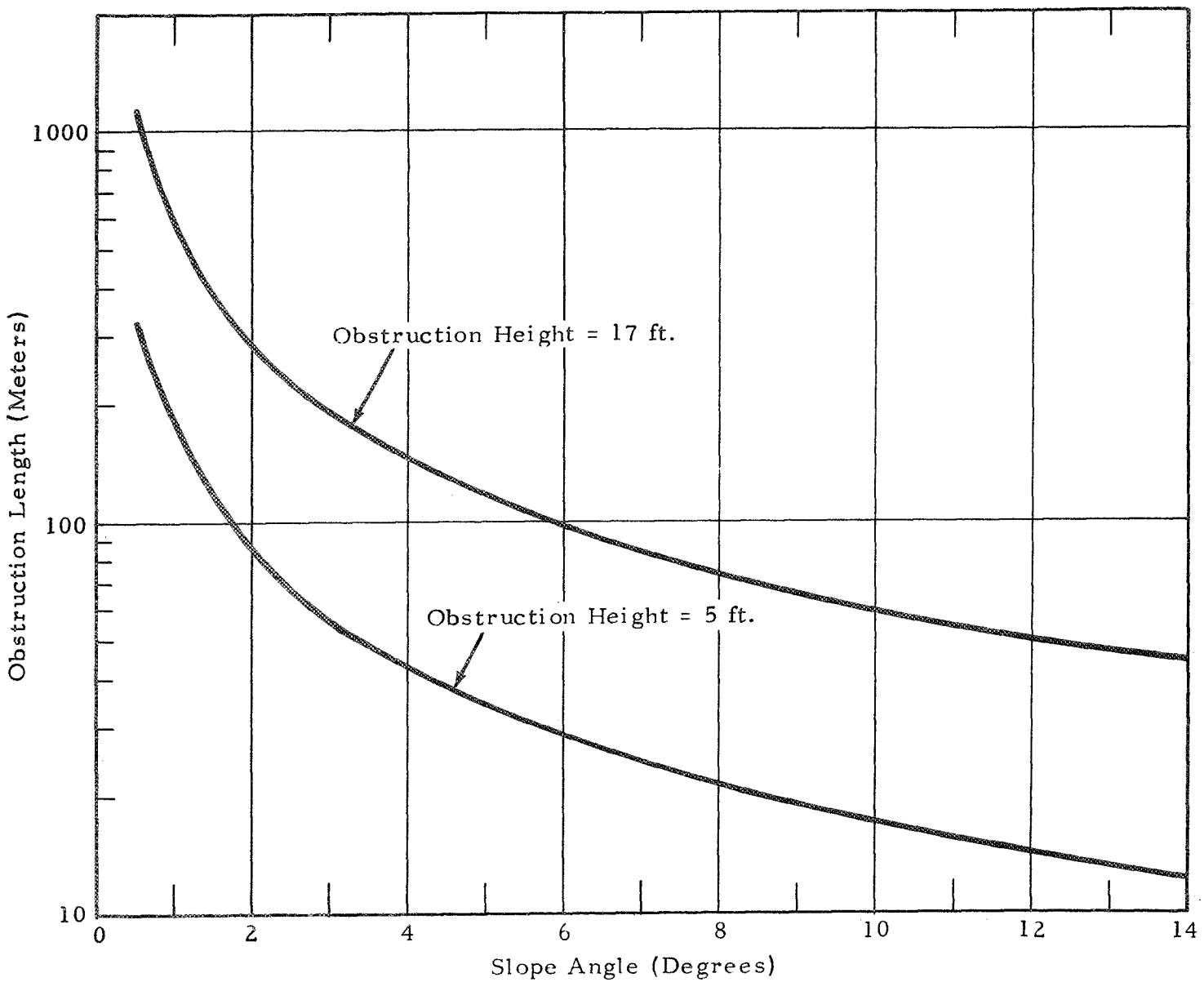

Figure 3-5 Length of Obstruction as a Function of Slope Angle and Obstruction Height

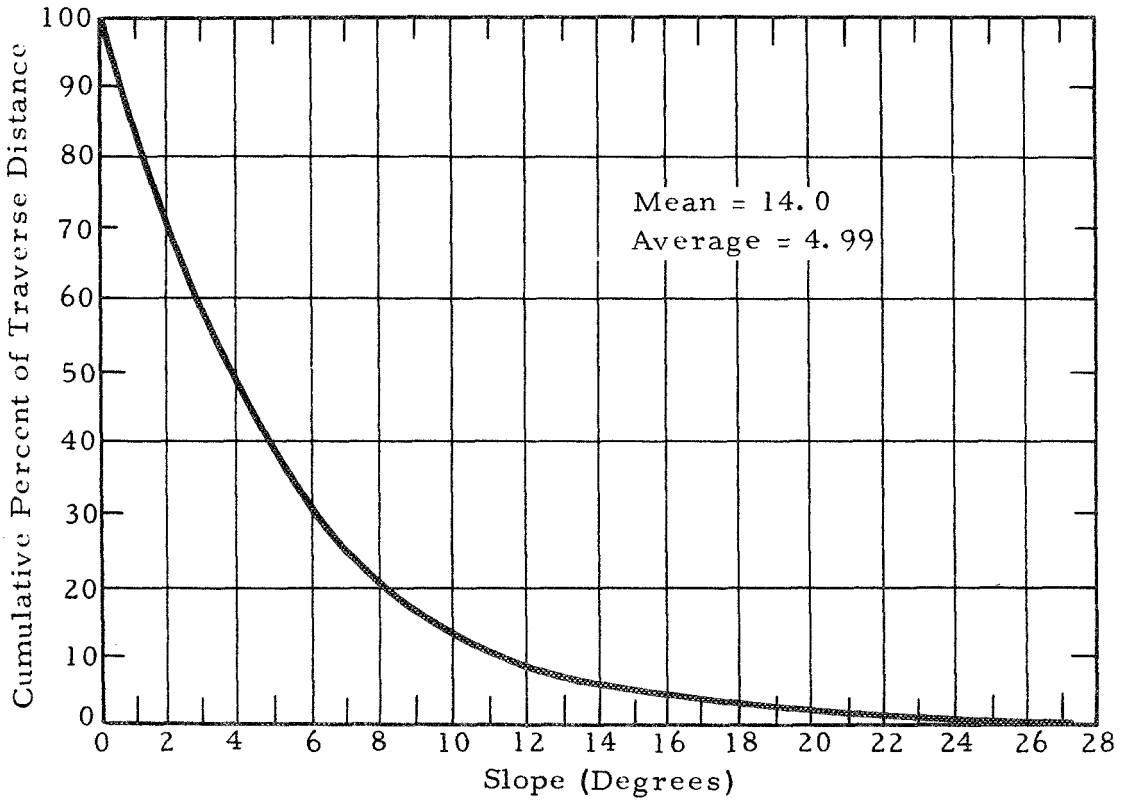

Figure 3-6 Slope Distribution at One Meter Sample Spacing

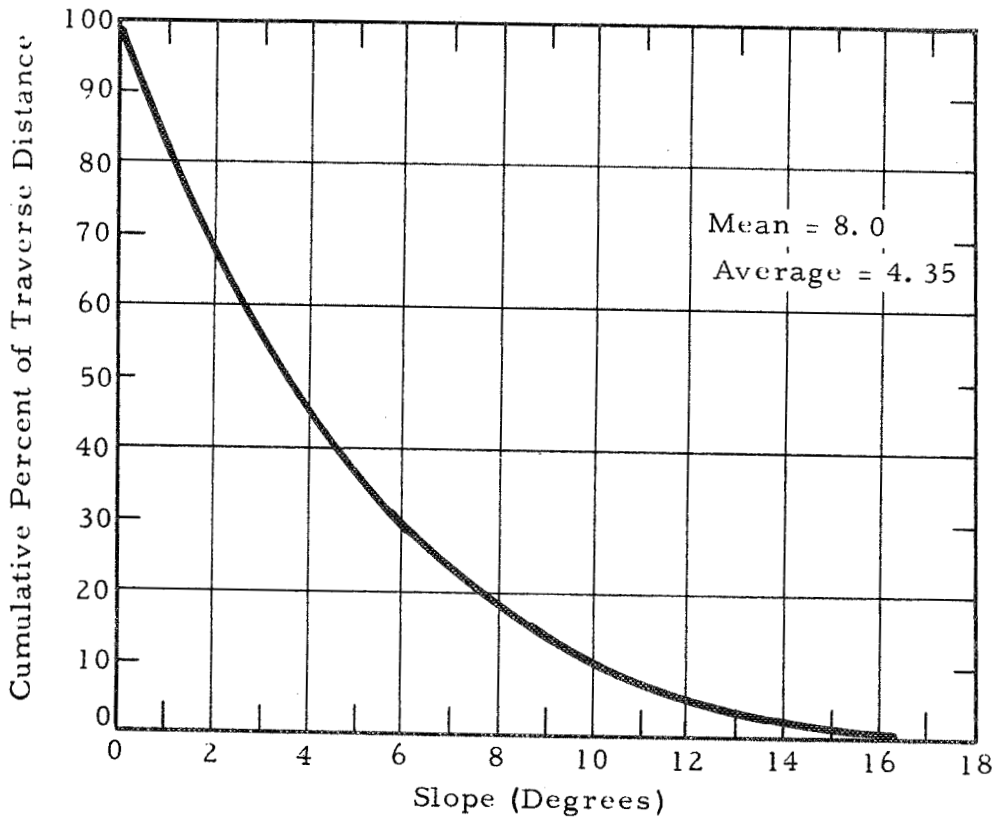

Figure 3-7 Slope Distribution at Three Meter Sample Spacing

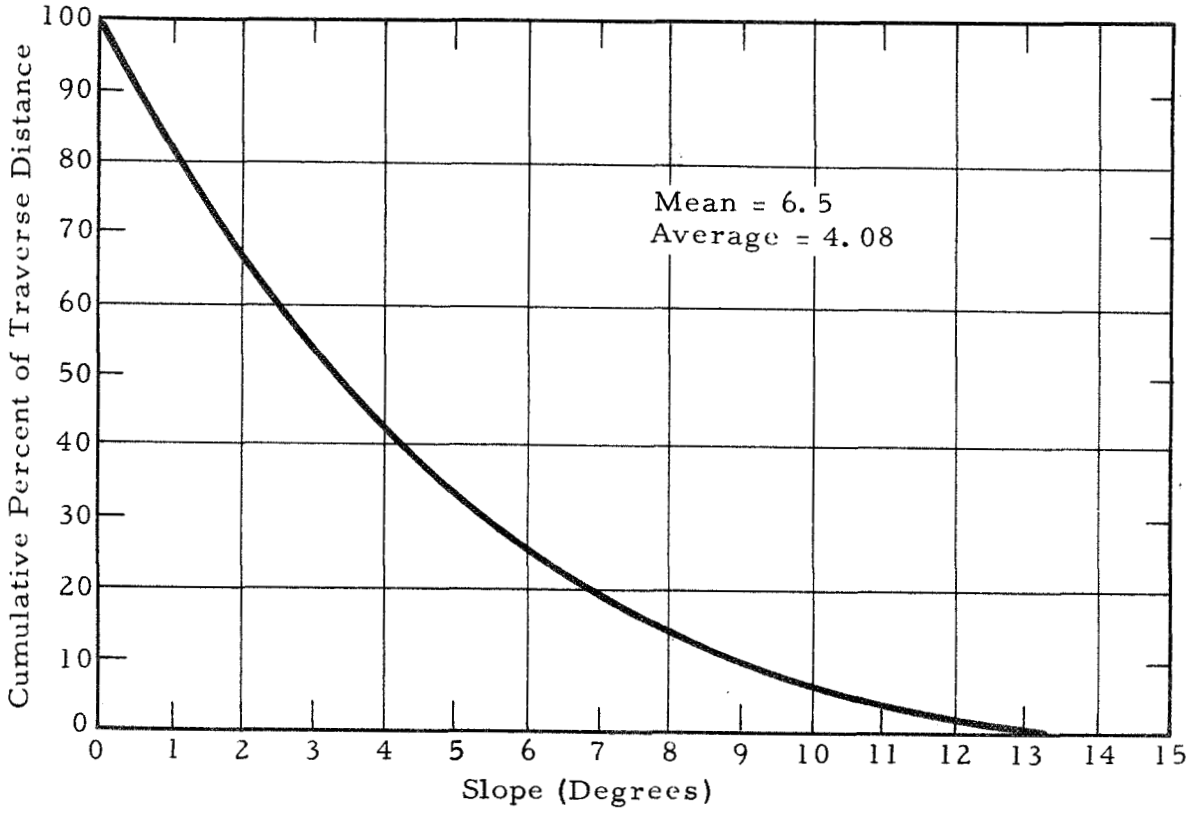

Figure 3-8 Slope Distribution at Five Meter Sample Spacings

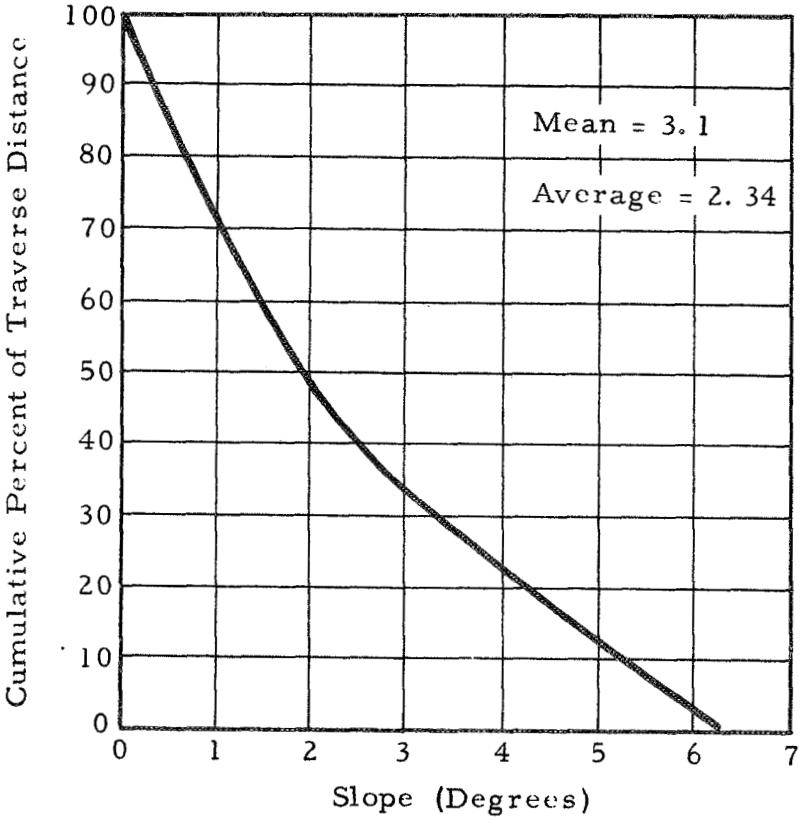

Figure 3-9 Slope Distribution at Ten Meter Sample Spacings

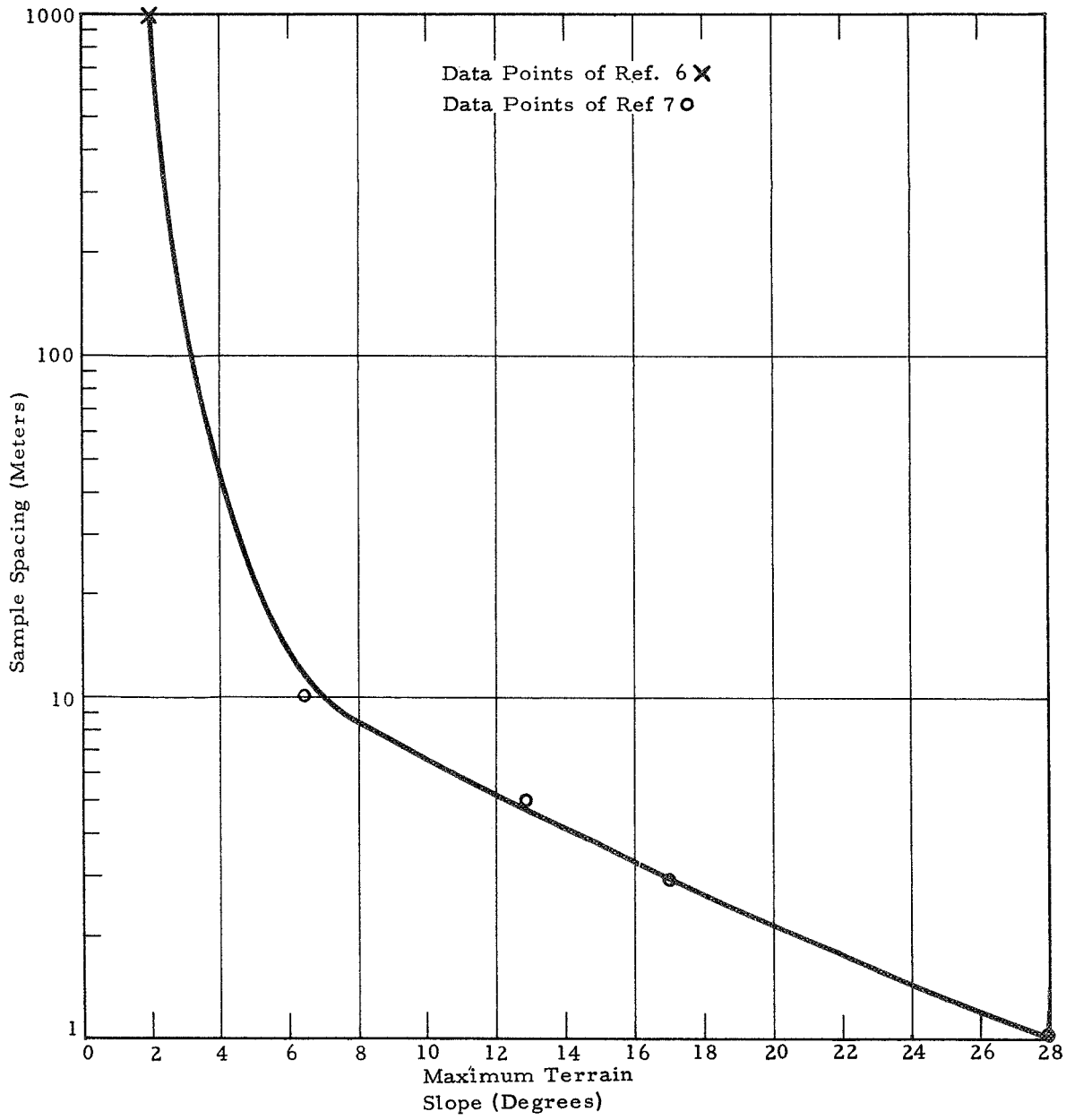

Figure 3-10 Sample Spacing vs. Maximum Slope Magnitude

This data is not to be considered as applicable to all areas of the moon but certainly to the earlier (relatively smooth) landing areas.

