N70-35662

Copy No. 30

NASA PROGRAM APOLLO WORKING PAPER NO. 1159

AIRCRAFT SIMULATION OF LUNAR LANDING APPROACH TRAJECTORIES

DISTRIBUTION AND REFERENCING

This paper is not suitable for general distribution or referencing. It may be referenced only in other working correspondence and documents by participating organizations.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

February 9, 1965

NASA PROGRAM APOLLO WORKING PAPER NO. 1159

AIRCRAFT SIMULATION OF LUNAR LANDING APPROACH TRAJECTORIES

Prepared by: Joseph F. Stegall
Joseph F. Stegall
AST, Operations Support Section
Spacecraft Operations Branch

Authorized for Distribution:

D K Slayton
Donald K. Slayton
Assistant Director for
Flight Crew Operations

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

February 9, 1965

TABLE OF CONTENTS

LIST OF FIGURES

AIRCRAFT SIMULATION OF LUNAR LANDING APPROACH TRAJECTORIES

By Joseph F. Stegall
Manned Spacecraft Center

SUMMARY

An aircraft simulation of Lunar Excursion Module (LEM) landing approach trajectories was conducted over the Craters of the Moon region in south-central Idaho during September 2-6, 1964. The basic program objectives were to study pilot visibility problems under earthshine conditions and pilot capability to detect off-nominal approaches under both sunshine and earthshine conditions. A standard T-33 aircraft was used to provide a free flight simulation of LEM approach velocities between 15 000 and 1500 feet above the terrain. The approaches were flown by the rear seat pilot while the front seat pilot provided data on detection of terrain features, motion with respect to the terrain and off-nominal approach conditions.

Study results indicate the minimum acceptable reflected earthshine on the LEM approach for both terrain avoidance and safe pilot control of the trajectory is approximately 0.02 ft-L.

On off-nominal low approaches under sunshine, the pilot could recognize the need for correction at a safe altitude, but on similar approaches under low values of reflected earthshine such recognition did not occur until safe recovery would have been marginal.

INTRODUCTION

There has been general speculation regarding the undesirability of a lunar landing under earthshine conditions, but only recently were free flight simulation data obtained to indicate the minimum earthshine required for a safe landing. These data were gathered by the Flight Crew Support Division of the Manned Spacecraft Center in late 1963 in a helicopter simulation of the LEM approach from 1000 feet to touchdown (ref. 1). Results of the study indicated the minimum operationally acceptable reflected earthshine required for landing site selection and a safe manually-controlled touchdown is approximately 0.06 ft-L without artificial lighting aids.

Because of its velocity limitations, the helicopter could not be used to study earthshine visibility problems at the higher altitudes of the LEM approach where successful terrain avoidance, landing area selection, and transition to manual control of the LEM will be greatly influenced by the degree of pilot visibility.

In May 1963, a preliminary aircraft simulation of the LEM landing approach was conducted by the Flight Crew Support Division using a standard T-33 aircraft (refs. 2 and 3). That study indicated aircraft simulations were a valuable means of presenting the operational perspective of the LEM landing approach. It also showed that the T-33 aircraft could simulate a representative LEM trajectory within 10 percent of desired values of altitude, range, velocity, time and dive angle from 15 000 to 5000 feet altitude.

On the basis of the initial T-33 study and the desire to extend the earthshine studies to develop a more complete evaluation of LEM pilot visibility problems, a second earthshine study, the subject of this report, was conducted by the Flight Crew Support Division in September 1964. In this study, a standard T-33 aircraft was flown along a LEM approach trajectory by the rear cockpit pilot while the front cockpit pilot provided visibility data. In addition, during this study a "quick look" was taken at the capability of the pilot to detect off-nominal LEM trajectories through out-the-window visual cues under both sunshine and earthshine conditions.

FACILITIES AND EQUIPMENT

Test Area

The Craters of the Moon region of south-central Idaho was selected for the test site because it contains extensive areas of low-contrast black lava flows. The lava type is basalt. Its albedo (percent luminous reflectance) ranges from 6 percent to 28 percent, with an average of about 13 percent. By comparison, lunar surface albedos range from approximately 5 percent for maria to 16 percent for the bright rays (ref. 4). The average elevation of the lava beds is 5700 feet above sea level, with cinder cones through the central portion rising to about 500 feet above the otherwise level terrain. Figure 1 shows the location of the area and the two ground tracks used for data runs. Track no. 1 was used for all but five runs because of the large expanse of flow on both sides of track.

Ground Facilities

The test aircraft and personnel were based at Hill Air Force Base, Utah, 130 miles southeast of the Craters of the Moon region during the test period. Flight crews and ground support engineers used an area in the Base Operations Building for preflight trajectory calculations, briefings, and preliminary data analysis. A UHF transmitter/receiver in the Base Weather Station was used for relay of information between flight and ground crews.

Aircraft and Test Equipment

A USAF T-33 aircraft, 57-0722, assigned to the NASA Manned Spacecraft Center, was used for this study. It was instrumented with the following test equipment:

1. Motion picture camera in the nose of the aircraft to photograph the terrain ahead of the aircraft as seen by the front cockpit pilot (fig. 2).

2. Motion picture camera in the rear cockpit to photograph instrument panel readings of flight data (fig. 3).

3. Voice tape recorder for front cockpit pilot commentary and visibility data recording.

4. Total temperature sensor/indicator unit for use with other flight instruments in providing data for postflight trajectory calculations (figs. 2 and 3).

5. Attitude indicator with a 5-inch ball calibrated in 2°-increments of dive angle for accurate flight path control (fig. 3).

Hand-Held Equipment

Several pieces of hand-held equipment were carried in the front cockpit for use in simulating earthshine conditions:

1. Neutral density glass and gelatin filters with a range of visible light transmittance between 0.002 percent and 80.0 percent to simulate various levels of reflected earthshine. A greater range of transmittance was obtained by combinations of filters.

2. Goggles to be fitted with appropriate filters and worn by the front cockpit pilot.

3. Spectra Brightness Spot Meter to measure reflected surface illumination, with an acceptance angle of 1.5° and a scale range of from 10^{-4} to 10^{4} ft-L.

4. Filter Selection Charts to relate light meter readings to filter combinations for test values of simulated earthshine (fig. 4).

TEST CREWS

Three astronauts, three pilot-engineers from the Flight Crew Support Division, and one research pilot from the Aircraft Operations Office formed the flight crews for the study. All but seven data runs were flown with astronauts in the front cockpit as data pilots. Seven runs were made by two pilot-engineers who had extensive LEM approach simulation experience.