STEP F

The fine structure LOS obstruction length is defined as twice the length of the terrain slope associated with a specific slope angle. This condition, shown in Figure 3-11, was assumed for determining the minimum LOS distance.

STEP G

With the assumption of Step F, the terrain slope data of Figure 3-10 may be interpreted as terrain object data. This data is presented in Figure 3-12.

STEP H

To identify objects of the Lunar Object Model whose parameters lie within the obstruction portion of the Obstruction Geometry, Figure 3-5 may be superimposed on the curves of Figure 3-12. The resulting combination of data curves is shown in Figure 3-13. Table 3-5 summarizes the object data which limits the fine structure LOS.

TABLE 3-5

Fine Structure, LOS, Limiting Object Data

	LOS Distance (meters)	Terrain Slope (degrees)
Minimum Obstruction	30	5.6
Maximum Obstruction	185	3.3

The LOS obstruction situation which is presented by the 3.3 to 5.6 degree slopes might best be related to desert regions of the earth where the terrain can be composed of overlapping and adjacent terrain undulations having lengths of the order of 30 meters and slopes of 5.6 degrees (or 185 meters in length and 3.3 degrees of slope).

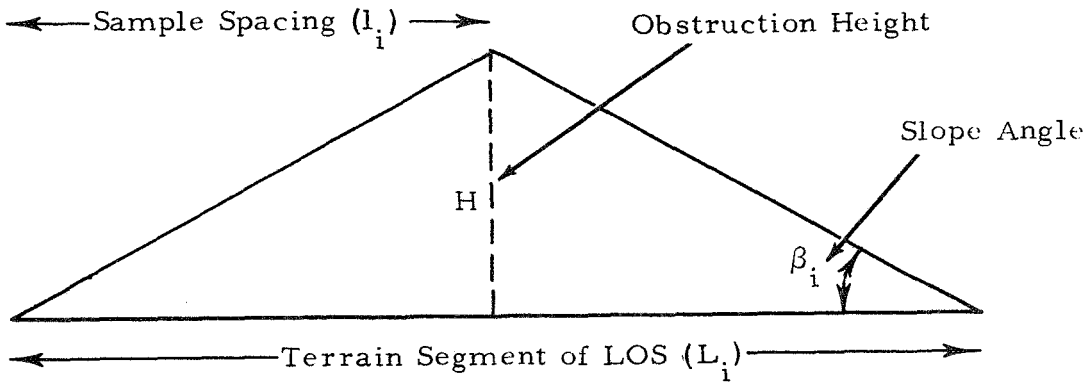

Figure 3-11 Structure LOS Obstruction Geometry

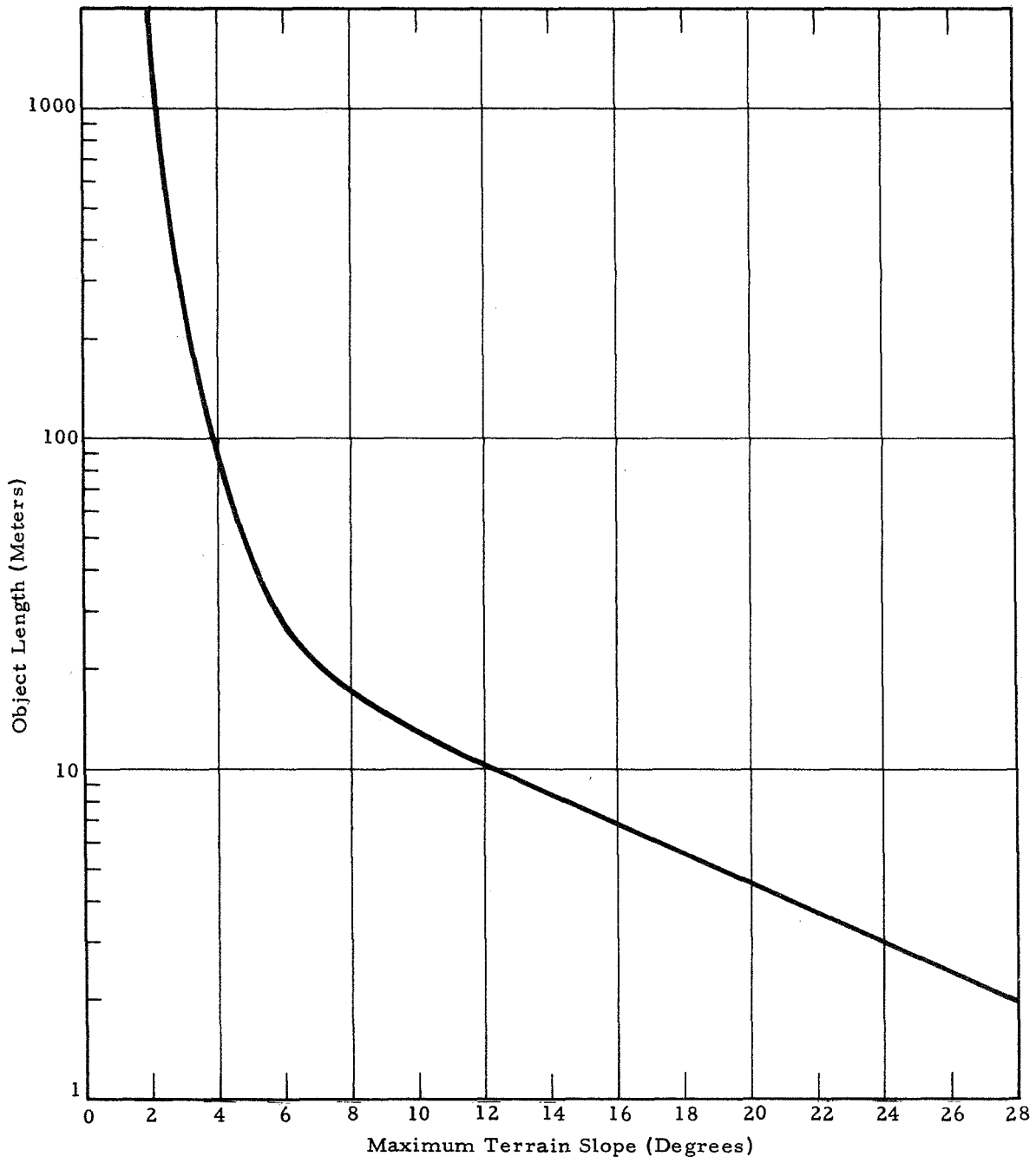

Figure 3-12 Object Length vs. Maximum Slope Magnitude

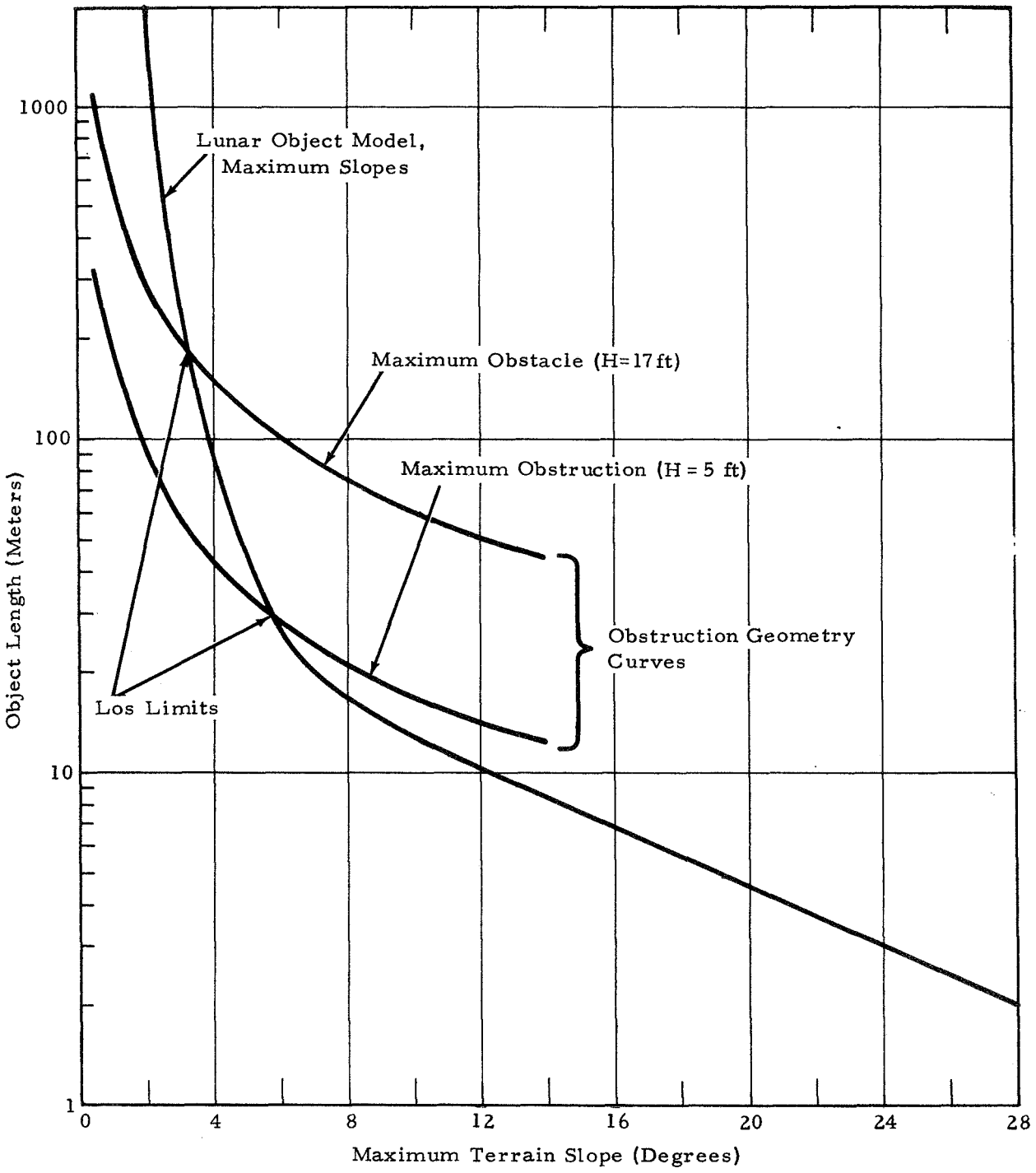

Figure 3-13 Fine Structure LOS Limitation Determination

Based on the stated assumptions and the existing lunar data, the range of the LOS fine structure distance is found to be 30 to 185 meters. Actually, these objects with their associated low magnitude slopes cannot be located immediately adjacent to LSSM or Shelter as shown in Figure 3-4. The object peaks will rather be located at the center of the object length which is also the LOS midpoint. When displaced from the LSSM or Shelter, these objects will no longer exactly represent the limiting conditions; however, they bound the range of obstruction objects. The relationship is shown in Figure 3-14.

3.3 ASSURED RECOGNITION DISTANCE

The Assured Recognition Distance was shown to be a function of Shelter detection and recognition range and lunar line-of-sight. Table 3-6 summarizes the analysis results. The minimum assured recognition distance was determined to be 0.03 to 0.185 km (LOS, fine structure).

The most detrimental conditions presented are not considered as practical constraints to the navigation system design due to the maximum condition assumptions at certain points in the analysis (i.e., slope reversals yielding terrain object length equal to 2 times the slope length, the maximum slope conditions, and the minimum obstruction or LSSM located object). A statistical analysis, as previously described, is required to define a probability of fine structure LOS distance. This type of analysis will become more feasible as more data is compiled from Ranger photographs.

One other method by which the analysis may be performed is to consider the average terrain slope associated with the Ranger data sampling spacing (rather than maximum terrain slope).

Data is presented in Appendix D which identifies the terrain slope length with this average slope. This data results in a LOS, fine structure, distance of 0.09 to 0.46 km.

In order to present a single value estimate of the expected ARD limitation which is due to the fine structure of the lunar surface, the average is taken of the limiting conditions for both maximum and average slope data. This process yields an estimate of 0.19 km.

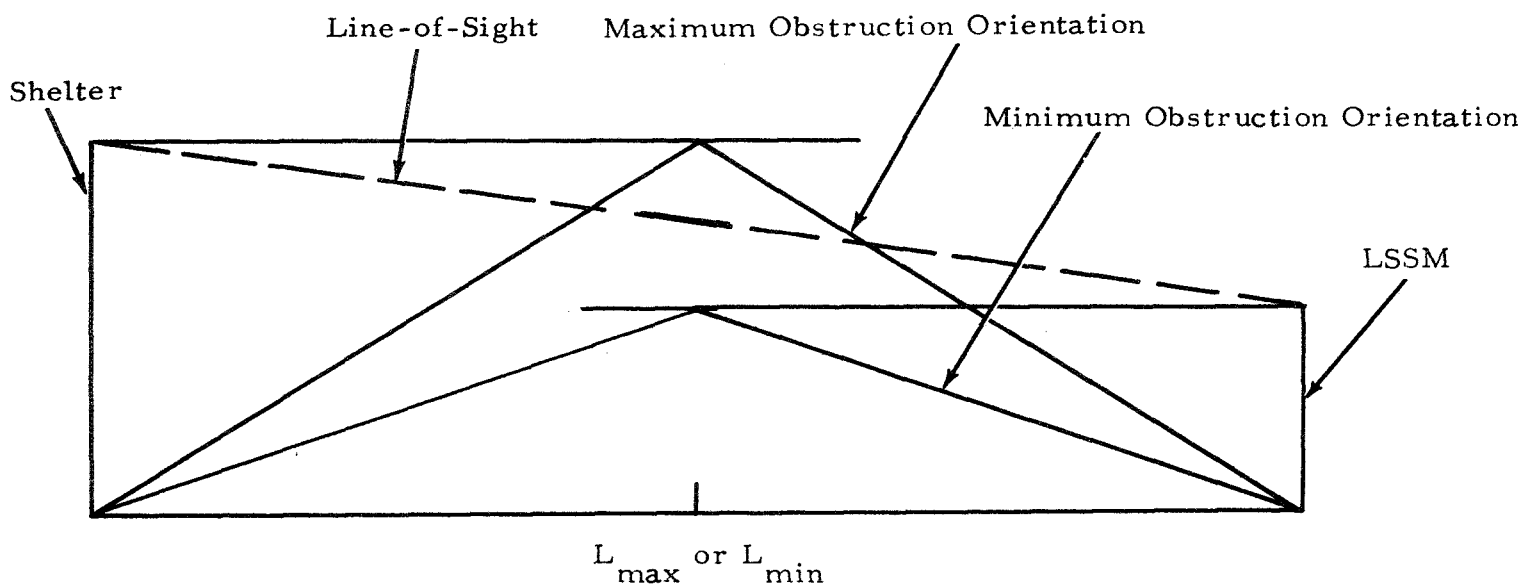

Figure 3-14 Minimum and Maximum Obstructions

TABLE 3-6

Assured Recognition Distance

ARD Parameters	Range
Detection and Recognition	1.5 to 3.5 km
LOS, Lunar Curvature	6.0 km
LOS. Gross Structure	0.75 to 4.0 km
LOS, Fine Structure	0.03 to 0.185 km

Thus, it is concluded that the LSSM Navigation System must have the capability to navigate the vehicle to within 0.19 km of the Shelter in order to be within the Assured Recognition Distance.

4.0 NAVIGATION WITHIN THE ASSURED RECOGNITION DISTANCE

The LSSM navigation function can be accomplished by the vehicle operator by maintaining visual contact with the Shelter. However, the range of visual contact is restricted to an area surrounding the Shelter limited to a radius equal to the Assured Recognition Distance. Thus, a mission which depends on Shelter visual contact by an astronaut is constrained to an operating radius as derived in Section 3.0 of about 0.19 km.

The three classes of LSSM missions described in Section 2.0 require an operating radius capability of 5.5 to 8 km. Geologists have stated [8] that an LSSM operational range of 8 km is minimum and 15 km would be more useful for geological investigation. This operating range is needed to permit observation and examination of areas sufficient in size to contain geological variations.

Further, to examine a significant lunar feature, an LSSM range exceeding 800 meter (the expected landing CEP) may be required in order to allow the vehicle to move from the Shelter landing point to the selected feature.

The analysis of Section 3.0 describes a more or less worst case situation so that there is a reasonably high probability that the assured recognition distance in a specific instance will be greater than 0.19 km. Also, this ARD may vary as a function of direction from the Shelter so that operation out to greater distances may be possible with the limitation that the return path not diverge greatly from the outbound path.

If, taking a very conservative approach, investigations were to be limited to within about 190 meters of the Shelter, a surface vehicle such as a "Pack Mule" serving essentially as an equipment carrier would be more suitable than an LSSM.

It is probable however, that a greater operating range is possible with appropriate restrictions. Therefore, to more fully utilize the mission capabilities of an LSSM type vehicle, it is highly desirable that, as a minimum, the Assured Recognition Distance by extended with the use of some form of navigation aid.

5.0 NAVIGATION AIDS FOR EXTENDING ASSURED RECOGNITION DISTANCE

The Assured Recognition Distance, the distance from the Shelter within which the LSSM must navigate to assure visual homing, can be extended by: (1) extending the detection and recognition distance and the LOS distance, or (2) by providing an indicator beyond the ARD vicinity to aid in maneuvering the LSSM to within the actual ARD.

Navigation techniques and concepts applicable to the extension of ARD are:

1) Visual Beacon
2) Radio Frequency Beacon
3) Piloting
4) Trail Blazing

These techniques and concepts for LSSM navigation are considered in the following sections.

5.1 VISUAL BEACON

A visual light beacon mounted above the LEM-Shelter may possibly be used as a homing aid for the astronaut on an LSSM. This beacon if raised to a sufficient height might provide a reference by which the LSSM can be navigated to within Shelter visual homing distance. Its actual usefulness depends upon the ability of the astronaut to see it under expected lunar conditions.

The threshold illumination, at the eye, for 95% probability of detection of a bright steady achromatic point source viewed against a uniform background , when the observer knows where to look, is given in Figure 5-1 as a function of background luminance.

A flashing light rather than a steady source will enhance the discriminability of the beacon with any naturally occuring bright spots on the lunar surface. A colored light is not recommended because: (a) it is less efficient to generate; (b) the brightness threshold for color discrimination is higher than for simple brightness discrimination [9], and (c) too little is known about the small scale or local coloration of the lunar surface to rely on this means of coding.

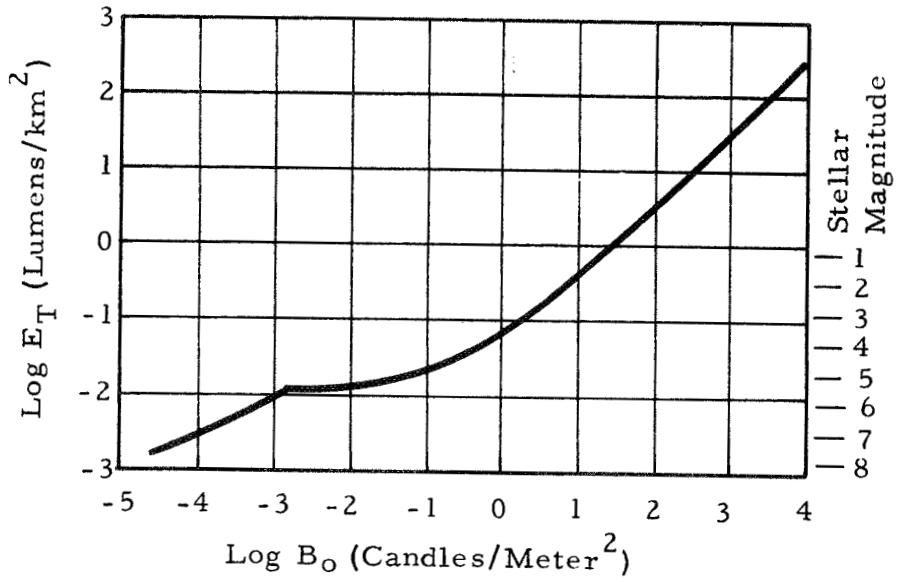

Figure 5-1 Threshold Illuminance (E_T) vs. Background Luminance (B_o) for a Fixed, Achromatic Point Source

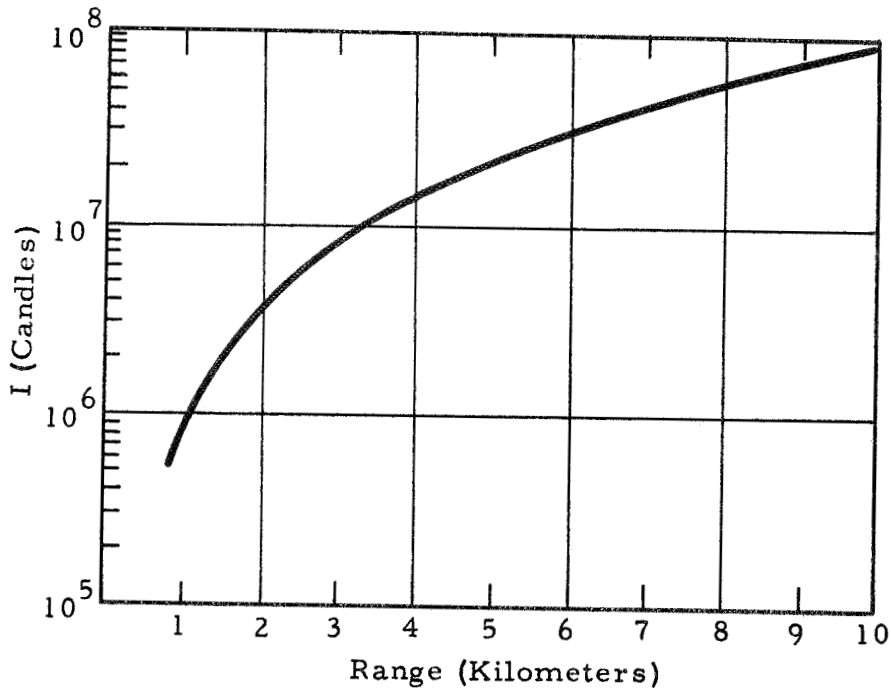

Figure 5-2 Threshold Beam Intensity (I) vs. Sighting Range (R) for Worst Case Lunar Background

Low power flashing beacon lights using xenon flashtubes have been used in space on the Mercury and Gemini programs. These flashtubes typically have flash durations of the order of 10^{-5} to 10^{-2} seconds. The flash duration is not a critical value; however, so long as the total energy per flash remains constant.

The worst case viewing condition will occur when the beacon appears against a bright lunar surface. When the observer is searching for the beacon with the sun to his back, the lunar photometric function will approach 1.0. The brightness of the lunar surface will be 8.6×10^3 candles/meter^2 for an albedo of 0.18 (maximum expected value) and solar illumination of 15×10^4 lumens/meter^2. This value of brightness and a typical flash duration of 10^{-3} yields the relationship of beam intensity versus range shown in Figure 5-2. For a range of 6 kilometers, (the maximum LOS between the LSSM and the Shelter on a smooth spherical moon), a beam intensity of 3.3×10^7 candles is required. The total energy per flash is related to the solid angle over which the flashed beam is radiated.

The beacon energy per flash for visibility against the worst case background is shown in Figure 5-3. For a range of 6 km, the beacon would have to provide 5.6×10^4 lumen-seconds per flash. This is regarded as an absolute minimum requirement. Theoretically, an infinite search time would be required if only threshold illumination were provided. Thus, practically, the actual illumination provided should be at least double the threshold. A beacon flash rate of about 1 flash per second is generally accepted as typical for beacon detection. This rate was used on the Mercury and Gemini beacons. Available flashtube specifications indicate that a single flash output of 10^5 lumen-seconds is feasible but not at a constant rate of 1 flash per second due to an average power limit on the tube. Thus, it is not possible to provide for the assumed worst case condition.

If, however, the beacon could be viewed against the dark sky it would be easier to see than when viewed against a sun-lit lunar surface. If only the sky were in the observer's visual field and he were dark adapted, a beacon apparent illumination equivalent to that of a second magnitude star would be sufficient[10]. The energy per flash for this magnitude source is given versus range in Figure 5-4 which shows a requirement for only 4 lumen-seconds/flash. This is a lower bound on the beacon requirement. The Shelter situation; however, is such that the beacon will, at best, appear only slightly above the horizon. (For the case of a beacon located 10 meters above the surface viewed from 6 km, the elevation angle above a

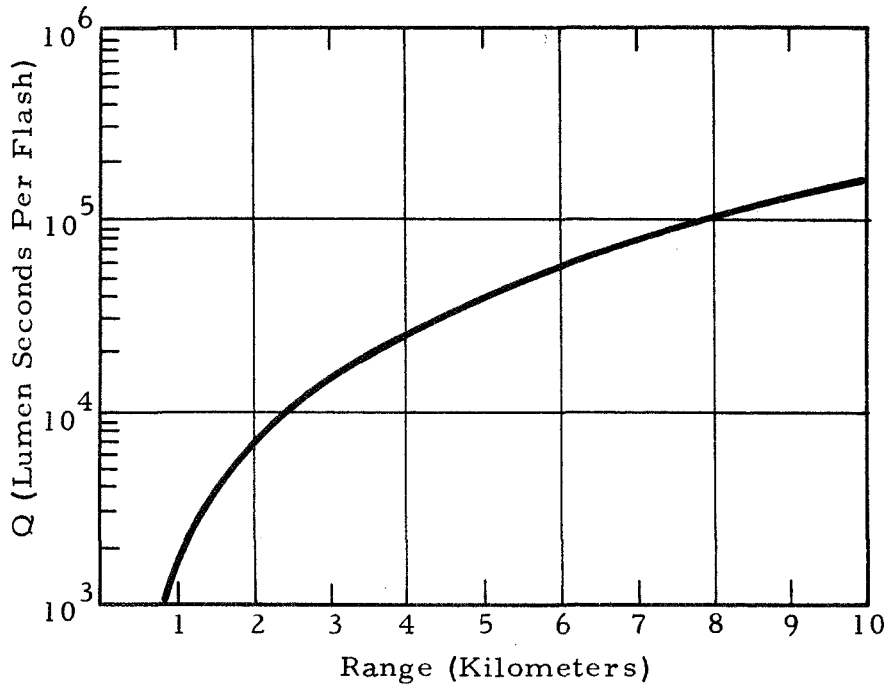

Figure 5-3 Minimum Beacon Energy (Q) vs. Sighting Range (R) for Worst Case Lunar Background

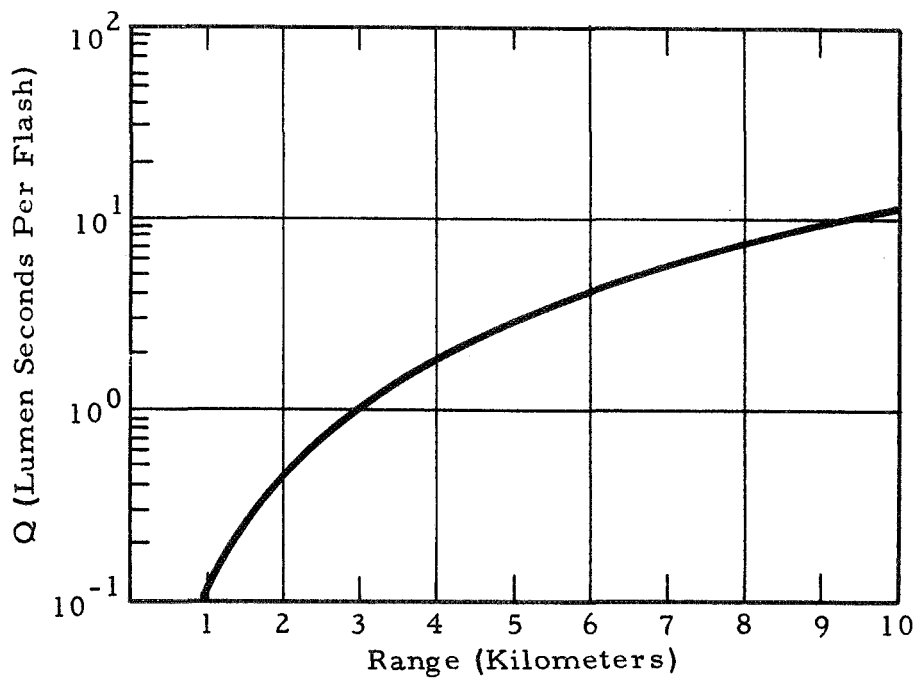

Figure 5-4 Beacon Energy (Q) vs. Sighting Range (R) to Produce Apparent Second-Magnitude Illumination

smooth lunar horizon would be only about 0.1 degree.) The relatively bright lunar surface will still be within the observer's visual field and thus affect his adaptation. A practical design point thus lies somewhere between 4 lumen-seconds per flash and the worst case value of 10^5 lumen-seconds per flash.

If operations are constrained to sun elevation angles greater than 45° (the middle portion of the lunar day) then the maximum value of the photometric function is about 0.45 and could easily approach zero for areas near the horizon. Assuming a typical photometric function value of 0.1 and the average albedo of 0.07, the required energy per flash would be 4×10^3 lumen-seconds.

Overall efficiencies of xenon flashtube systems, including the DC power converter, are between 10 and 25 lumens/watt. Thus, the required power of a beacon that would produce the 4×10^3 lumen-seconds would be between 160 and 400 watts, for a flash rate of 1 flash per second. Because of probable variations in the photometric function (>0.1) even this beacon would not be detectable at all times. The weight of such a beacon is estimated at about 15 lb.

Increasing the beacon height by as much as 100 meters (a factor of 10 above the 10 meters assumed) produces a beacon viewing angle above the horizon of only 1° at 6 km or 2° at 3 km. These angles are still insufficient to remove the beacon from the lunar background.

The practicality of using a flashing light beacon as a navigation homing device is highly questionable. A 160 to 400 watt beacon source is useful under rather limited conditions. A source of the order of 4 kilowatts is required to provide relatively certain visibility.

5.2 RADIO FREQUENCY BEACON

A Radio Frequency (RF) homing concept appears capable of providing the LSSM data required to navigate the vehicle during the return to Shelter phase of a sortie. A study of the parametric considerations in the selection of a ground wave RF homing system is contained in Reference 11. A consideration of the terrain surface structures described in Section 3.0 indicates that a VHF system which is LOS limited will not provide the required homing signal over an extended distance.

The RF homing system consists of a homing beacon located on the Shelter and a direction finder aboard the LSSM. The referenced report analyzed the operational range as a function of beacon transmitter power for selected frequencies from 1 to 35 Mc.

Assumptions underlying the data are:

1. Homogeneous lunar surface with conductivity of 10^{-4} mhos/meter and dielectric constant of 2. Smooth sphere of radius 1738 km.

2. Vertically polarized transmission from an antenna with the base at a height of nine meters. Antenna gain at each end is 5 db.

3. Signal bandwidth of 100 cps and signal-to-noise ratio of 10 db.

4. Surface wave attenuations and external noise factors derived from Reference 12.

A 35 Mc system will operate out to a range of about 25 km with a transmitter power output of 1 watt. Such a system would require a transmitter at the Shelter weighing about 3 lb and consuming about 2 watts. An automatic receiver on the LSSM including antenna, cables, and servomechanism would weigh about 12 lb and consume 28 watts. A manual version providing an audible tone null indication would weigh about 8 lb and require 3 watts.

Heading angle to the Shelter is the only navigation data provided by this simple homing concept. Except for possible errors caused by spurious reflections, which would be a local problem, accuracy is expected to be within 5° (one-sigma) for any frequency out to a range of 25 km from the Shelter.

An appreciable amount of astronaut time is required for operating the manual system. However, it does provide a good means of extending the assured recognition over ranges appropriate to LSSM operation with a low weight and power penalty.

5.3 PILOTING

The piloting technique requires that the astronaut note distinguishable characteristics of the lunar terrain as the sortie progresses away from the

Shelter, that these items of note be recorded mentally, photographed, or recorded in the form of a crude map by the astronaut, and that at the time of return to the Shelter, these noted terrain characteristics be recognized and their sequence interpreted to provide a "marked" return path. Historically this navigation technique predates all others.

A basic assumption with regard to the terrain is required. First, that the mission area contains a sufficient number of suitable reference features, and second, that once the astronaut has noted such features that he will be able to recognize them during the return to the Shelter.

The distinguishable features must be small scale and frequent, that is, a large mountain or crater located several kilometers away from the sortie route is of little value in piloting to a specific Shelter area. The recent Ranger photographs did not indicate frequent distinguishable objects protruding above the surface. A high number of craters (of all sizes) did appear, but these are not favorable reference objects.

If a number of satisfactory reference objects do exist throughout the mission area, the second factor of the piloting assumption with regard to recognition of the reference feature must be considered. The lack of color and unfamiliar illumination conditions may present a difficult recognition situation. In some instances, for example, the reference object, viewed from the direction of the sun and fully illuminated during the initial portion of the sortie, will be viewed from the other side and be in complete darkness during the final phase of the sortie.

The requirement on the astronaut to search for and to note the reference objects is a major disadvantage of this concept. Not only is his time utilized while driving the vehicle but constant effort must be applied to the task of remembering or mapping the surface features.

It appears that terrain recognition will always be used to some extent in surface vehicle navigation, but because of the uncertainty with regard to both the existence of distinguishable reference features and the ability of the astronaut to orient himself within a reasonable time, this mode of navigation does not appear satisfactory. When good and complete horizontal photographic coverage of the mission area is available by which the astronaut can be provided a map (assuming features exist) then this technique may prove more valuable.

5.4 TRAIL BLAZING

The trail blazing technique pertains to the method of returning to the Shelter over the route used previously in the outgoing phase of the sortie by means of artificial marker recognition. The markers, provided by the LSSM vehicle and crew include: flags or stakes, vehicle wheel tracks, inflatable objects, paint (on surface objects), a continuous connecting line, and a trail of miscellaneous objects (articles from the spacecraft or peculiar arrangement of natural objects). A brief sketch of some of the significant points of consideration for the various marker utilization follows:

Flags or Stakes

Low cost and short time development program; must be placed at relatively short intervals to assure recognition; weight estimated at 30 lb per km of sortie travel beyond ARD (3 lb, 10 ft stakes separated by 100 meters); reusable as retrieved during return phase of sortie; astronaut implaced and thus a high consumer of astronaut time and effort; favorable illumination conditions required; vehicle average velocity constrained due to marker implacement and retrieval; area of exploration limited by restricting the return route to be identical to outgoing route; in event of emergency crew safety possibly compromised by restricting return route options.