SIMULATED EARTHSHINE ENVIRONMENT

Simulated lunar surface brightness was obtained from the photometric model described by:

$$B = E \rho \phi \text{ (ref. 4)}$$

where:

B = surface luminance

E = incident illumination

ρ = normal surface albedo

ϕ = photometric function

Figure 5 shows the relationship of the angles that determine the photometric function ϕ. The angle i is the angle of incidence of source illumination measured from the normal to the reflecting plane, ϵ the viewing angle measured from the normal and α is the included angle between the direction of incidence and the direction of viewing (ref. 5). Since it has been observed that lines of isobrightness follow the lunar meridians and since the nominal landing areas are within $\pm 10^\circ$ latitude, the normal to the reflecting plane can be assumed to lie in the plane containing α (refs. 4 and 8). With that assumption, the photometric function can be expressed in terms of only two parameters, α and ψ.

The variable α remains the phase angle and ψ is the projection of the viewing angle ϵ onto the phase plane containing α. Figures 6 and 7 illustrate the relationships between angles α and ψ and the photometric function ϕ.

The earthshine conditions simulated in this study ranged in values of reflected earthshine from 0.0027 to 0.088 ft-L. Figures 8 and 9 illustrate photometric parameters that could produce some of the earthshine conditions. A normal albedo of 7 percent was used for all conditions, closely approximating the average lunar maria albedo of 6.5 percent.

Filter selection for a predetermined earthshine condition was based on measured transmissibility of each filter and light meter readings of reflected sunshine, expressed as follows:

$$\text{percent filter transmissibility} = \frac{B}{B'} \times 100$$

where: B = simulated reflected sunshine

B' = measured reflected sunshine

An example of a Filter Selection Chart is illustrated in figure 4. As shown, a filter or filter combination was listed for each small range of possible light meter readings. An attempt was made to induce no more than 10 percent error in the matching of a light meter reading to a filter combination to simulate a given earthshine condition.

PROCEDURES

Aircraft Trajectory

Prior to the start of operations, tables and nomograms were developed that related LEM approach velocity, altitude, and range to T-33 indicated airspeed, indicated altitude, dive angle and total temperature. Before each flight, predicted flight level temperatures, pressures, and winds were input to the tables and nomograms to produce an airspeed-altitude-dive angle profile for each data run. The rear cockpit pilot used the profiles, in the form of checkpoint parameters, to control the flight path.

To establish the T-33 on a simulated LEM approach, the aircraft was dived through approximately 3500 feet to increase airspeed to that required at trajectory entry altitude. This altitude was 15 000 feet above the terrain for normal simulated earthshine runs, and either 4000 feet higher or lower for off-nominal trajectory runs. At that point, the start of the run, the pilot reduced throttle to idle, assumed the correct dive angle (near 14°) and lowered speed brakes. While the front cockpit pilot provided visibility data, or off-nominal detection data in cases of off-nominal trajectories, the rear cockpit pilot controlled the aircraft and recorded airspeeds, altitudes and total temperature readings to be used for postflight checks of trajectory simulation accuracy. Aircraft control on the trajectory consisted of holding the proper heading and making small dive angle adjustments as called for on the precomputed trajectory profile.

Each data run trajectory was reconstructed after operations ended from rear cockpit camera data of airspeed, altitude, total temperature, and time. After conversions of indicated airspeed to equivalent airspeed and indicated pressure altitude to ambient flight level pressures, using charts in the T-33 Flight Handbook (ref. 6), tables based on the following equation were used to calculate true airspeed:

$$V_t = 49.05\ V_e \left(\frac{5\ T_{to}}{V_e^2 + (2947.2)Pa} \right)^{\frac{1}{2}}$$

where: V_t = true airspeed (ft/sec)

V_e = equivalent airspeed (ft/sec)

T_{to} = total temperature ($^{\circ}$R)

P_a = ambient pressure (lb/ft^2)

The derivation of the above equation is shown on page 16. Ground speed was calculated by adding or subtracting the predicted true wind speed. Strip integration was performed on plots of ground speed versus time to calculate range.

Figures 10 and 11 show the relationships between the average nominal T-33 trajectory and two proposed LEM trajectories. The Guidance and Control Division (GCD) trajectory "d" was used as the standard for this study because it is representative of a number of proposed trajectories, and it, more than any other available at the beginning of study planning, can be more closely simulated with the T-33 aircraft. The current MIT LEM trajectory (as of July 1964) was received during the data runs.

T-33 drag characteristics are such that the LEM approach can be closely matched between 15 000 and 5000 feet. During the approach, the lift-to-drag ratio gradually increases so that, as shown on figure 10, an overspeed builds up that reaches 20 percent higher than LEM velocity on the GCD trajectory "d" at about 3700 feet.

Two types of off-nominal approaches were simulated, one 4000 feet too high and the other 4000 feet too low. An error of 4000 feet was assumed to exist in LEM inertial system calculations of altitude without benefit of landing radar data. This represents an estimate of the combined three-sigma (3σ) uncertainties in the inertial system altitude and altitude rates, plus the minimum expected displacement inaccuracies of lunar surface elevation as a result of a projected lunar orbiter mission.

The high approach simulation was not productive, primarily because of the previously mentioned lack of T-33 drag at low airspeeds. It was impossible to reduce airspeed sufficiently for the data pilot to reconize the high altitude — low velocity relationship of an off-nominal high trajectory.

The off-nominal low trajectory was flown on eleven data runs. Entry to the low trajectory was at 11 000 feet above the terrain at the velocity corresponding to 15 000 feet on the nominal LEM trajectory. Figures 12 and 13 show comparison between the average T-33 low trajectory and estimates of low LEM trajectories based on the GCD and MIT trajectories.

Nominal Earthshine Approaches

Before each flight the front cockpit pilot (data pilot) was given four values of reflected earthshine to be simulated. In preparation for each approach, he accomplished the following:

1. Take several light meter readings with the Spectra Brightness Spot Meter along the approach trajectory toward the simulated landing area. Calculate average light meter reading.

2. Enter the Filter Selection Chart for the desired simulated earthshine with the average light meter reading and select appropriate filters.

3. Place filters in the goggles, put on goggles and begin dark adaption. Continue dark adaption for 15 minutes.

During the approach the data pilot viewed the terrain ahead, limiting his field of view to the lava flow by cupping his hands around the goggle rims as necessary to exclude from view the horizon and terrain outside the lava flow that would produce unrealistic cues. Figure 14 is a series of nose camera photographs of the terrain ahead on a typical approach.

The data pilot was encouraged to comment at will on visibility conditions during each approach. In addition to comments, he was asked to signal by voice when he observed the following:

MARK I - Point at which he could first see the terrain.

MARK II - Point at which he had adequate visual cues to take positive terrain avoidance action.

MARK III - Point at which he could define the character of the terrain and his motion with respect to it to the extent that he estimated he could judge the trajectory to be safe or unsafe.

Voice data was recorded on the onboard tape recorder. It was time-correlated to film data by the rear cockpit pilot simultaneously actuating a film-marking circuit and recording a voice-time hack at the start of each approach.