Vehicle Wheel Tracks

No development program; no weight penalty; astronaut observes tracks while performing driving task, thus no time penalty assessment; favorable illumination conditions required; area of exploration limited by the restriction that the return route to be identical to outgoing route; in event of emergency crew safety possibly compromised by restricting return route options; constrains mission to general lunar area where vehicle will create tracks (i.e., soft soil); constrains sorties to avoid intermittent hard surface segments.

Inflatable Objects

Relatively low cost and short time development programs; weight is less than that of the stakes; weight estimate 10 lb per km (1 lb, 10 ft objects [13] spaced at intervals of 100 meters); astronaut actuated inflation and placement during outgoing phase of sortie imposing minor time penalty;

reusable if retrieved by astronaut during return phase of sortie; must be deflated for storage on LSSM if of a large circular size; if not retrieved large number of markers required for entire mission; favorable illumination conditions required; vehicle average velocity constrained due to the marker retrieval; area of exploration limited by restricting return route to be identical outgoing route; in event of emergency crew safety possibly compromised by restricting return route options.

Paint or Powder

May require extensive development program; must be placed at close intervals to assure recognition; difficulty in covering anticipated irregular, jagged, and porous material; not reusable for other sorties of mission; astronaut implaced and thus a high consumer of astronaut time and effort; favorable illumination conditions required; vehicle average velocity constrained due to marker implacement; area of exploration is limited by restricting return route to be identical to outgoing route; in event of emergency crew safety possibly compromised by restricting return route options.

Continuous Connecting Line

Relatively low cost and short time development program; weight estimated at 1 lb per km of sortie travel plus 10 lb fixture (automatically implaced); reusable if retrieved during return phase of sortie; probably not retrieved; vehicle average velocity limited due to marker emplacement; area of exploration limited by restricting the return route to be identical to the outgoing route; in event of emergency crew safety possibly compromised by restricting return route options; restricts vehicle operations in maneuvering about surface objects; favorable illumination conditions required.

Trail of Miscellaneous Objects

Trail marked by objects from spacecraft that are no longer critical to overall lunar mission (as portions of descent stage), or by lunar surface objects arranged in a manner peculiar to the natural terrain and therefore distinguishable; no development program; no weight penalty associated with lunar delivery; weight penalty imposed on LSSM vehicle to transport spacecraft objects; astronaut emplaced and therefore possibly a high consumption of astronaut time and effort; reusable if desired by

retrieval during return phase of sortie; favorable illumination conditions required; vehicle average velocity constrained due to marker emplacement and retrieval; area of exploration limited by restricting return route to be identical to outgoing route; in event of emergency crew safety possibly compromised by restricting the return route options; concept assumes portions of the spacecrafts available for marking purposes or that lunar terrain will provide loose objects which can be arranged in a distinguishable pattern at intervals along the route.

The marking of a route by one of the above described techniques does provide the astronaut the information required to drive the LSSM vehicle in the direction of the Shelter. A prime advantage of low program cost and a short development program exists for most implementations. The major disadvantage to this technique is that the return to Shelter route must be along the same route as that covered in the initial portion of the sortie. The mission is further limited in that utilization of most of the noted markers requires a high degree of astronaut time and effort, both in marker placement and marker detection. Also, the technique is either dependent on a particular terrain condition or requires the LSSM transportation of large and/or heavy artificial markers.

5.5 CONCLUSIONS, NAVIGATION FOR EXTENDING ASSURED RECOGNITION DISTANCE

It has been shown that the Assured Recognition Distance, the distance within which the LSSM must navigate to the Shelter, can be extended by the use of navigation aids to a range practical for LSSM mission consideration. However, except for the RF beacon, each of the techniques and concepts considered (Visual Beacon, RF Beacon, Piloting and Trail Blazing) imposed a constraining limit on the planned mission, the mission operation, or the navigation system weight. The visual beacon does not appear to be a practical LSSM navigation aid. The RF beacon, which can provide the Shelter bearing angle throughout the mission area, is superior to the piloting and trail blazing techniques.

These methods which extend the ARD may at first appear to be the simplest and most practical solution to affording navigation beyond the limited line-of-sight. It appears, however, that these "simple" methods may actually be difficult to implement, fail to provide the required navigation data, or unduly constrain the mission.

Other more conventional navigation methods should thus be considered. These methods include: remote tracking, position fixing and dead-reckoning for operation beyond the Assured Recognition Distance.

6.0 NAVIGATION AIDS FOR OPERATION BEYOND ASSURED RECOGNITION DISTANCE

In addition to the navigation techniques and concepts described for extending the ARD (Section 5), an additional class of navigation aids should be considered to provide the LSSM vehicle with the capability of returning to within the visual homing range of the Shelter. This class includes the conventional navigation techniques of remote tracking, position fixing, and dead-reckoning. These aids, in contrast to the homing aids capable of extending the ARD, provide LSSM position throughout a sortie. Thus, not only do the aids of this class assure visual homing on the Shelter, they enable the vehicle operator to navigate a specific course and establish the position of terrain features and scientific experiments.

6.1 REMOTE TRACKING

There are two remote tracking concepts for LSSM vehicle position determination. The first uses earth based tracking networks; the second uses RF tracking or visual observation from the orbiting CSM vehicle.

6.1.1 Earth Based Tracking [14, 15, 16]

Two radio networks will be available to support spacecraft on the moon: (1) Manned Space Flight Network (MSFN), and (2) Deep Space Instrumentation Facility (DSIF). At strategic locations around the earth, the MSFN will have 12 stations, the DSIF, four stations. All stations transmit at a nominal frequency of 2100 Mc. The space vehicles use transponders which retransmit the received carrier by a coherent fractional multiple of 240/211. The carrier received at the earth station will be altered from the transmitted frequency by this multiple and the Doppler component.

The Doppler frequency measures the radial range rate and the pseudo random noise codes are used to measure the radial range. No skin tracking is contemplated. Schemes other than range and range rate are unlikely, unless the MSFN and DSIF capabilities are shown to be not adequate.

The accuracy to which the position of lunar-based vehicles can be determined is a function of:

1. Location of transponder (vehicle carried)
2. Data type and ranging and/or doppler
3. Data accuracy
4. Total tracking span
5. Number and locations of tracking stations
6. Phase angle of observable libration effect
7. Accuracy of celestial mechanics description of earth-moon system

Figure 6-1 shows the semi-major axis of the one-sigma (marginal) ellipse on the lunar surface as a function of tracking time.

Assumptions used in deriving this figure are: ;

(1) Data Accuracies (1σ)

	Reasonable	Optimistic
Ranging (1 pt/6 hr)	25 m	5 m
Doppler (1 pt/min)	4 mm/sec	0.4 mm/sec

(2) Nominal Vehicle Location

Longitude	-35°
Latitude	-4°
Distance from lunar center	1748 km

(3) The a priori statistics on the vehicle location are ignored in the computation of the estimate error statistics.

(4) The accuracy of the celestial mechanics description of the earth-moon dynamics and the lunar motions is imperfectly known. This situation influenced the selection of the accuracy figure for the ranging system.

Figure 6-1 was prepared assuming the "reasonable" data accuracies stated above.

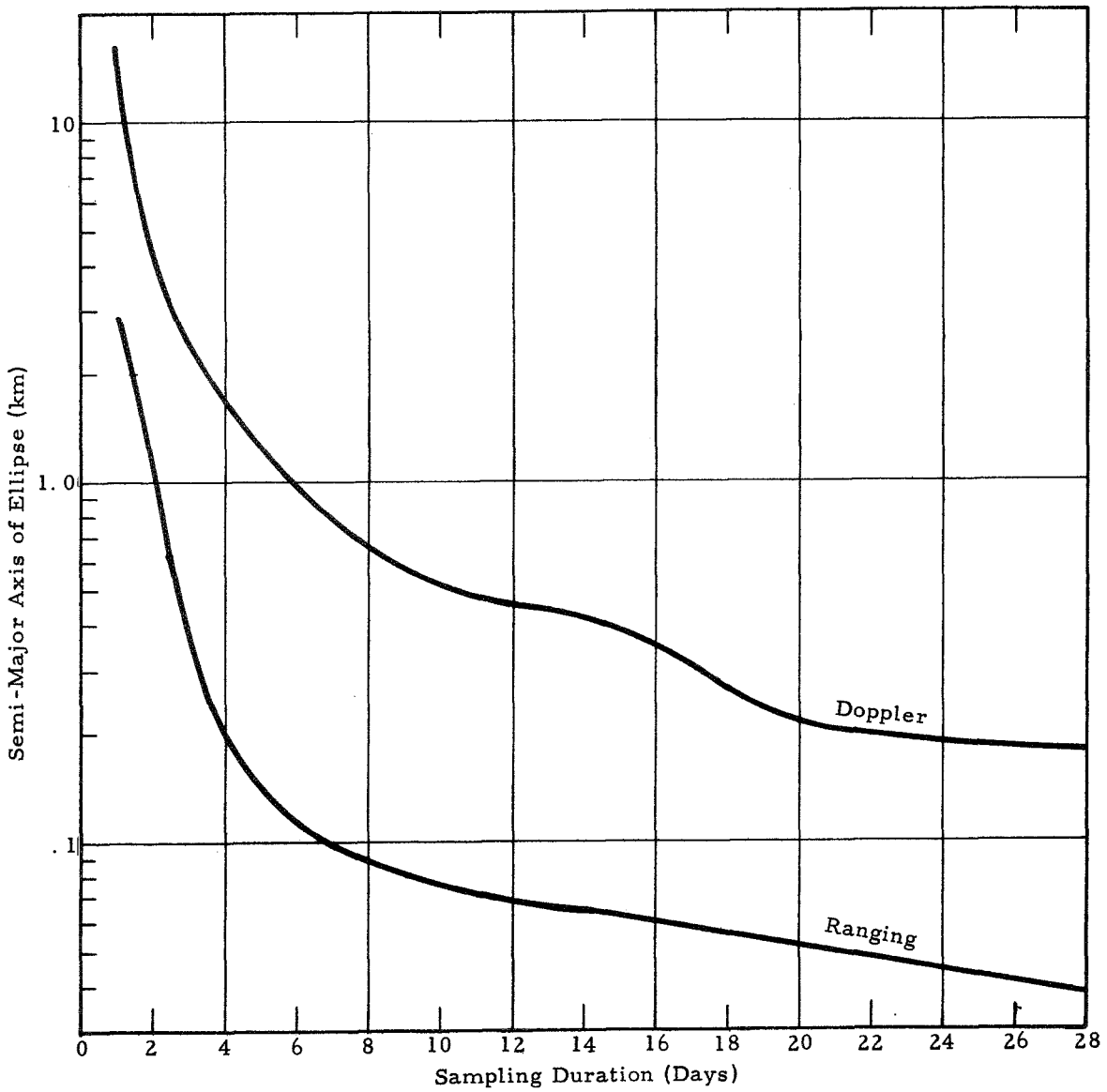

Figure 6-1 Post Landing Location Estimate Accuracy

This tracking analysis is based on locating a stationary object on the lunar surface. The performance of such a system in tracking a non-stationary object has not been determined. It appears that due to the long data correlation time required for sufficient accuracy, this method is inadequate to navigate the LSSM during a typical 6-hour sortie.

Furthermore, the system, even if feasible, is dependent upon a communications system on-board the LSSM, which includes an S-band transponder and a receiver for the earth-derived navigation information.

6.1.2 CSM Based Tracking

The primary disadvantage with regard to the CSM based tracking concept is the limited availability of the CSM with respect to a surface position. A cursory discussion of this limited availability, a disadvantage sufficient to eliminate this concept from further consideration as a primary concept, follows.

Lunar physical parameters assumed were:

1. Homogeneous spherical shape
2. Radius of 1738 km
3. Acceleration of gravity of 1.62 meters/sec^2
4. Motion considered was limited to a constant rotational rate about a N-S axis; librations were neglected
5. Period of rotation of 27.5 days

CSM vehicle operating parameters assumed were:

1. Circular orbit
2. Altitude of orbit equal to 157 km

These assumptions define a CSM orbital period of 113 minutes. Assuming a 5-degree viewing angle above the horizon, the CSM to LSSM line-of-sight (LOS) will exist over a lunar central angle of 39 degrees, or an interval of 12.2 minutes, for an orbit which passes directly overhead of the LSSM (refer to Figure 6-2). This LOS interval (11% of orbit) will decease as the CSM orbit precesses.

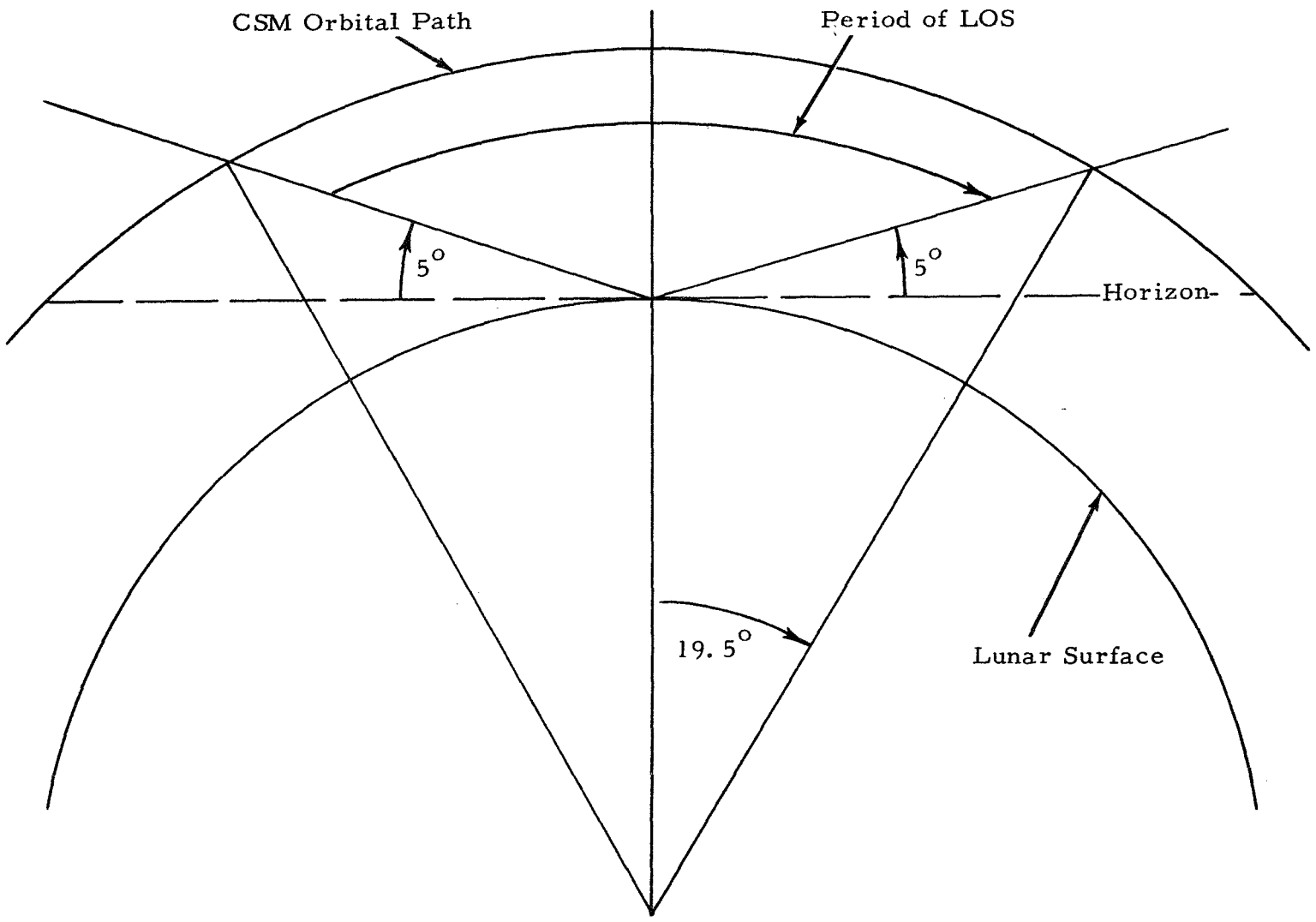

Figure 6-2 CSM-LSSM Line-of-Sight Geometry

The lunar surface rotates 360° in 27.5 days or has a rotational rate of 13.1 degree/day. The lunar rotation with respect to a CSM vehicle revolution, noted as the vehicle precession, is 1.03 deg/revolution. Figure 6-3 depicts the 1.03 degrees of precession at the lunar equator for successive CSM orbits.

The angular separation decreases as the latitude of the surface point of interest increases: for an assumed maximum mission latitude of 10°, the angular separation is 1.01 degrees. Referring again to Figure 6-2, it can be seen that the CSM will be beyond LSSM line-of-sight after approximately 19 orbits (1.5 days) and will not reappear again for approximately 141 more orbits (11 days).

The combination of precession and limited observation time per orbit or even the limited observation time per orbit alone, places this concept of LSSM navigation in an unacceptable category.

6.2 REPEATED ABSOLUTE POSITION FIX

The LSSM vehicle can be navigated to the Shelter by repeated position fixes. The frequency of these fixes depends on: (1) the ability of the astronauts to "feel" how far they have traveled since the previous fix, and (2) the Shelter-LSSM separation distance determined by the previous fix operation. The position fix can be performed with respect to two primary classes of references: (a) celestial bodies, and (b) surface terrain objects.

In order to perform a position fix using either of these references, a precision theodolite is required. Such an instrument suitable for use by an astronaut in the lunar environment would have to be developed.

The major disadvantages of this technique include:

1. Intermittent data availability (lack of continuous information for navigating a defined course resulting in possible excess travel)

2. High astronaut time required except for automatic star tracker implementation

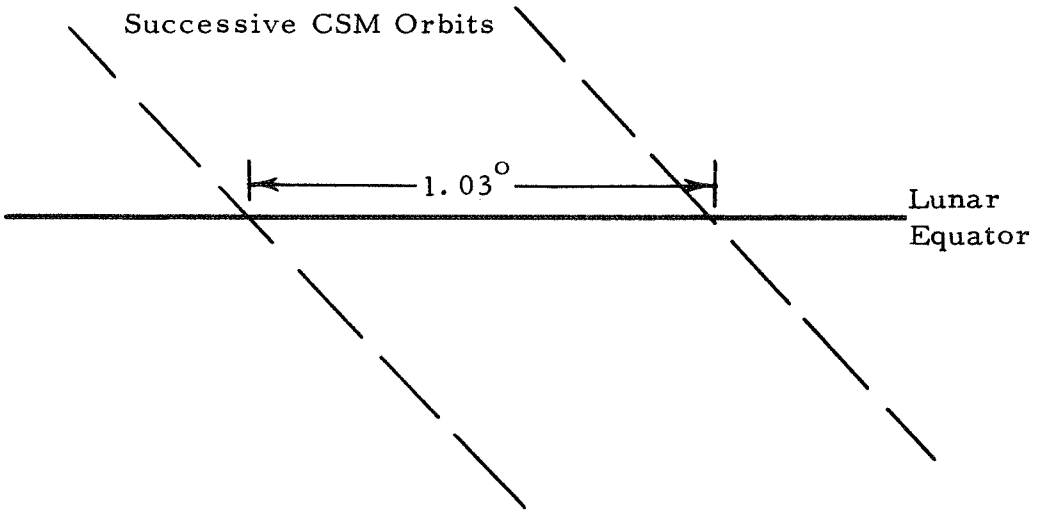

Figure 6-3 Orbital Precession at the Equator

6.2.1 Celestial Fixing

The use of celestial observation is the primary concept of position fixing proposed in the various lunar navigation studies. The art of fixing by referencing stars has been highly developed through extensive usage in earth-based marine and air navigation.

On the moon's surface, the availability of stars for sighting at all times and the slower apparent movement of the stars reduce some of the limitations of astro fixing implicit in its use on earth.

The accuracy of determining position by this technique is dependent on the sensor errors (including the human error), the reference data uncertainties, and the computation precision. For an absolute celestial fix, orientated with respect to a defined coordinate system, the major error would be contributed by the uncertainty in the knowledge of the lunar gravity anomalies. However, by assuming continuity of anomalies and realizing the limited Shelter-LSSM separation, a relative position fix is possible which avoids the anomaly source of error. By utilizing accuracy obtainable by earth based state-of-the-art sensors and precision computers, the LSSM position relative to the Shelter can be determined to within 0.31 km. This is based on the relative position fix accuracy of 0.22 km stated in Reference 17 (RSS of LSSM position error of 0.22 km and Shelter position error of 0.22 km). Thus, the accuracy afforded by this concept is marginal.

The computation required to implement this concept is the simultaneous solution of two spherical triangles. This can be accomplished by manual calculation and plotting (not to the above accuracy) or by a digital computer. The manual computation operation is extremely limited by the space suit. Utilization of an on-board LSSM computer is not practical; utilization of an earth-based or Shelter-based computer appears undesirable due to the communications penalty.

Star reference data is required to find the appropriate star for angular measurement and to use in the fix computation. Thus, the astronaut must either carry the tabulated data in form usable in a space suit operation or depend on the communications link.

Operation of the precision sensor equipment under the space suit constraints imposes a further difficulty of the concept. This operation,

in addition to the computation, will require an appreciable amount of astronaut time. It is estimated that the time for a position fix will be from 15 to 30 minutes.

The disadvantages of the celestial fix concept with regard to astronaut precision instrument operation can be avoided by use of an automatic star tracker rather than a manual theodolite. However, the reference data and computation difficulties still exist in addition to the system penalties introduced with regard to weight, power, and reliability.

6.2.2 Lunar Terrain Fix

Terrain fixing techniques are applicable to surface navigation under certain conditions. These techniques relate principally to the determination of position and heading through recognition of mapped local terrain features and correlation of the observed data with mapped data. Examination of maps of the proposed lunar landing sites (Section 3.0) indicates that there are significant terrain features which should be visible from any point within the area.

It is assumed that prior to LSSM missions, good aerial photographs of the proposed areas will have been obtained so that suitable maps with absolute horizontal and vertical accuracies of better than 1 km can be provided to the vehicle operator. Maps of this accuracy are not sufficient to enable the LSSM operator to navigate within the Shelter Assured Recognition Distance. However, by supplementing the pre-mission region maps with more precise maps (accurate to 100 meters) of the ARD area, the vehicle can be navigated grossly throughout the mission area and precisely during the return to the Shelter by use of terrain fixing.

The success or failure of this concept depends upon the ability to designate prior to a mission those objects as references, which can be recognized by the observer from his viewpoint. Photogrammetrists have stated that current state-of-the-art techniques utilizing stereo photographs and simple optical instruments, such as a theodolite, should be adequate for navigation in virgin territory with a high order of reliability if the reference objects can be identified. However, a great deal of work has yet to be done to establish the procedure by which aerial survey data on the features of unexplored terrain can be classified in terms of an observer's ability to recognize those features from various locations on the surface of the terrain and under various illumination conditions.

6.3 DEAD-RECKONING

Dead-reckoning is peculiarly suited for the LSSM sortie navigation tasks; by definition, it is a relative navigation technique, where in this case the required navigation is relative to the Shelter. A dead-reckoning system determines the motions of the vehicle and integrates these motions to develop a position relative to the initial point.

Several dead-reckoning concepts have been developed and proven capable of performing the function required for LSSM sortie navigation. These concepts include: inertial platforms, accelerometers, gyros, doppler radars, odometers, computers, manual plotting, etc.; however, the concept whose capabilities appear to more nearly match the LSSM system requirements is that of gyros, vehicle wheel odometers, and a mechanical analogue computer.

This gyro-odometer concept is light weight, 14 lb, low power, 15 watts, imposes no requirements on the vehicle operator, does not limit the mission operation in any manner, and is highly reliable. The dependability of this concept is illustrated by the existence and proven performance of similar systems. Certain components are currently used in systems of aircraft, missiles, and ocean vessels: the greatest system similiarity is with the military tank navigation system.

The performance of the dead-reckoning system is shown by error envelope along a typical sortie route in Figure 6-4. This performance corresponds to: (1) a directional gyro accuracy typical of a simple ball bearing type (earth drift rate of 0.25 degrees/hr), which has been proven through many hours of use, (2) an odometer system composed of a wheel revolution sensor on each wheel (error of 1 to 2% of distance travelled), (3) a high accurate mechanical analog ball resolver (0.3%) as used in military land vehicles, and (4) a vertical gyro accurate to 0.25 degrees used to compensate for directional gyro tilt.

The dead-reckoning system described is relatively independent of the lunar terrain conditions, is operable over a range consistent with the LSSM sortie defined, and does not require astronaut operation. The development cost and development time to implement a lunar environment dead-reckoning system are certainly greater than those of a simple trail blazing concept; however, by use of existing developed components and modifications to the components, the development penalties do not outweigh the system capability advantages.

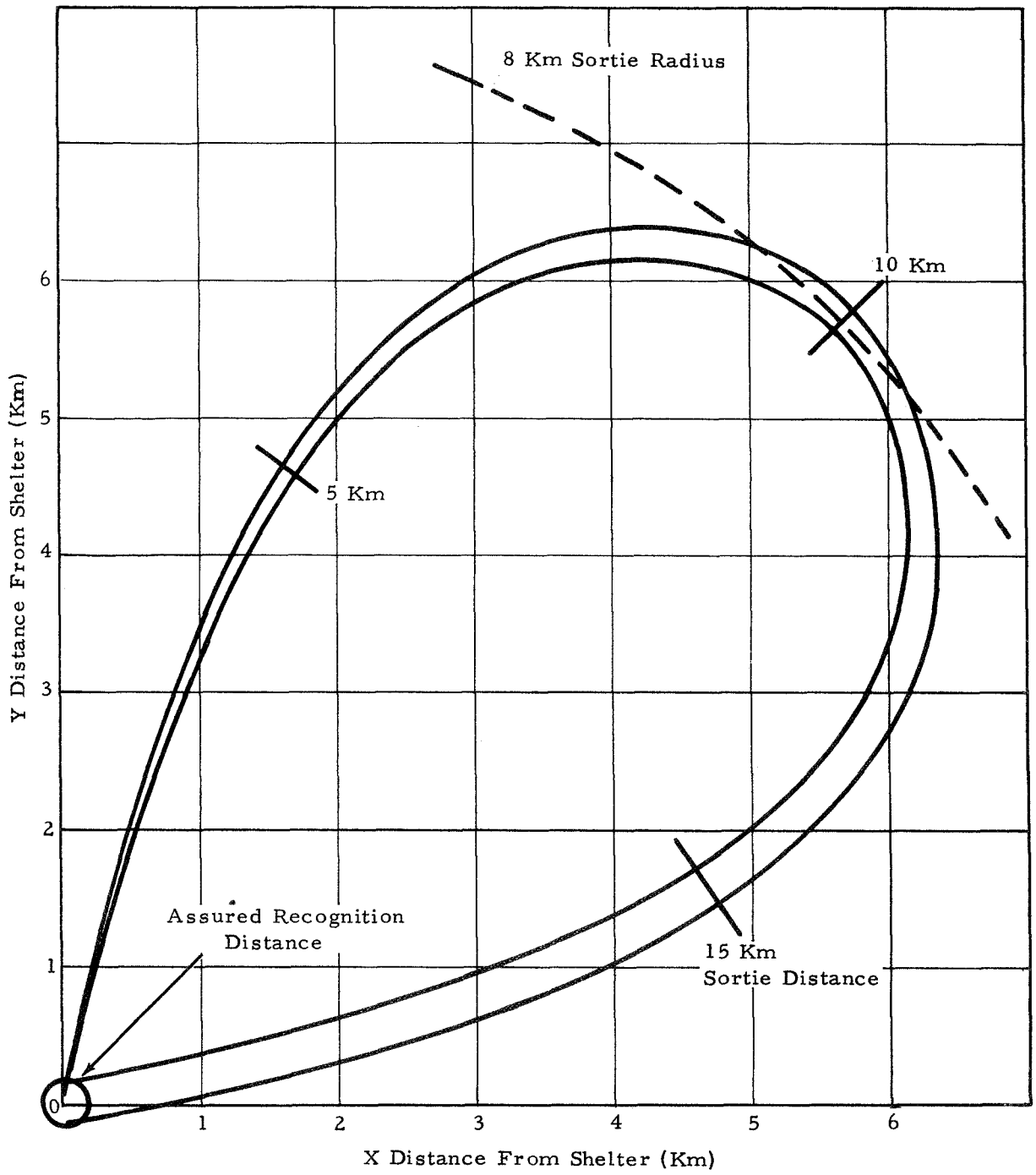

Figure 6-4 LSSM Dead-Reckoning Navigation Performance

6.4 CONCLUSIONS, NAVIGATION BEYOND ASSURED RECOGNITION DISTANCE

It thus appears that navigation by remote tracking, position fixing, or dead-reckoning might be utilized to define the LSSM position throughout a sortie in addition to establishing the return route to the Shelter. However, the capability of the tracking and fixing techniques to provide the data accuracy required to navigate to within the Assured Recognition Distance is questionable. The dead-reckoning technique offers a suitable system implementation since it meets the required accuracy, is self-contained, requires no astronaut attention, and is relatively independent of lunar environmental characteristics (soil and lighting conditions, visible surface features, RF propagation).

7.0 SUMMARY AND CONCLUSIONS

The LSSM navigation function associated with the mission operation which included three classes of exploration sorties (1. Geological, geophysical reconnaissance, 2. Deep refraction seismic surveys, and 3. Geological observation), was primarily one of crew safety. Specifically, the navigation system is functionally required to provide the capability to navigate to the Shelter from any point within 8 km radius sorties. This requirement can be satisfied under conditions whereby the astronaut is able to visually contact the Shelter and thus visually home on the Shelter.

The distance at which visual contact is assured was defined as the Assured Recognition Distance (ARD). The ARD, a function of the Shelter detection and recognition distance and the lunar line-of-sight distance, was determined to be only approximately 190 meters. This distance was established by the line-of-sight limitations due to the fine structure of the lunar surface. This fine structure consists of gentle sloping terrain segments (ranging in slope from approximately 1 to 6 degrees) whose peaks reach a height on the order of the LSSM and Shelter heights.

Navigation functions supporting scientific investigations by developing vehicle position and of providing the return distance to the Shelter, were considered as secondary to the principal function of establishing the Shelter bearing angle such that the LSSM could be navigated to within the ARD. All practical navigation techniques by which this primary function could be accomplished were considered for potential implementation. A fundamental assumption made with regard to the navigation system selection was:

> The LSSM navigation system shall be based on a technique which has been proven simple in operation, reliable, adaptable to the various lunar environmental conditions, and accurate to the defined requirements.

The navigation techniques and concepts which were considered in this report are summarized in Table 7-1. Three operational categories of systems were investigated: (1) operation within the assured recognition distance, (2) operation within the extended assured recognition distance, and (3) operation beyond the assured recognition distance.

The analysis results produced three favorable concepts, one from each operational category. They are: visual shelter contact, RF beacon, and gyro-odometer.

TABLE 7-1

Applicable Navigation Techniques and Concepts

Operational Assumption	Technique	Concept
Within Assured Recognition Distance	Homing	Visual Shelter Contact
Within Extended Assured Recognition Distance	Homing	Visual Beacon Contact
	Homing	Radio Frequency Beacon
	Piloting	Terrain Recognition
	Trail Blazing	Artificial Markers
Beyond Assured Recognition Distance	Remote Tracking	Earth Based Tracking CSM Based Tracking
	Repeated Absolute Position Fixing	Celestial Fixing Lunar Terrain Fixing
	Dead - Reckoning	Gyro - Odometer

The operational ranges of these concepts are quite different. Visual Shelter contact is only applicable over the Assured Recognition Distance which was shown, based on the detrimental terrain conditions assumed in this report, to be about 190 meters. The RF beacon and the gyro-odometer concepts can be used to navigate the vehicle throughout the anticipated mission area (8 km radius from Shelter) and return the vehicle to within the Assured Recognition Distance of the Shelter for visual homing.

The first concept, visual Shelter contact, may enable a worthwhile LSSM mission to be performed without the assistance of a LSSM navigation system if a more detailed analysis or actual lunar exploration shows that visual contact with the Shelter (Assured Recognition Distance) is possible beyond that identified in this report. However, based on a visual contact distance of only 190 meters, the mission is so extremely constrained without a beyond-ARD-navigation-system that it is not very useful.

The second concept, the RF homing beacon, provides only the bearing angle to the Shelter; it does not provide a means of assuring that the LSSM sortie does not extend beyond a point of vehicle return capability. However, if the lunar surface RF propagation characteristics are found to be no worse than the conditions assumed in this report, the RF beacon will provide a limited degree of navigation confidence.

The third concept, the gyro-odometer system, determines the position of the LSSM relative to the Shelter. This assures that the vehicle will not be driven beyond the point of return capability and that the bearing angle to the Shelter is provided to perform the return phase of a sortie. The accuracy of the system is sufficient to navigate the LSSM to within the Shelter Assured Recognition Distance.

Based on the results of the analysis presented in this report, a simple gyro-odometer dead reckoning navigation system is recommended for implementation on the LSSM vehicle.

APPENDIX A

OBJECT DETECTION DISTANCE ON THE LUNAR SURFACE [3]

A. 1 VISIBILITY OF MAN-MADE OBJECTS ON THE LUNAR SURFACE

For purposes of navigation on the lunar surface, it is necessary to know the maximum range at which certain objects are visible. The possible combinations of targets and sensors include other man-made reflecting objects or lunar terrain targets, and either visual search or use of a television sensor.

The maximum range at which a target can be detected (not identified) depends on seven parameters: target-to-background contrast, the required probability of detection, the transmittance of the light path (expressed as meteorological range), the absolute background luminance, the uniformity of the background luminance distribution, the target area, and the target shape.

Of these, the three most significant parameters are absolute background luminance, contrast, and target area. The effect of target shape is believed to be least significant, as long as the target shape is not a long extended narrow one. For this analysis, a hemispherical target has been assumed. Background uniformity should be as high as possible to maximize sighting range (the lunar surface has been assumed to be fairly uniform). The required probability of detection can be empirically related to the contrast. For man-made targets, an 80% reflectance has been assumed; a lunar maria albedo of 0.073 was assumed. A 99% probability of detection was obtained by multiplying the contrast required for a 90% detection probability (the measured case) by an empirically determined factor. Finally, on the lunar surface it is highly likely that atmospheric attenuation will be quite small, hence a meteorological range of infinity was used.

Based on the above assumptions and parametric values of absolute background luminance and target area, visibility nomograms for visual sighting range were developed. These nomograms are presented Figures A-1 through A-4.