Off-Nominal Approaches

Both sunshine and earthshine off-nominal approaches were flown. Off-nominal trajectories were intermixed with nominal ones so that the data pilots would not know when to expect an off-nominal approach. The data pilot was encouraged to comment at will, but to record the following:

1. Sunshine Runs – detection of off-nominal condition and required takeover point.

2. Earthshine Runs – normal earthshine data (MARKS I, II, and III) and required takeover point.

The required takeover point was defined as the point on the low trajectory at which the pilot judged the altitude – altitude rate relationship to be undesirable to the extent that manual takeover was necessary.

RESULTS AND DISCUSSION

A total of 44 data approaches were flown during this study, summarized as follows:

3 nominal trajectory sunshine approaches

29 nominal trajectory earthshine approaches

1 high trajectory sunshine approach

7 low trajectory sunshine approaches

4 low trajectory earthshine approaches

The nominal trajectory sunshine approaches were used before off-nominal operations to familiarize data pilots with the nominal altitude-altitude rate relationships. Adequate photo-panel recording was achieved on each of the 44 runs to successfully determine aircraft trajectories, and data was recorded on MARKS I, II, and III for each run.

Earthshine Approaches

The results of both nominal and off-nominal approaches will be discussed in this section.

As stated earlier, on simulated earthshine approaches the pilots recorded three data points, MARKS I, II, and III, from observations of the terrain ahead. The pilots were generally able to see the terrain immediately upon approach entry at 15 000 feet (MARK I). Occasionally, at brightnesses below 0.02 ft-L, MARK I was delayed to as low as 10 000 feet; but the data distribution was random and could not be directly related to degraded visibility.

Figure 15 shows the relationship found between reflected earthshine brightness and estimated capability to take terrain avoidance action. No terrain avoidance problems are indicated at brightness levels above 0.01 ft-L. In fact, at 0.02 ft-L and above, most pilots called this point (MARK II) at the start of the approach. Below 0.01 ft-L, the data indicate a rapid deterioration in the pilots' capability to distinguish terrain features. This is believed to be partially due to the normal transition from cone to rod vision that occurs near 0.01 ft-L. Rod vision consists of no color, but rather shades of gray and black shadows, making it difficult for one to perceive relative shapes or sizes of low-contrast objects.

Figure 16 shows the MARK II data from one astronaut who used a different definition of terrain avoidance capability. Instead of using gross differences in terrain features, as other pilots were doing, he called MARK II when he could perceive relative elevations of objects within a low-contrast area. It can be seen by comparing figures 15 and 16 that the latter definition, more restrictive than the first, resulted in lowered terrain avoidance capability down to about 0.005 ft-L brightness; however, at about that brightness level all pilots' data were grouped closely together. In summary, figure 15 indicates the terrain avoidance capability under earthshine based upon gross differences in terrain features in several low-contrast areas; whereas, figure 16 indicates that capability when relative elevations are used within a low-contrast area.

The data enclosed by the solid lines in figure 17 represent pilot capability to characterize the terrain and his motion with respect to it to the extent he estimated that he could judge the trajectory to be safe or unsafe (MARK III). As expected, the data indicated a significant difference in individual pilot judgement. Therefore, the worst-case data appear to be the most significant. It varies from 2000 feet at 0.005 ft-L to 7800 feet at 0.053 ft-L. Some pilot comments on visual capability are listed on page 15. They indicate a lack of confidence in pilot ability to safely determine approach conditions at earthshine brightnesses below 0.02 ft-L.

The data marked by "x" in figure 17 represent the altitudes on off-nominal low trajectories at which the pilots detected the need for manual takeover because of excessive velocity, particularly altitude rate. The "x" data point at the extreme right of figure 17 represents the average takeover point on off-nominal low trajectories under sunshine conditions. Average deviation for that point was ±1100 feet.

The limited off-nominal trajectory data indicates that at low earthshine brightness levels the LEM pilot may not recognize the need for manual takeover on a low trajectory in sufficient time to recover. Figure 18 shows a graphical relationship between a low trajectory and its "dead man curve." The "dead man altitude" is defined as the altitude at or below which recovery is impossible, even with maximum available spacecraft thrust, because of excessive descent rate. For any altitude-descent rate combination on the trajectory, the corresponding "dead man altitude" can be found from the following equation:

$$\text{DMA} = \frac{1}{2} at^2 + V_o t + V_o t_A$$

where:

DMA = dead man altitude (feet)

a = acceleration at maximum descent engine thrust (ft/sec^2)

V_o = initial descent rate (ft/sec)

t = time from application of maximum thrust to end of descent

t_A = time from pilot recognization of need for correction to rotation of LEM to vertical and application of full thrust (assumed 5 sec for fig. 18)

Also shown on the trajectory of figure 18 are the altitudes at which takeover was felt to be necessary on the low trajectory approaches. Note that takeover was not signaled on the low trajectory at 0.012 ft-L earthshine until very near the "dead man altitude."

The "dead man curve" shown on figure 18 is based on an abort using the descent engine. Should descent stage fuel depletion or other factors necessitate an abort using the ascent engine, then the "dead man altitude" would be considerably higher.

The possible effects of terrain shadows were investigated by comparing data from up-sun runs against data from down-sun runs. No appreciable differences could be found in the data, but pilots commented that when the sun was behind them the terrain shadows were more helpful.

In summary, the significant results from the earthshine portion of the study are:

1. Visibility for terrain avoidance appears to be adequate at earthshine brightness levels down to approximately 0.01 ft-L. Below that level this capability becomes questionable.

2. Estimated capability to judge the trajectory as safe or unsafe gradually deteriorated with decreasing values of simulated earthshine. Pilots indicated a lack of confidence in ability to safely determine approach conditions at reflected brightnesses below 0.02 ft-L.

3. Pilot capability to recognize a low approach under earthshine in time to execute a safe recovery appears questionable below 0.01 to 0.02 ft-L reflected earthshine.

Off-Nominal Sunshine Approaches

Although the primary purpose of this study was an investigation of pilot visibility problems during a LEM landing approach under earthshine conditions, a "quick look" was taken at pilot capability to recognize low off-nominal approaches. The off-nominal approaches under earthshine were discussed in the preceding section and will not be repeated here. The off-nominal approaches under sunshine conditions revealed two significant factors that should be considered in the development of LEM operational procedures.

First, study results show that under sunshine conditions with out-the-window visual cues alone, the pilots did not recognize the need to correct a 4000 foot low trajectory until between 3500 to 6300 feet above the terrain. Based upon visibility requirements alone, recognition of required takeover under sunshine came surprisingly late when one considers that it occurred between 1400 and 3400 feet on similar approaches under very low earthshine (fig. 17). This indicates that height above the terrain replaces degree of environmental illumination as the governing factor in detection of off-nominal trajectories as brightness level is increased from low earthshine to sunshine.

Secondly, during approaches directly toward the sun when it was low on the horizon, pilots commented that the sun in the field of view significantly degraded their capability to characterize the terrain ahead. Although the appearance of the sun as viewed through the earth's atmosphere is influenced by atmospheric scattering of light and cannot be equated to its appearance in the lunar environment, degraded pilot visibility can be expected on LEM approaches into a low sun simply because of its extreme brightness.

CORRELATION OF RESULTS WITH HELICOPTER STUDY RESULTS

A comparison can be made between the results from this study and the results from the earlier helicopter study over Pisgah Crater in California. In the helicopter study, approaches were made from 1000 feet altitude to landing sites 2000 to 6000 feet ahead. The average approach angle was 14°, as in this study. Minimum operationally acceptable reflected earthshine from 1000 feet to touchdown was indicated by that study to be approximately 0.06 ft-L. The same photometric model was used as a basis for both studies, and two pilots participated in both studies.

In contrast to the pilot tasks of landing site selection and touchdown in the helicopter operation, this study was concerned with the visual cues available to the pilot at higher approach altitudes for gross terrain avoidance and manual takeover for a safe approach to a landing area. In view of the different pilot tasks in the two study areas, it is not surprising that results indicate a lower acceptable earthshine level for the approach phase than for the site selection and touchdown phase. Precise definitions of terrain slope and small objects that influenced site selection are necessary for the terminal approach phase but not for gross terrain avoidance and manual takeover.

While it is conceded that the minimum acceptable visibility for site selection and touchdown is the limiting factor, regardless of lower acceptable visibility down to that point, there remains the possibility that artificial lighting aids could be used to supplement environmental lighting near touchdown, and thus lower the minimum operationally acceptable brightness level recommended in the helicopter study. Such a relaxation in minimum earthshine requirements could result in a launch window extension; however, the extent to which the launch window would be affected cannot be determined until free-flight studies are made with artificial lighting aids and a simulated lunar surface.

Neither the helicopter nor the T-33 aircraft could be used to precisely simulate the critical portion of a nominal LEM approach between 3500 and 1000 feet because of flight performance restrictions. Preliminary analytical analyses indicate the T-38 aircraft can be used for a range of that portion of the approach, within 10 percent of LEM velocity, altitude and flight path angle, to provide continuing free-flight simulation to evaluate latest concepts in LEM trajectories and environmental lighting requirements.

CONCLUDING REMARKS

The significant study results are summarized below:

1. Visual cues for safe terrain avoidance action appear to be adequate down to 0.01 ft-L reflected earthshine.

2. Estimated capability to judge the trajectory as safe or unsafe gradually deteriorated with decreasing values of simulated earthshine, but, within the range of values simulated, no rapid deterioriation was noted. Pilot comments, however, show a lack of confidence in the

capability to monitor the approach and execute manual takeover under less than 0.02 ft-L reflected earthshine.

3. Very limited data on 4000-foot low trajectories under earthshine indicate that in the region of from 0.01 to 0.02 ft-L reflected earthshine the need for manual takeover of the LEM may not be recognized in sufficient time to execute the procedures and correct the trajectory.

4. The points at which pilots felt manual takeover was required on low trajectories under sunshine condition ranged from 3500 to 6300 feet, with an average of 5200 feet above the terrain.

Due to the limited time available for this study and the limitations of the T-33 aircraft for simulating the lower regions of the LEM approach, it was impossible to study in depth both nominal and off-nominal LEM trajectories under earthshine, as well as off-nominal sunshine approaches. For that reason no attempt will be made to recommend an absolute minimum acceptable reflected earthshine for safe pilot control of the trajectory. However, based upon study results and pilot opinions, such a minimum would appear to be approximately 0.02 ft-L.

Finally, it is recommended that the T-38 aircraft be considered for future free-flight simulations of the LEM approach because of its improved performance over the T-33 at the higher and lower altitudes and velocities of the LEM trajectory. The T-38 could be used for additional earthshine studies, if necessary, and for astronaut evaluation of changes to the LEM approach trajectory.

SYNOPSIS OF PILOT COMMENTS

Simulated Earthshine

0.0880 ft-Lamberts	Not much difference between this and a sunshine run.
0.0500	Plenty of visibility.
0.0256	Adequate visibility cues.
0.0182	Rate of descent not apparent until about 3000 feet above the ground (rate of descent used as cue for takeover capability).
0.0120	Marginal capability to detect rate of descent.
0.0046	No visibility cues for a long time. Extremely dark earthshine.
0.0027	Dark.

AIRCRAFT TRAJECTORY EQUATIONS

Definition of Terms:

V_t	=	true airspeed (ft/sec)
V_e	=	equivalent airspeed (ft/sec)
ρ	=	density (slugs/ft^3)
ρ_o	=	standard sea level density (0.002377 slugs/ft^3)
P_a	=	ambient pressure (lb/ft^2)
P_o	=	standard sea level pressure (2116 lb/ft^2)
T_a	=	ambient temperature ($^\circ$R)
T_o	=	standard sea level temperature (518.7°R)
T_{to}	=	total temperature ($^\circ$R)
M	=	Mach number
a	=	acoustic velocity (ft/sec)

True airspeed is related to equivalent airspeed by (ref. 6):

$$V_t = \frac{V_e}{\sqrt{\sigma}}$$

$$\sigma = \frac{\rho}{\rho_o}$$

Since

$$\frac{\rho}{\rho_o} = \frac{P_a}{T_a} \cdot \frac{T_o}{P_o} \, , \quad \sqrt{\sigma} = \sqrt{\frac{P_a \, T_o}{P_o \, T_a}}$$

and,

$$V_t = \frac{V_e}{\sqrt{\dfrac{P_a\ T_o}{P_o\ T_a}}} \quad \text{or} \quad V_t^2 = \frac{{V_e}^2}{\left(\dfrac{P_a}{P_o}\right)\left(\dfrac{T_o}{T_a}\right)}$$

Solving the above equation for T_a:

$$T_a = P_a \left(\frac{V_t}{V_e}\right)^2 \left(\frac{T_o}{P_o}\right) \tag{1}$$

For reversible adiabatic flow of air (ref. 7),

$$T_{to} = T_a + 0.2\ M^2\ T_a$$

or,

$$M = \sqrt{5}\ \sqrt{\frac{T_{to} - T_a}{T_a}} \tag{2}$$

True airspeed can be expressed as a function of temperature and Mach number (ref. 7).

$$V_t = M\ a \quad \text{and} \quad a = 49.05\ \sqrt{T_a}$$

or,

$$V_t = 49.05\ M \sqrt{T_a} \tag{3}$$

Substituting (2) into (3) and squaring both sides of the equation:

$${V_t}^2 = (5)\ (49.05)^2 \left(T_{to} - T_a\right) \tag{4}$$

Substituting (1) into (4) and using standard values for T_o and P_o :

$$V_t = 49.05\ V_e \left(\frac{5\ T_{to}}{V_e^2 + 2947\ P_a} \right)^{\frac{1}{2}}$$

REFERENCES

1. Lewis, J. L., Wheelwright, C. D.: "Lunar Landing and Site Selection Study, Phase II," Nasa Program Apollo Working Paper No. 1147. NASA Manned Spacecraft Center, Houston, Texas

2. Brickel, J. R.: Memorandum for Chief, Flight Crew Support Division re: Aircraft Simulation of LEM Final Approach Trajectories, NASA Manned Spacecraft Center, Houston, Texas, July 2, 1963.