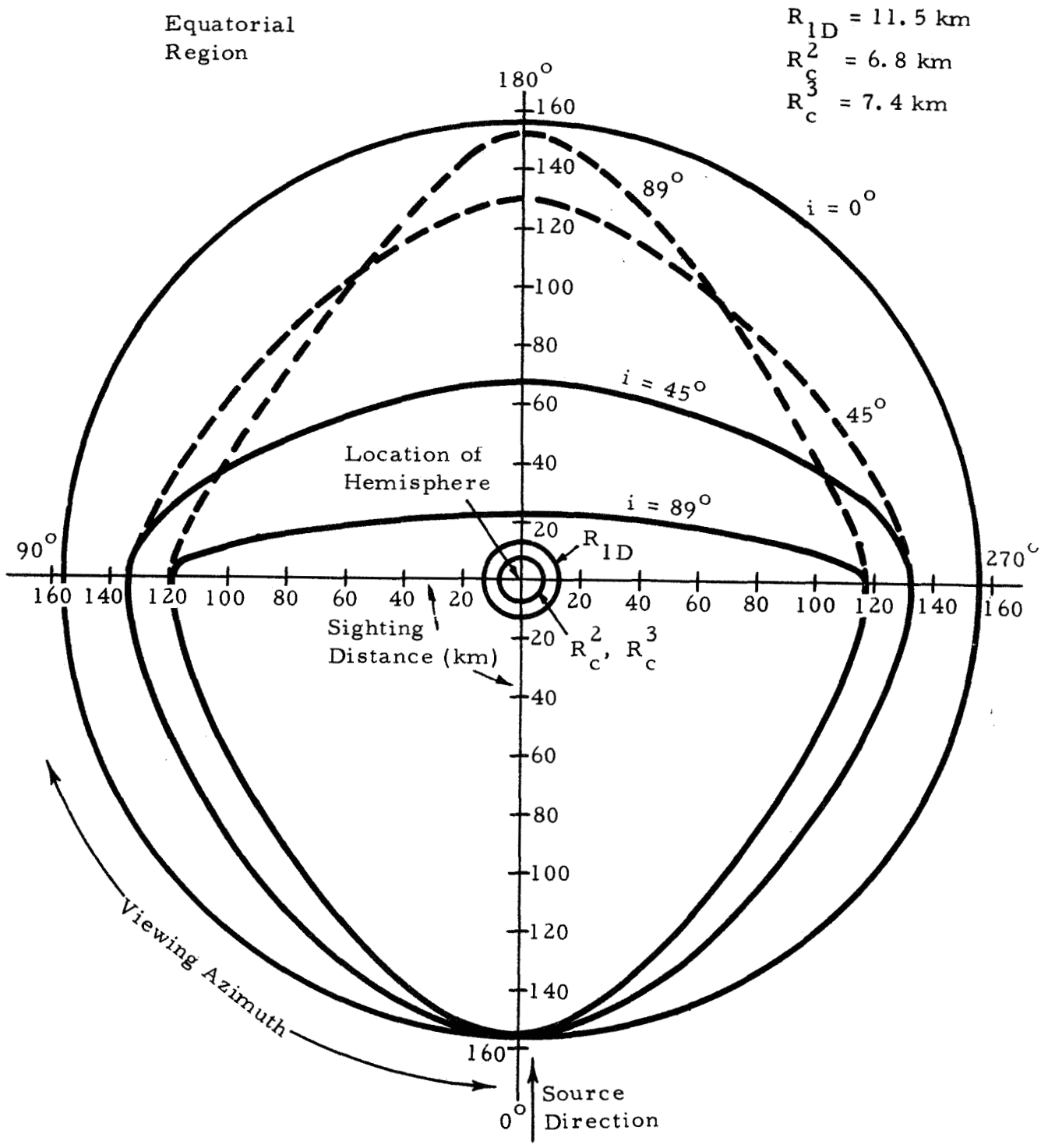

Figure A-1 Visual Sighting Distance vs. Viewing Azimuth; 5-Meter Hemisphere, Lunar Day

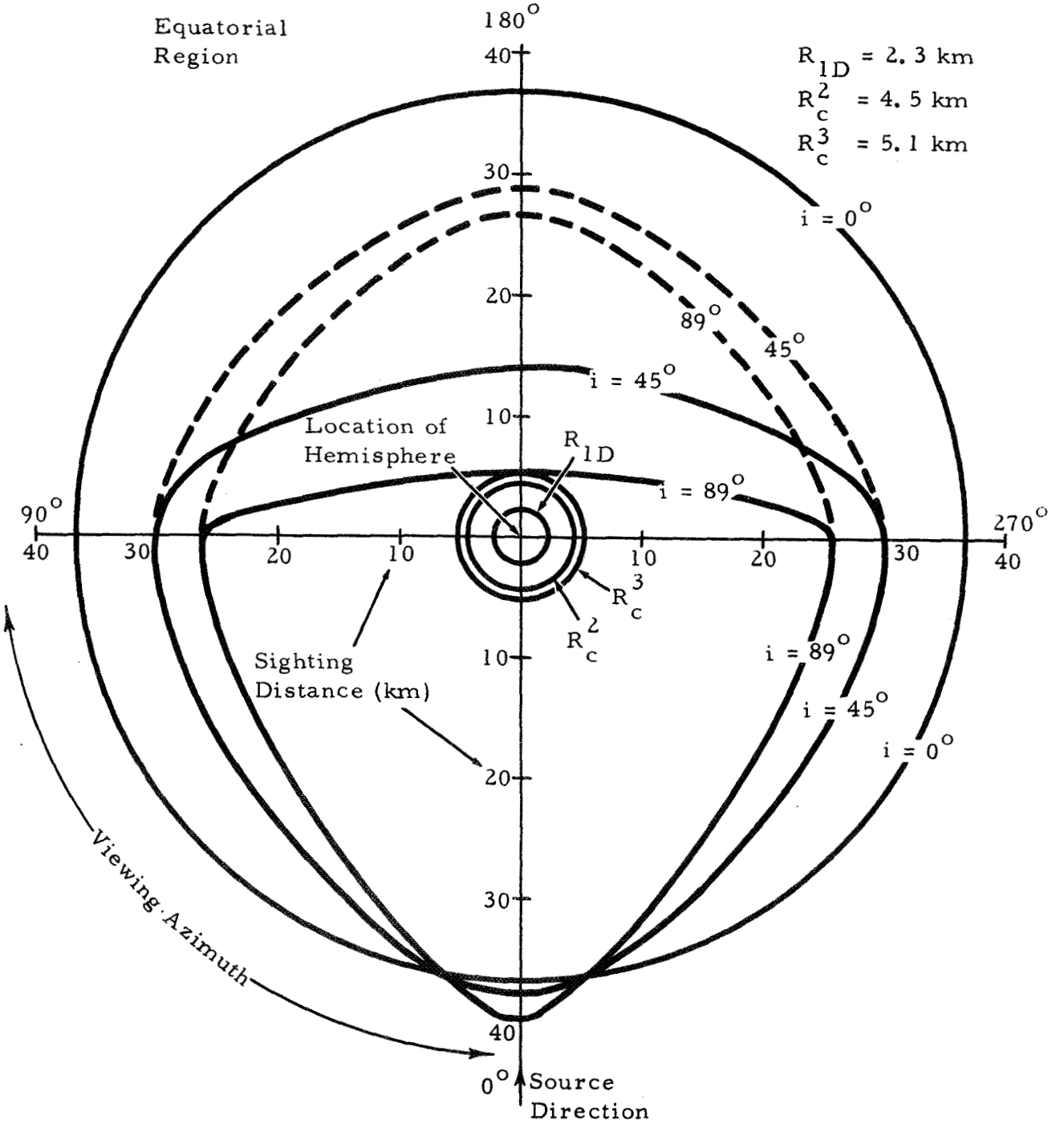

Figure A-2 Visual Sighting Distance vs. Viewing Azimuth; 1-Meter Hemisphere, Lunar Day

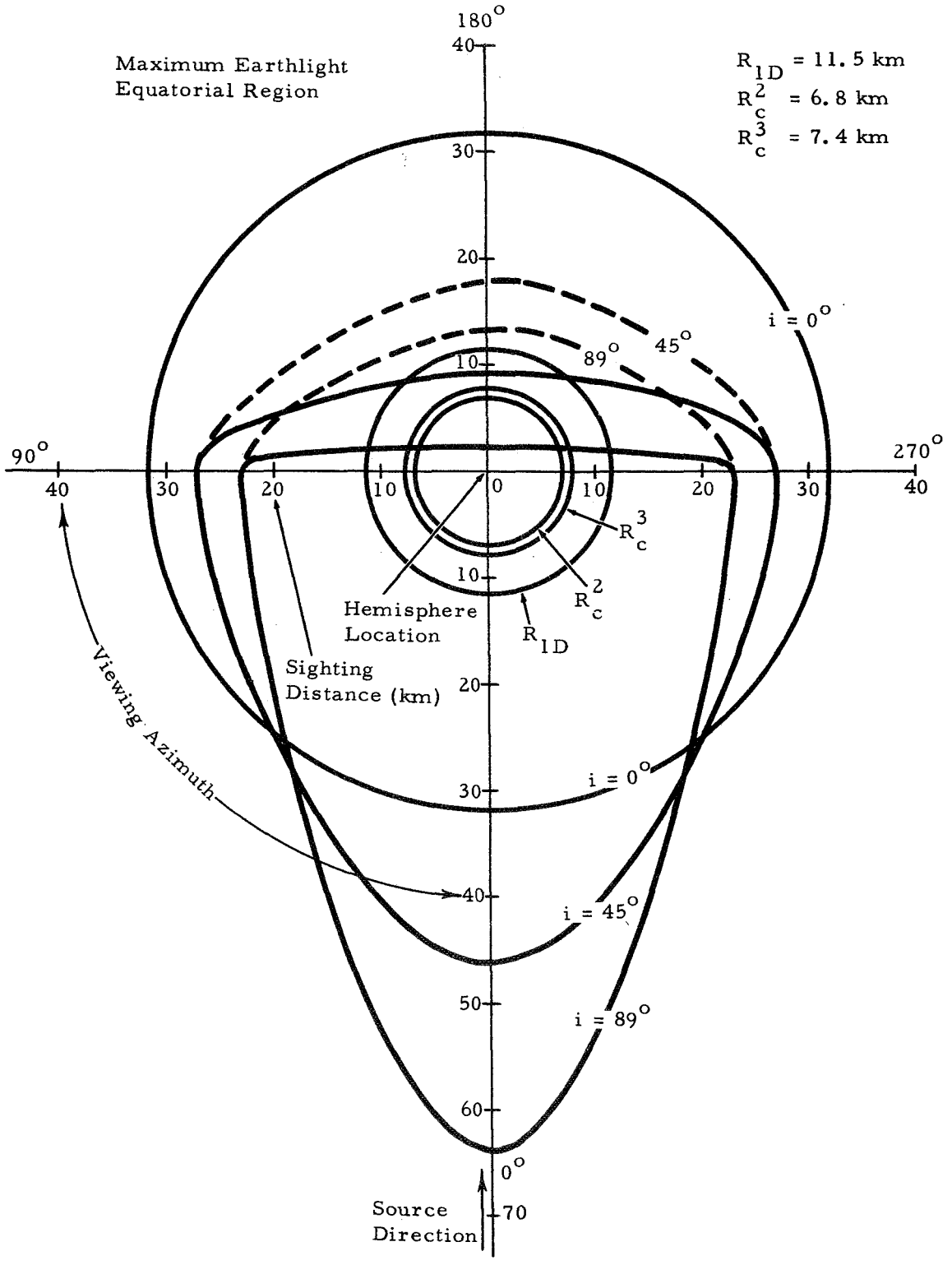

Figure A-3 Visual Sighting Distance vs. Viewing Azimuth; 5-Meter Hemisphere, Lunar Night

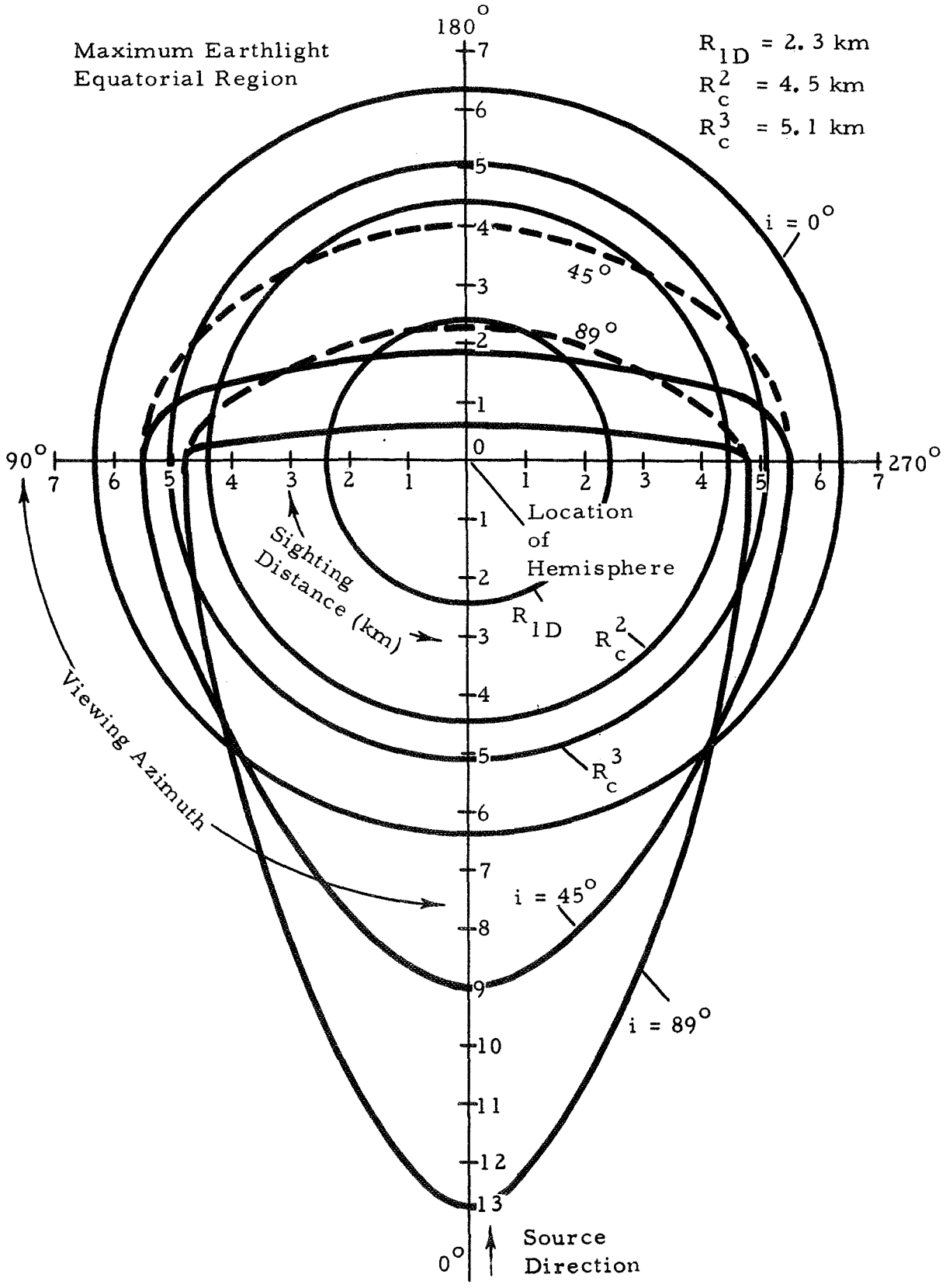

Figure A-4 Visual Sighting Distance vs. Viewing Azimuth; 1-Meter Hemisphere, Lunar Night

Figure A-1 gives the visual sighting range for a five-meter radius hemispherical target, in the equatorial region of the moon, under sunlight (i.e., lunar daytime), as a function of viewing aximuth. The target is at the center, and the curves labelled 0°, 45°, 89° give the visual sighting range in kilometers versus sensor azimuth with respect to source direction. The four 90° points are the calculated points, and the curves connecting them are merely reasonable interpolations. The 0°, 45°, 89° values indicate the declination angle of the sun, corresponding to noon, mid-afternoon, or mid-morning, and sunrise or sunset (a total span of 14 earth-days). The circular curve marked R_{ID} represents the approximate range at which the target can be visually resolved as a hemisphere. The curves $R_c^{(2)}$, $R_c^{(3)}$ represent the range at which the top of a five-meter hemisphere just appears above the lunar horizon to a sensor two or three meters above the surface (this assumes a smooth curved surface). This is called the curvature limit and it is an absolute limit, since the lunar curvature does not permit viewing of targets at any larger range regardless of how large the visual detection range may be.

It can be seen that the visual detection ranges near azimuths of 180° are quite small because the part of the hemispheric target that is illuminated by the sun is a very small crescent-shaped segment. The dotted lines labeled 45°, 89° represent the visual sighting range for that part of the hemisphere which is not sun-illuminated, but is illuminated by sunlight back-scattered by the surrounding lunar surface. This part of the hemisphere is also visible at large ranges, as shown, so that the true visual sighting range near 180° azimuth is greatly extended over the range for the small sunlit crescent target.

The ranges shown in Figures A-1 to A-4 are conservative; a target-to-background contrast of 10 was used from the true contrast range of a minimum of 10 to over 100.

Figure A-2 represents the same conditions as Figure A-1, for a one-meter radius hemisphere. Figures A-3 and A-4 represent the approximate visual sighting ranges in lunar equatorial regions under maximum earthlight illumination (lunar night) for five and one meter hemispheres, respectively. The 0°, 45°, 89° angles represent the earth zenith angles, which are equivalent to lunar longitudes, east or west of the central meridian. For the minimum earthlight illuminance condition, these values are reduced by about a factor of less than 2.

On the backside of the moon, the lunar day curves are represented by Figures A-1 and A-2. During the lunar night, since earthlight is absent, the surface luminances are so low that artificial illumination is required for a visual search, which is an entirely different problem.

For the case of the lunar polar regions, the sighting ranges are of the same order of magnitude as for the equatorial regions but the shapes of the curves are different.

In summary, Figures A-1 and A-2 show that during the lunar day, the curvature of the moon is the limiting factor for both the one and five meter target cases. This means that as long as part of the target is above the horizon, it can be visually detected with 99% probability. Figure A-3 shows that the same holds for a five meter radius hemisphere during earthlight. Figure A-4 indicates that the sighting range is the limiting factor for a one meter hemisphere during parts of the lunar night, for all but the central portion of the visible hemisphere of the moon, where curvature is again the limiting factor.