3. Brickel, J. R., Smith, H. E.: Memorandum for Chief, Flight Crew Support Division re: In-Flight Simulation of Earth-Light Visibility During LEM Final Approach, NASA Manned Spacecraft Center, Houston, Texas, August 30, 1963.

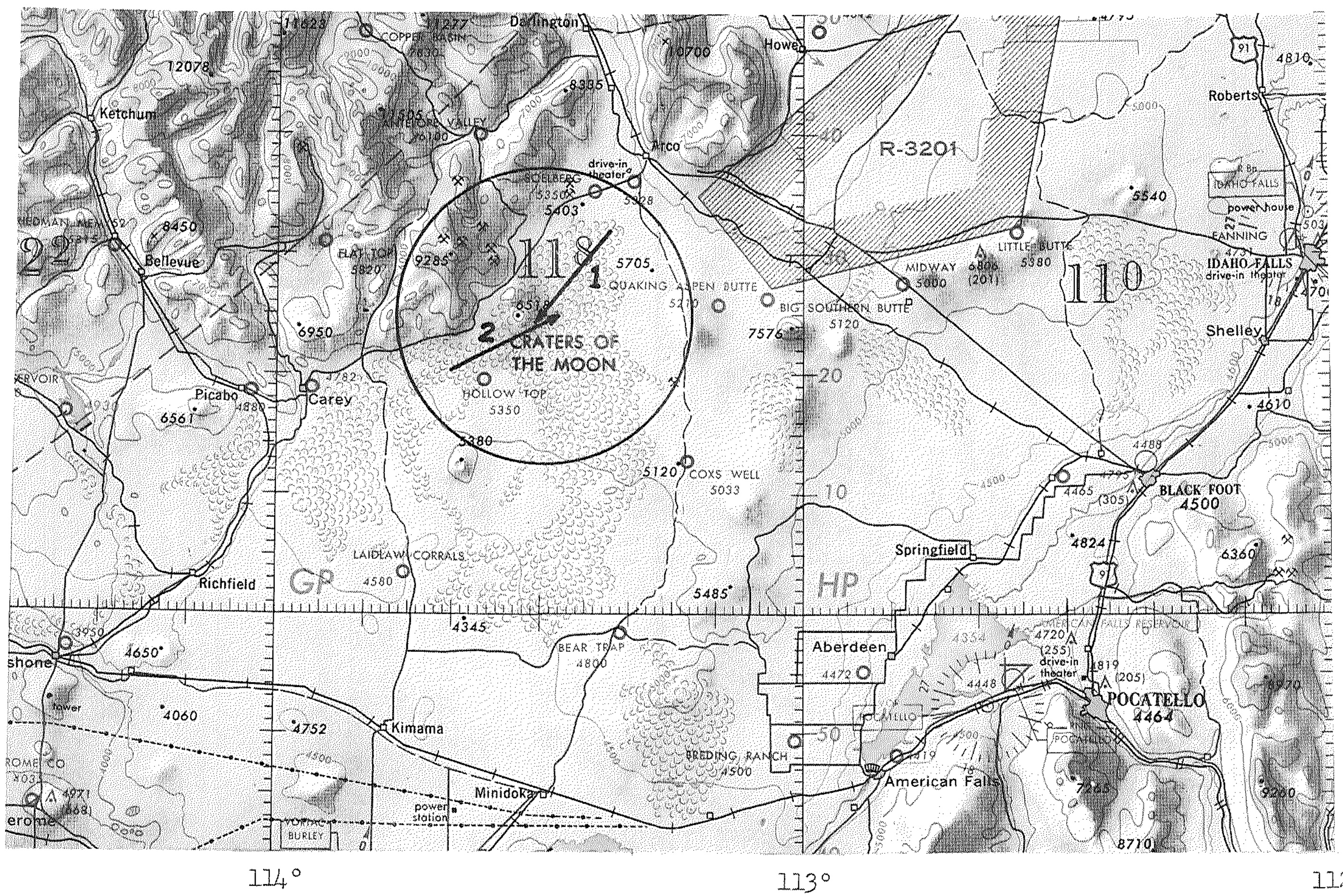
4. Eggleston, J. M.: "Factors Affecting the Choice of Lunar Landing Areas and the Choice of Environmental Conditions at These Landing Areas." NASA Program Apollo Working Paper No. 1100. NASA Manned Spacecraft Center, Houston, Texas, November 22, 1963.

5. Herriman, A. G., Washburn, W. H., and Willingham, D. E.: "Ranger Preflight Science Analysis and the Lunar Photometric Model." TR No. 32-384 (Rev.) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, Revised March 11, 1963.

6. USAF Series T-33A Aircraft Flight Manual T.O. IT-33A-1, May 1, 1963.

7. Durham, F. P.: "Aircraft Jet Powerplants," Prentice-Hall, Inc., Englewood Cliffs, New Jersey

8. Abel, R. W.: "Lunar Excursion Module Visibility Requirements." NASA Program Apollo Working Paper No. 1115. NASA Manned Spacecraft Center, Houston, Texas, June 15, 1964.



SCALE 1:1,000,000

Figure 1.- Craters of the Moon area and approach trajectory ground tracks.

NASA
S-64-31432

Figure 2.- Aircraft nose camera and total temperature sensor installations.

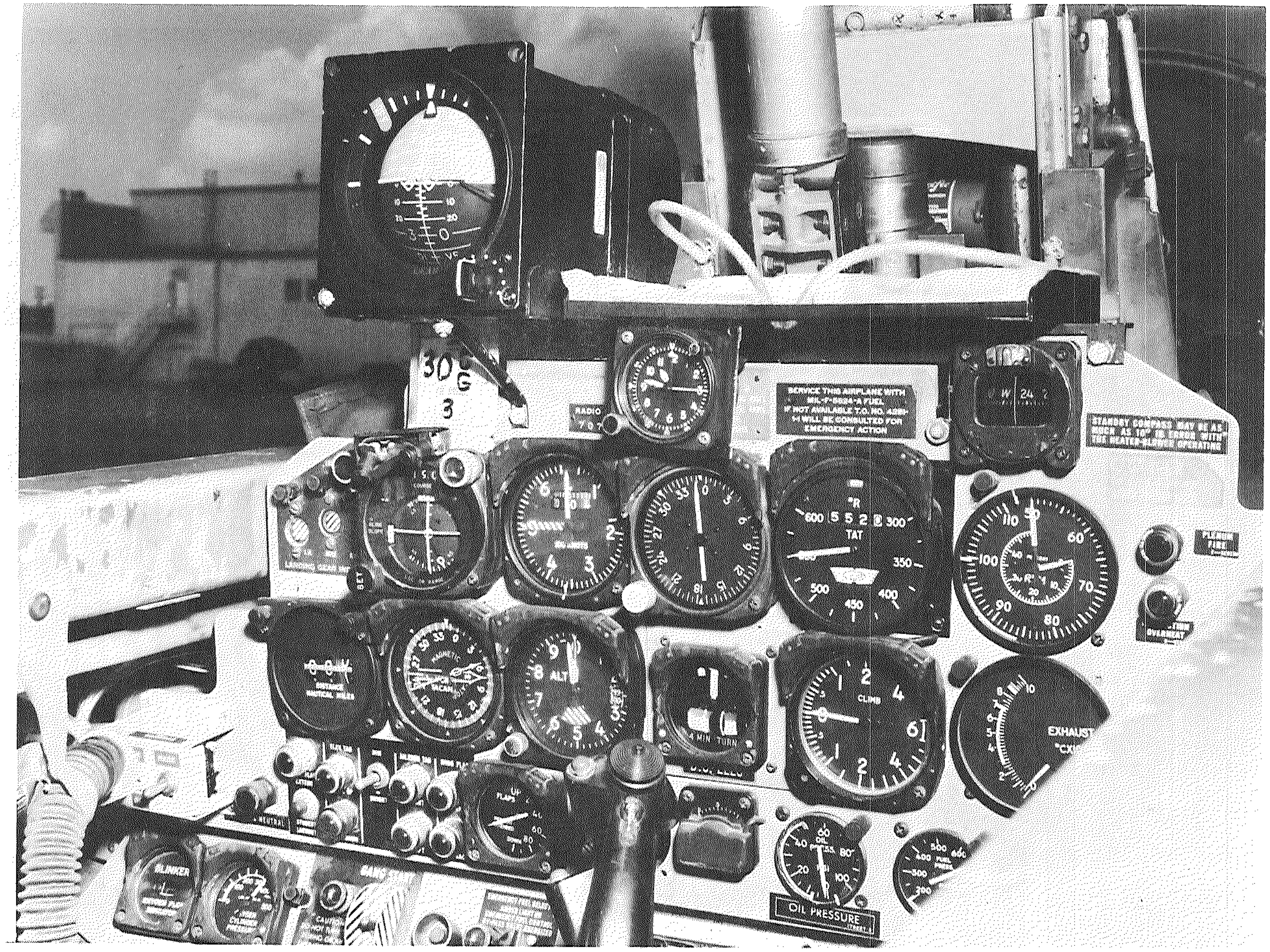
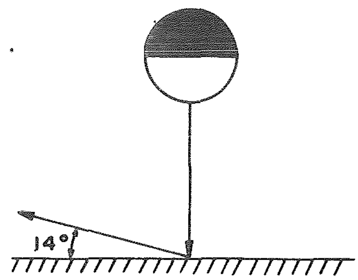


Figure 3.- Aircraft rear cockpit instrument panel.

B=0.022 FT-L.

FULL EARTH AT ZENITH



BRIGHTNESS FT-LAMBERTS	FILTERS	BRIGHTNESS FT-LAMBERTS	FILTERS
2000-1900	5-9	500-460	10-H
1880-1720	13-C	455-440	6-6
1700-1520	11-I	435-410	11-C
1500-1260	11-H	405-380	10-G
1240-1120	6-7	375-360	9-I
1100-1020	13	355-325	11-B
1000-910	10-K	320-310	6-L
900-860	12-C	305-300	9-H
850-840	11-F	295-285	10-F
830-750	7-L	280-275	11
740-690	5-8	270-265	5-7
680-650	12-B	260-225	9-G
640-600	9-K	220-200	8-K
590-570	10-I	195-190	10-D
560-510	12	185-170	9-F

Figure 4.- Filter selection chart for 0.022 ft-L simulated reflected earthshine.

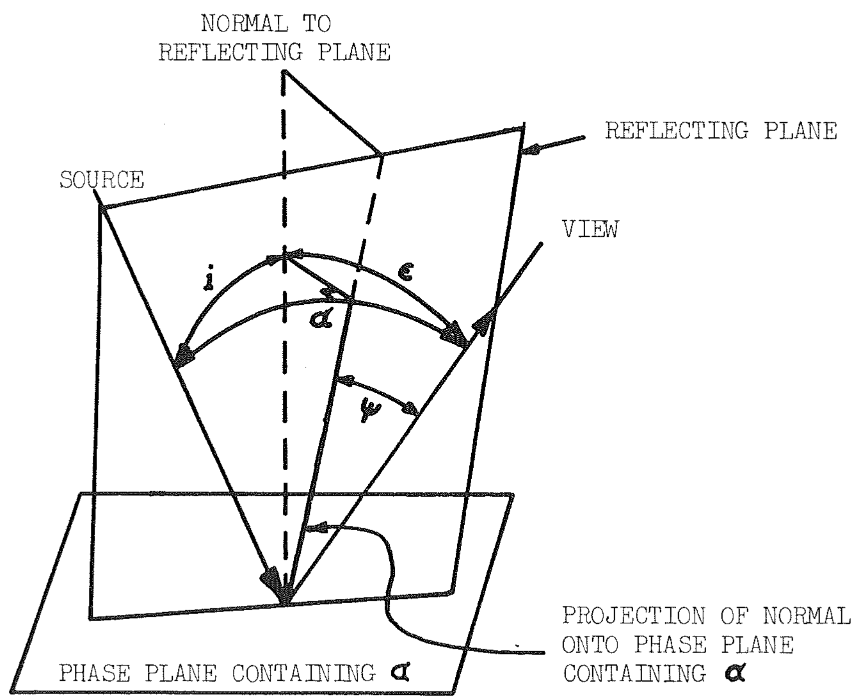


Figure 5.- Sketch of the photometric angles i, ϵ, α and Ψ.