A.2 COMPARATIVE VISIBILITY OF MAN-MADE AND NATURAL OBJECTS ON THE LUNAR SURFACE

This section defines the relative visibility between man-made objects (described in Section A. 1) and natural terrain features of comparable size. The visibility of natural features is, of course, basic to any navigation scheme depending on landmark recognition.

The problem of estimating visual sighting ranges for targets which are elements of the lunar terrain is much more difficult than for an artificial target. This is because the reflectance of most artificial targets is essentially Lambertian, while the reflectance of the lunar surface has a complex directional form, depending on the orientation of the target, the sensor, and the source. This makes it difficult to calculate the variation of surface luminance with sensor azimuth for even a flat surface, as was done in Section A. 1, to determine the background luminance. When a target even as simple in shape as a hemisphere is added having this complex directional reflectance, the calculation is greatly complicated.

A very rough estimate was made for the visual sighting range of a lunar block, for comparison with the values derived for the five meter hemisphere man-made target. The seven parameters defining maximum

detection range (discussed in Section A. 1) were considered identical to the man-made target case except for the target reflectance. Thus, for the condition of a 99% detection probability, an infinite meteorological range, the background luminance used previously with uniform distribution, and a hemispherical lunar block with five meter radius target, the only difference is the target-to-background contrast due to different target luminances.

The mean albedo for the lunar maria was again assumed as 0.073, defining a maximum target reflectance that is 11 times lower than for the 0.80 reflectance hemisphere. It is obvious that with the resulting much lower contrast, the sighting range for these targets is much smaller. From the lunar photometric function (the directional factor in the high value of reflectance, which varies from about 0.01 to 1.0), a high value of contrast is 1.0. The resultant visual sighting ranges for the lunar block are shown in Figure A-5. For comparison purposes, the values for the five meter artificial hemisphere are also included, as are the LOS and curvature distances.

The sighting ranges for a five meter hemispherical lunar block, under the same conditions as stipulated for the five meter hemisphere case, are about 3 to 5 times smaller. And this is a maximum case, since the artificial target curves represent a minimum range, while the lunar block curves represent a maximum range. However, for this maximum case, the curvature range is again the limiting factor at most sensor positions. This is not true for smaller terrain features. Further, under many conditions, the target-to-background contrast may be much smaller than 1.0, so that very small sighting ranges will result.

In summary, the sighting ranges for a lunar block, under identical conditions to that of a similarly shaped and sized artificial target, are much lower than the sighting ranges for the highly reflecting artificial target. Actual calculations of the sighting range depend completely on the lunar photometric function, and are too time consuming to be included in this study.

Some preliminary work has been done at BSD to determine experimentally the sighting and recognition ranges for lunar features such as craters, crevices, and cones, using a simulated lunar photometric material to provide a proper surface response. This work has shown that under certain illumination conditions, targets can blend completely into the background and crevices cannot be differentiated from fault faces (cliffs), using monoptic systems.

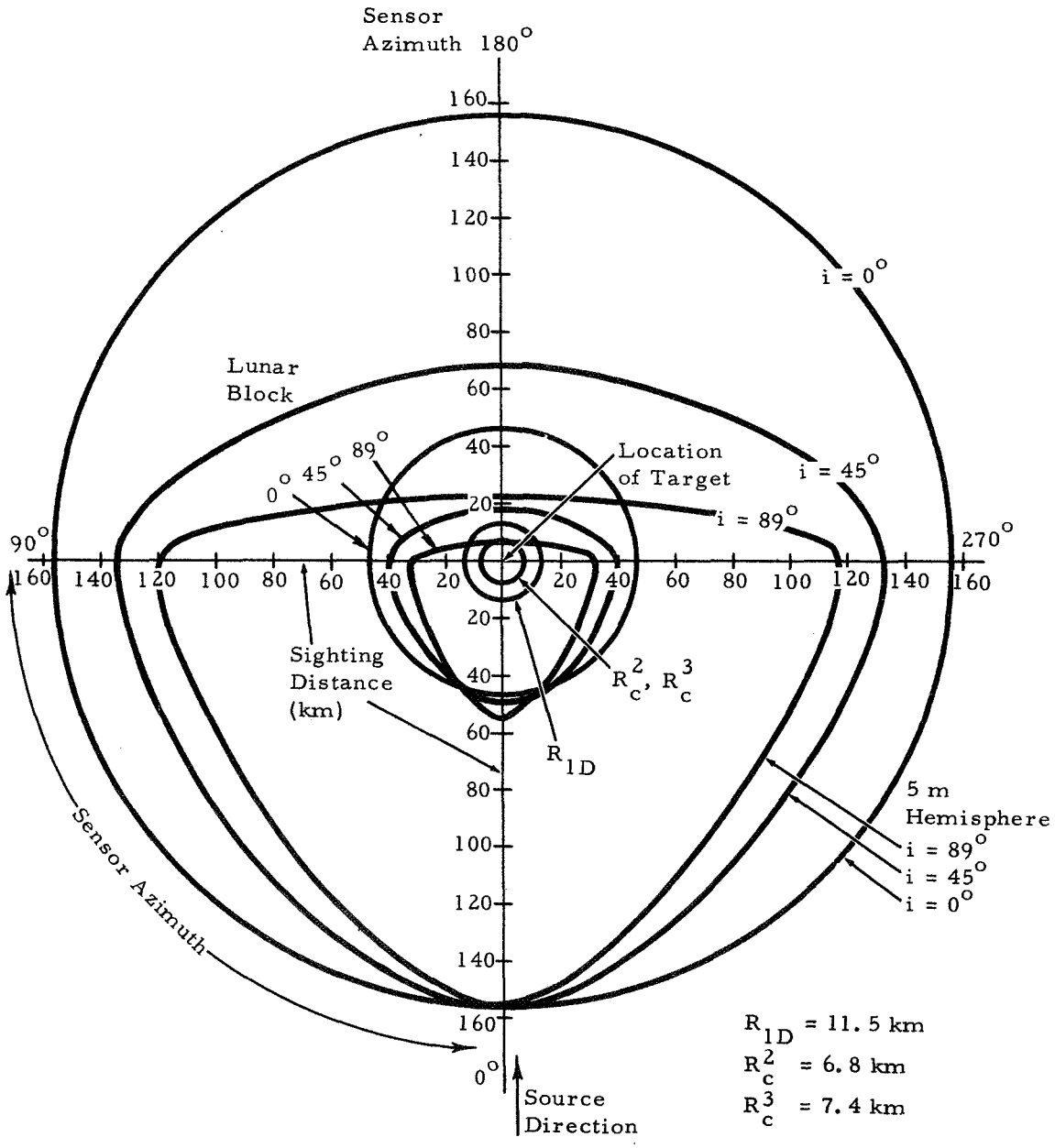

Figure A-5 Visual Sighting Distance vs. Viewing Azimuth; 5-Meter Hemisphere and 5-Meter Lunar Block, Lunar Day, Equatorial Region

APPENDIX B

LOS, LUNAR CURVATURE

The line-of-sight distance on a smooth, spherical moon as a function of the heights of the line-of-sight objects is shown in the nomograph of Figure B-1.

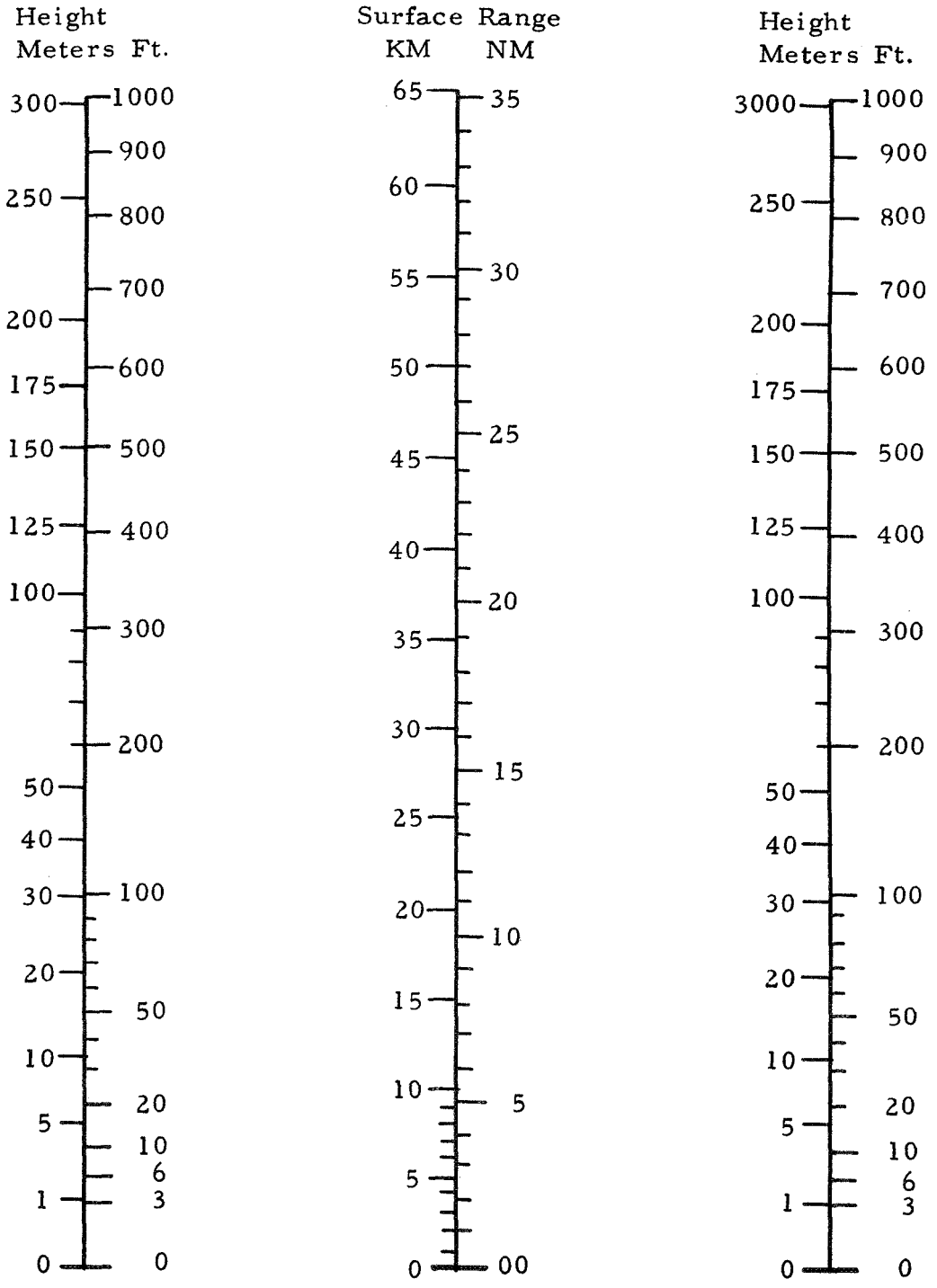

Figure B-1 Lunar Surface Range vs. Objectives' Heights

APPENDIX C

LOS, GROSS STRUCTURE

In addition to the Alphonsus mission as shown in Section 3.0, four other missions were investigated in Reference 2: Hyginus Rille, Moltke B, Capella M, and Far Side Highlands.

Contour maps of the additional sites which indicate the target landing site, the 800-meter CEP, and the minimum line-of-sight distance are presented in Figures C-1, C-2, C-3, and C-4.