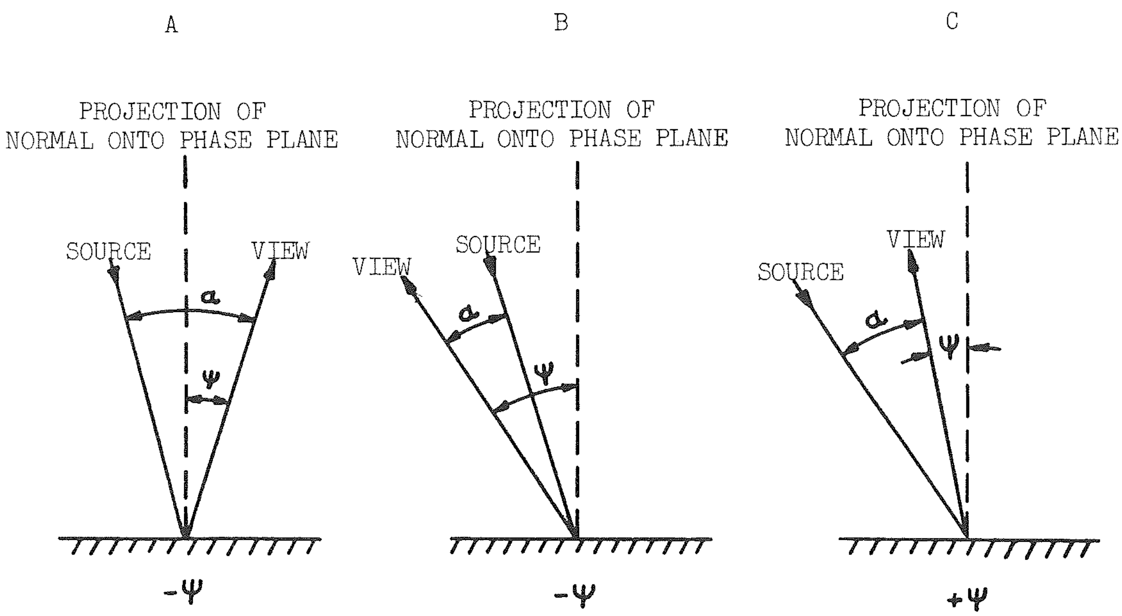


Figure 6.- Sketches of α - Ψ relationships.

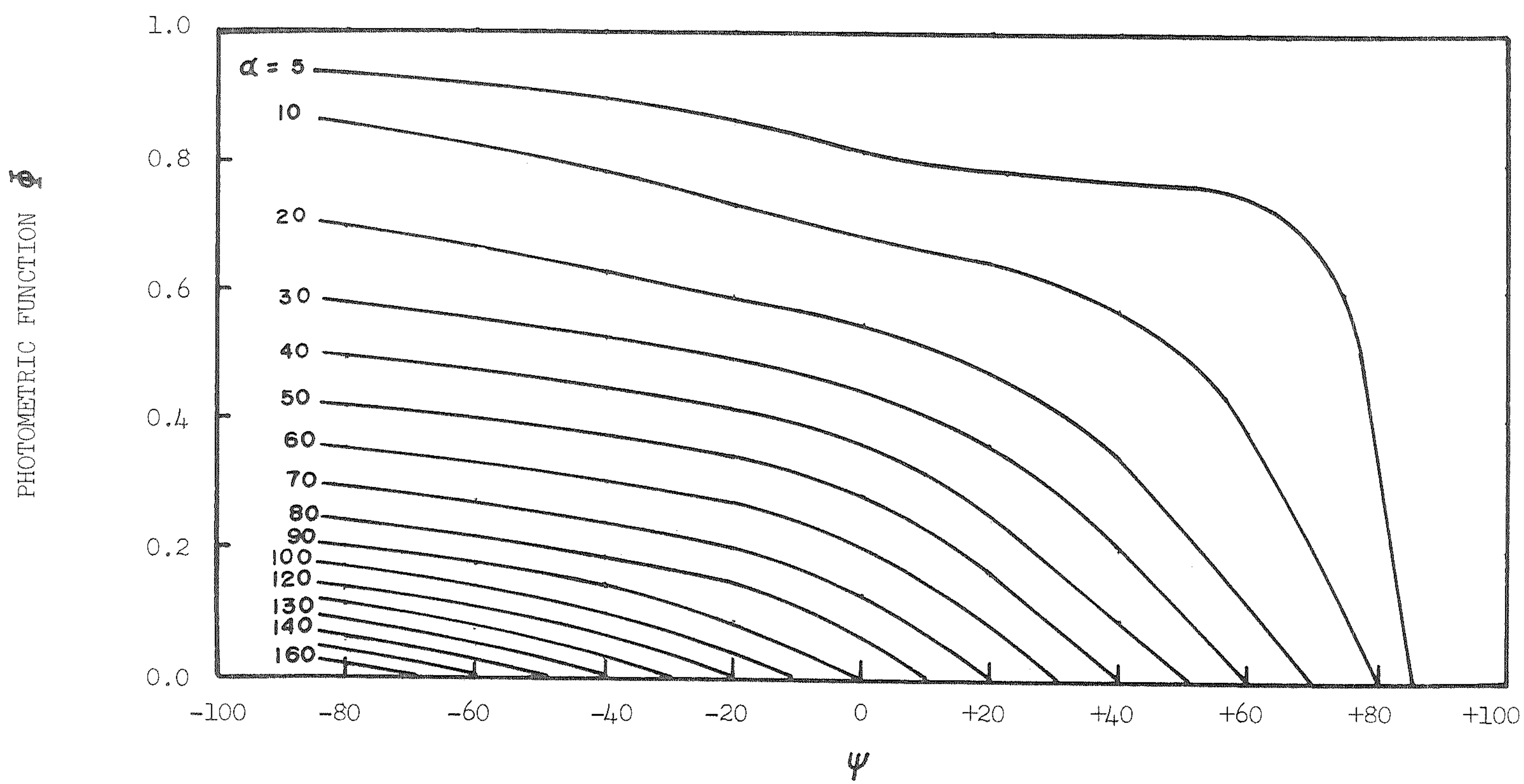


Figure 7.- Sketch of the relationship between the photometric function Φ and the angle Ψ.