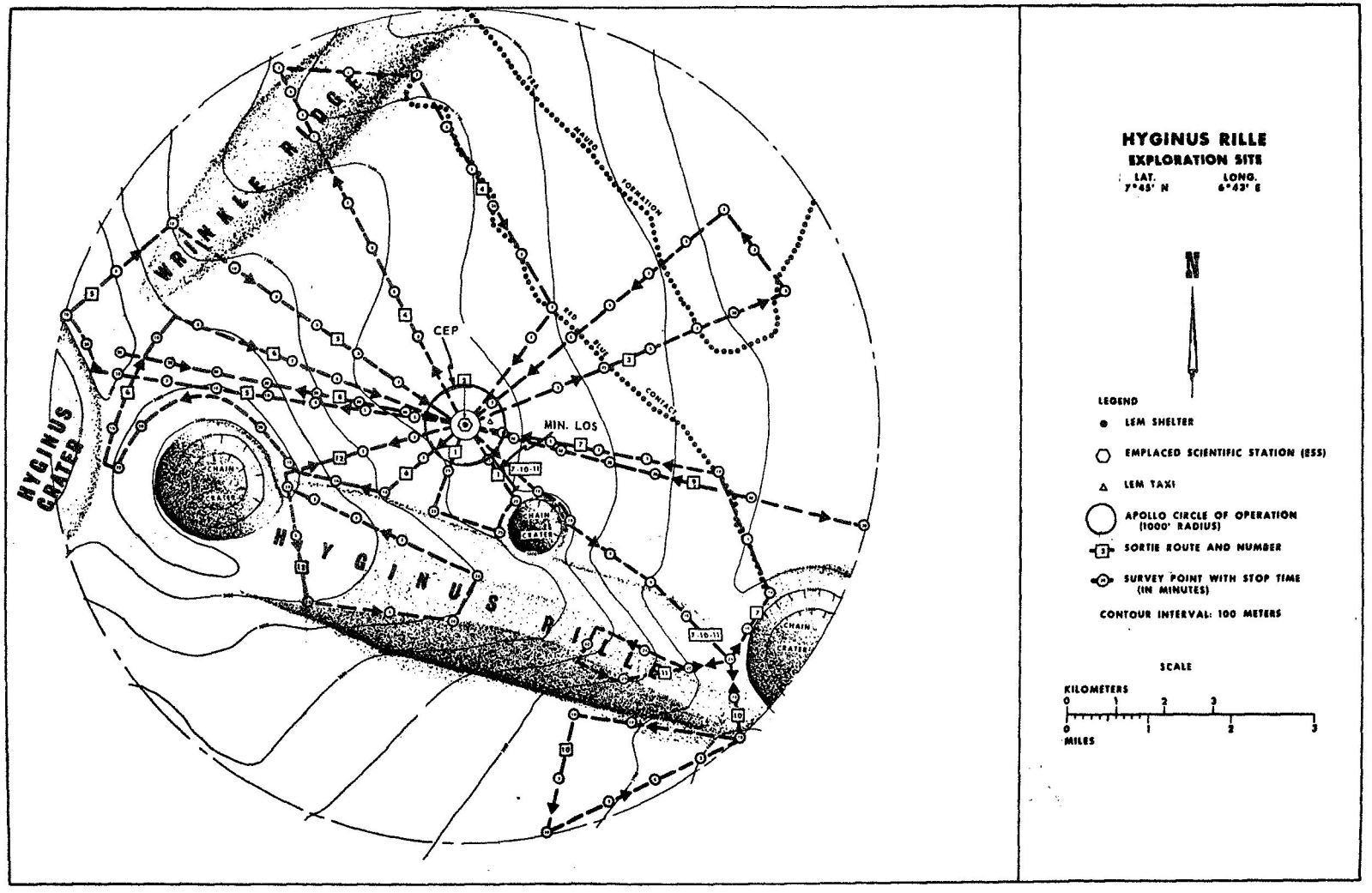

Figure C-1 Hyginus Rille - LSSM Traverse Map

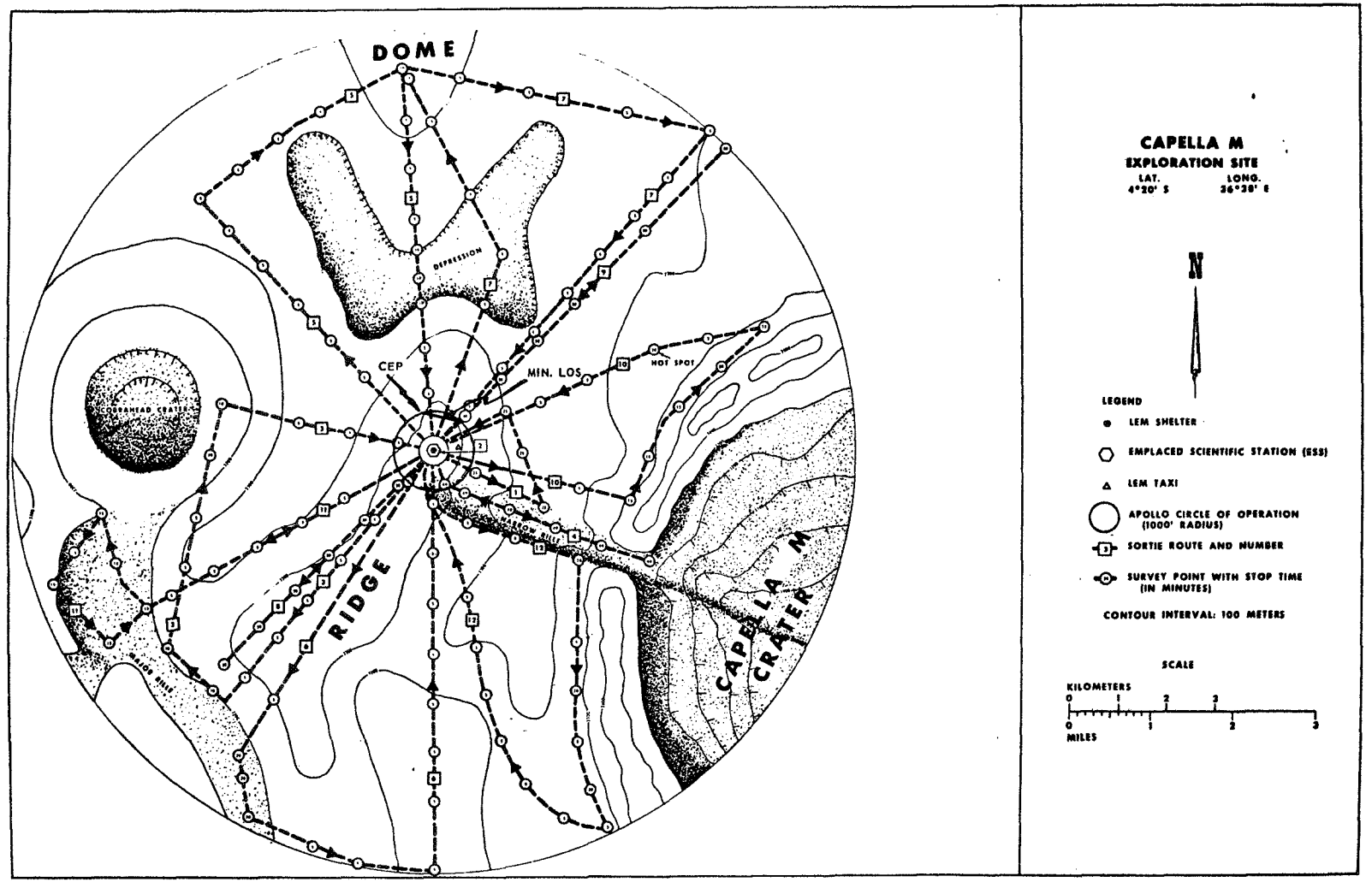

Figure C-2 Capella M - LSSM Traverse Map

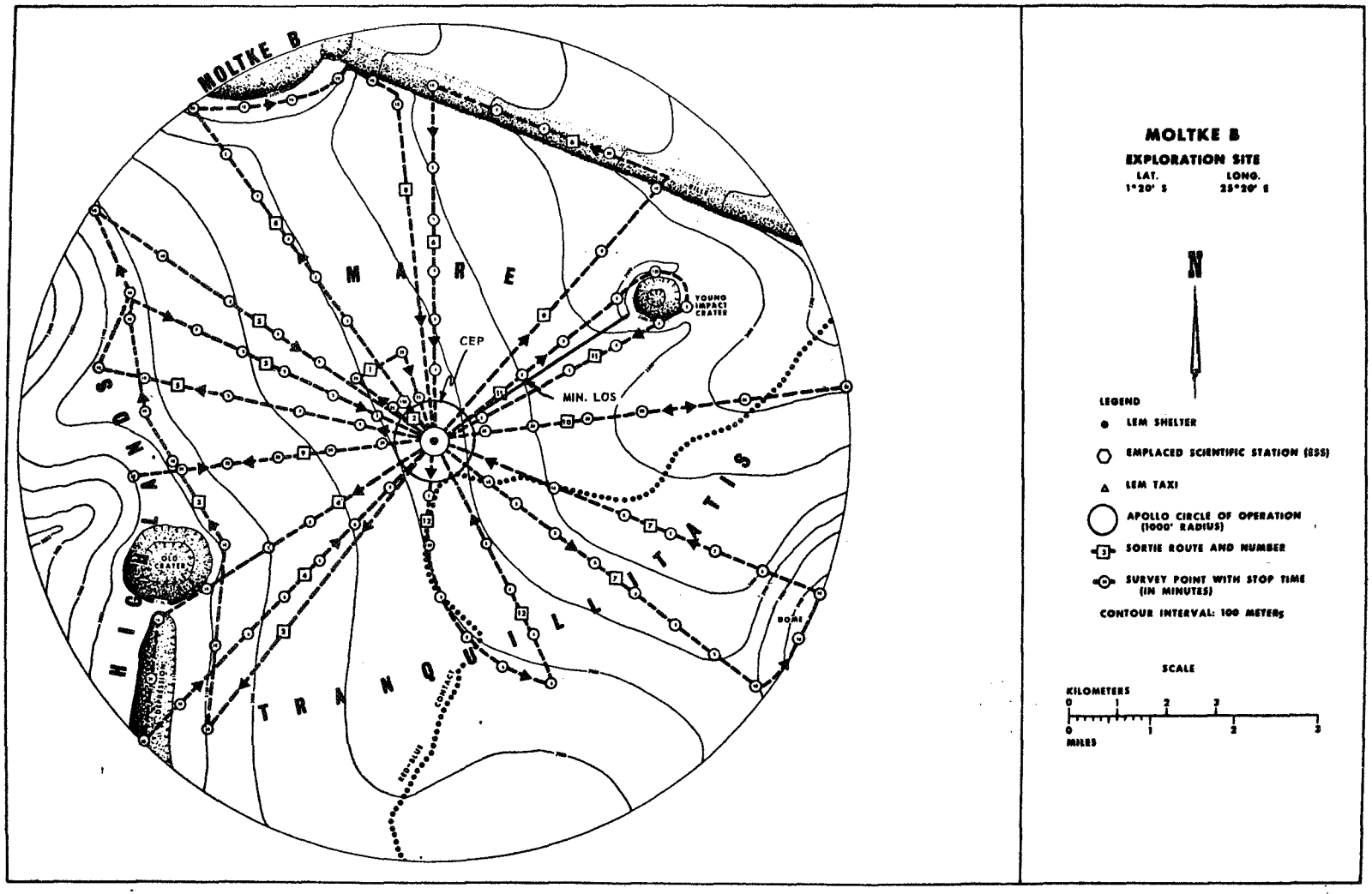

Figure C-3 Moltke B - LSSM Traverse Map

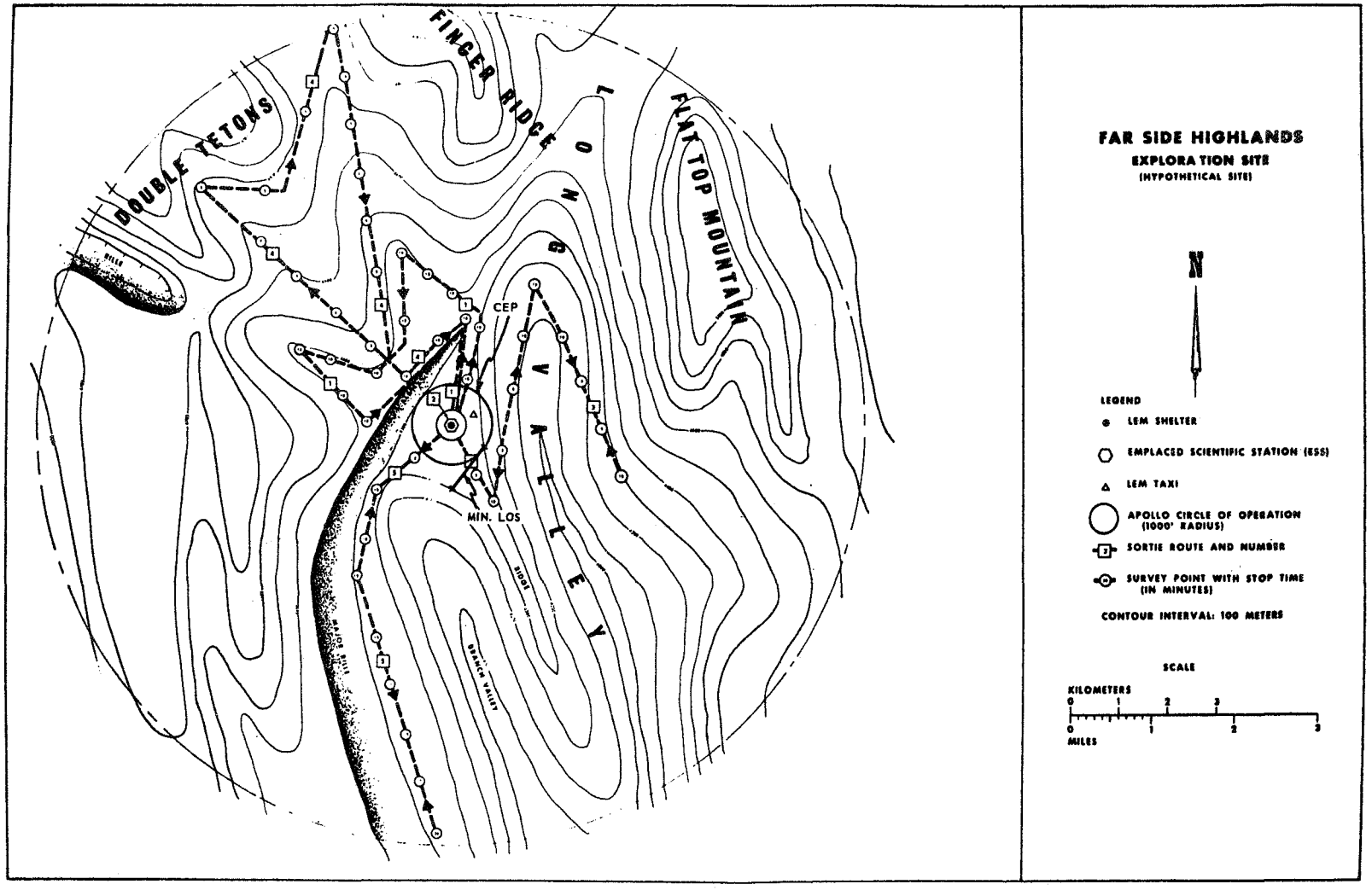

Figure C-4 Far Side Highlands - LSSM Traverse Map

APPENDIX D

SLOPE LENGTH AS A FUNCTION OF AVERAGE SLOPE ANGLE

Lunar terrain data of the form of Figure 3-10, Section 3.0, was obtained from the USGS Branch of Astrogeology at Flagstaff, Arizona [7]. This data covered a greater range of slope lengths (including data obtained from earth-based measurements) than that of Figure 3-10, and applied to the average slope rather than the maximum slope. This data is presented in Figure D-1.

Superimposing an obstruction geometry curve, similar to that of Figure 3-5 (slope length rather than object length), defines the parameters of the terrain object which limits the line-of-sight.

This is illustrated in Figure D-2. Figure D-2 is similar to Figure 3-13; however, the average slope rather than the maximum slope was assumed. This slope criterion establishes a fine structure LOS of 0.09 to 0.46 km.

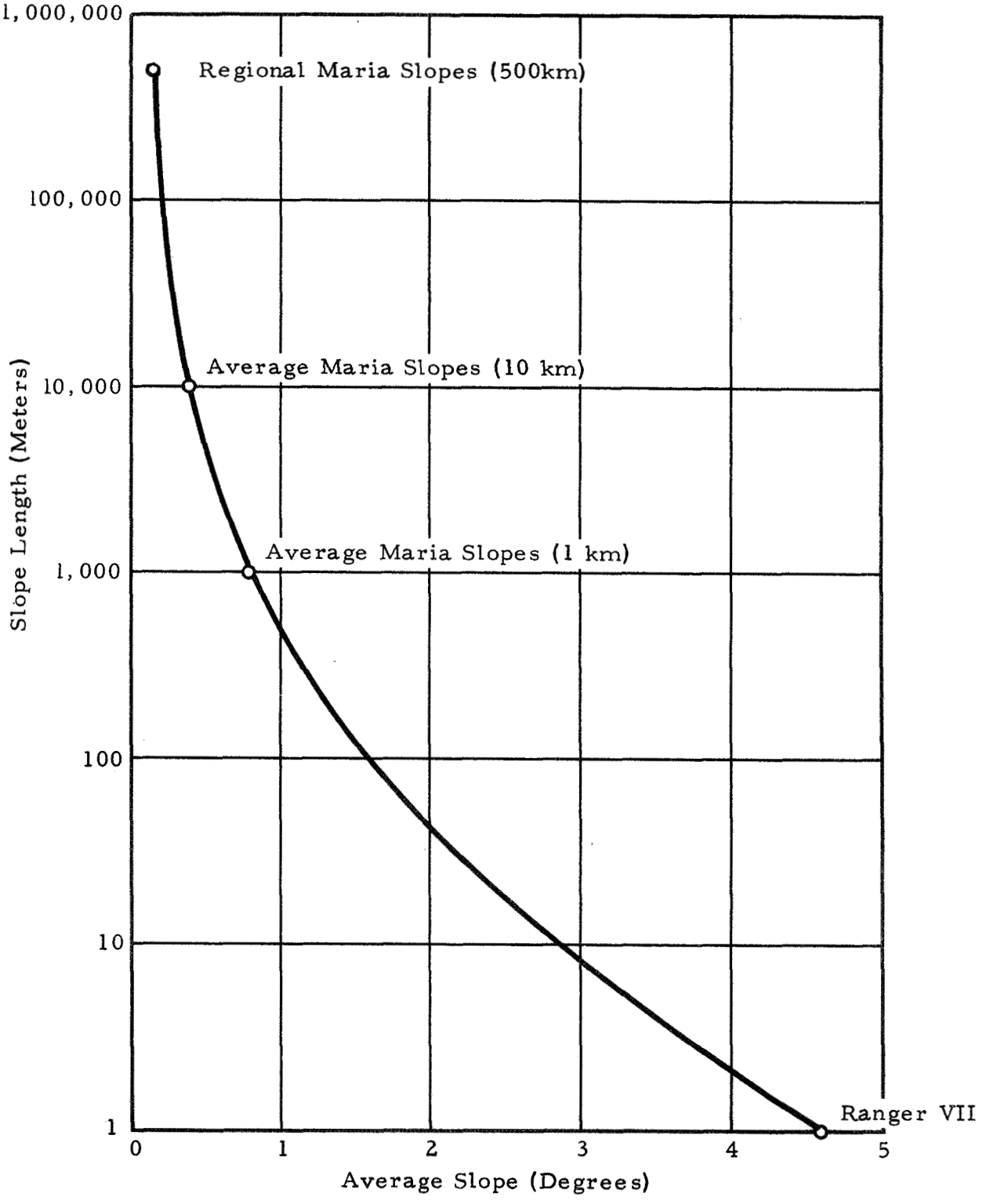

Figure D-1 Slope Length vs. Median Slope Magnitude

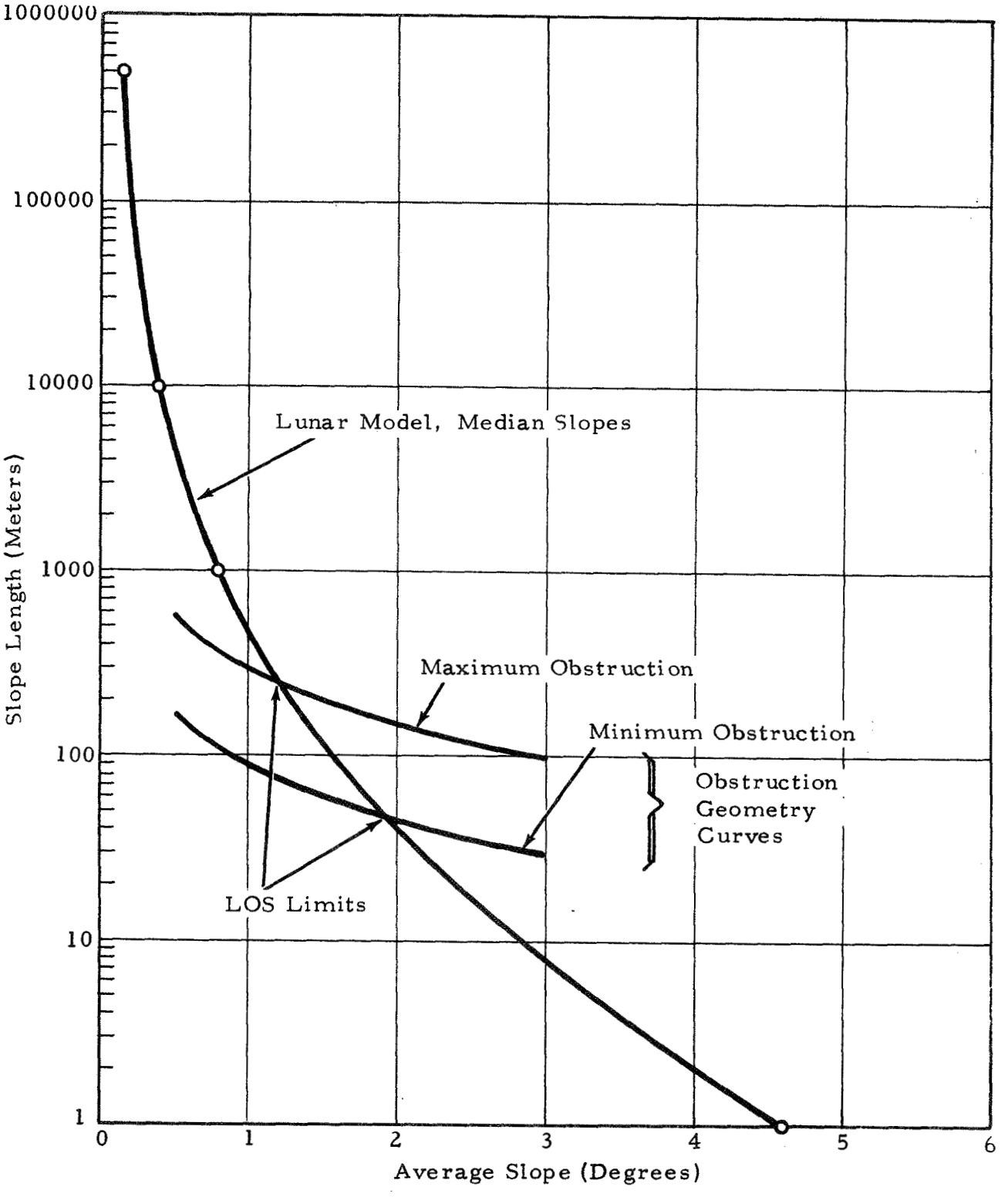

Figure D-2 Fine Structure LOS Limitation Determination

APPENDIX E

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