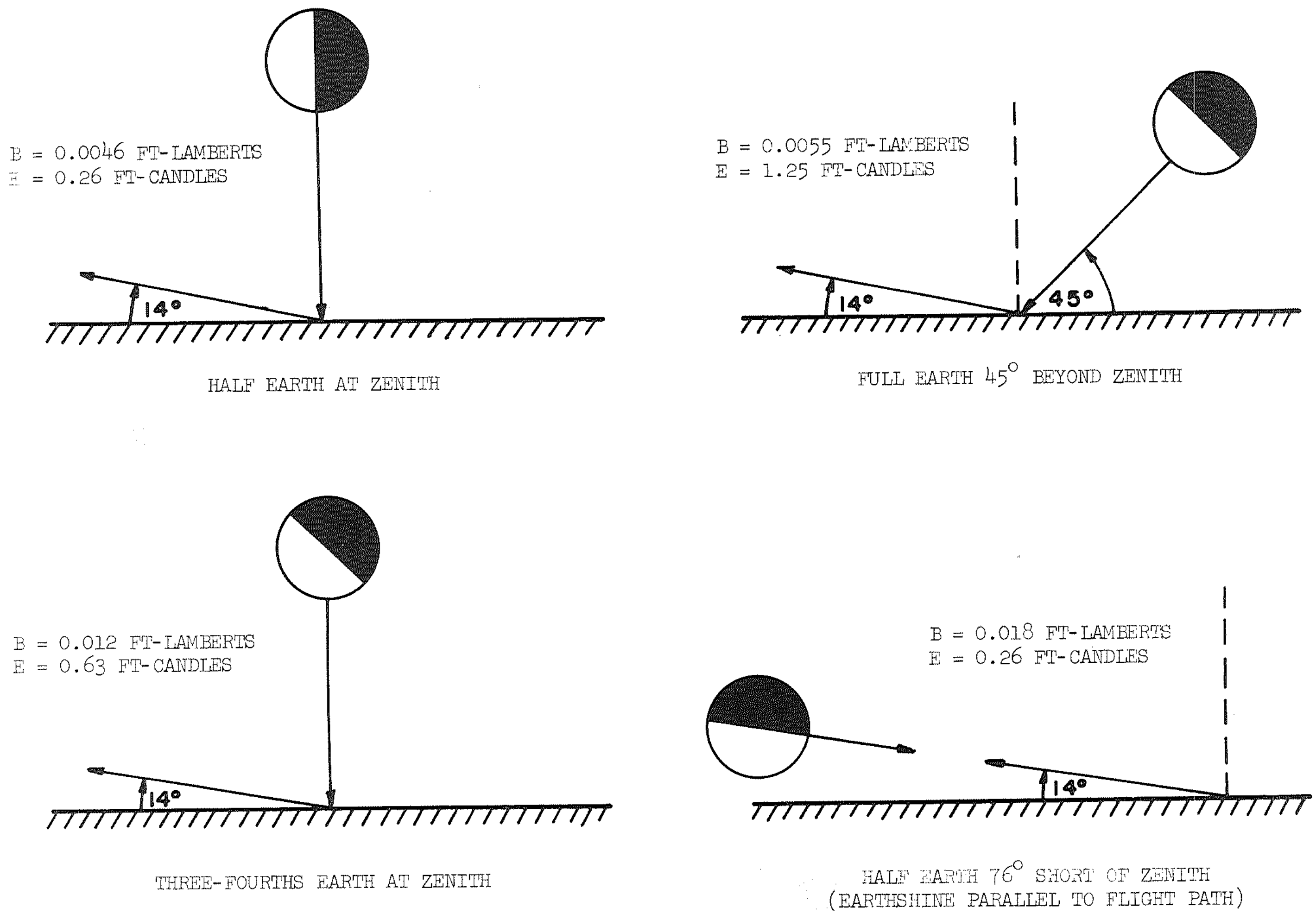


Figure 8.- Sketches of possible earth-moon relationships producing the earthshine values simulated.

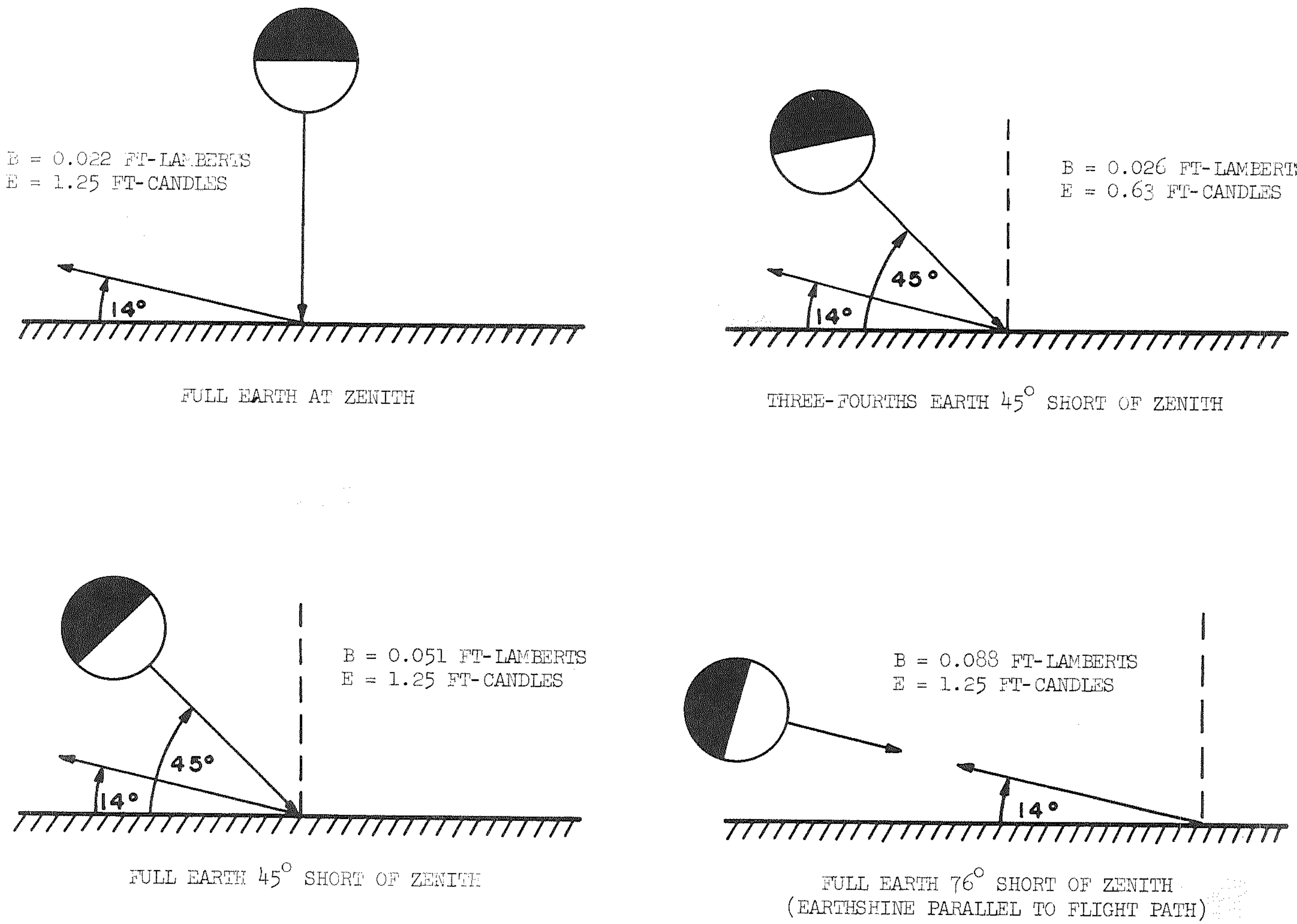


Figure 9.- Sketches of possible earth-moon relationships producing the earthshine values simulated.

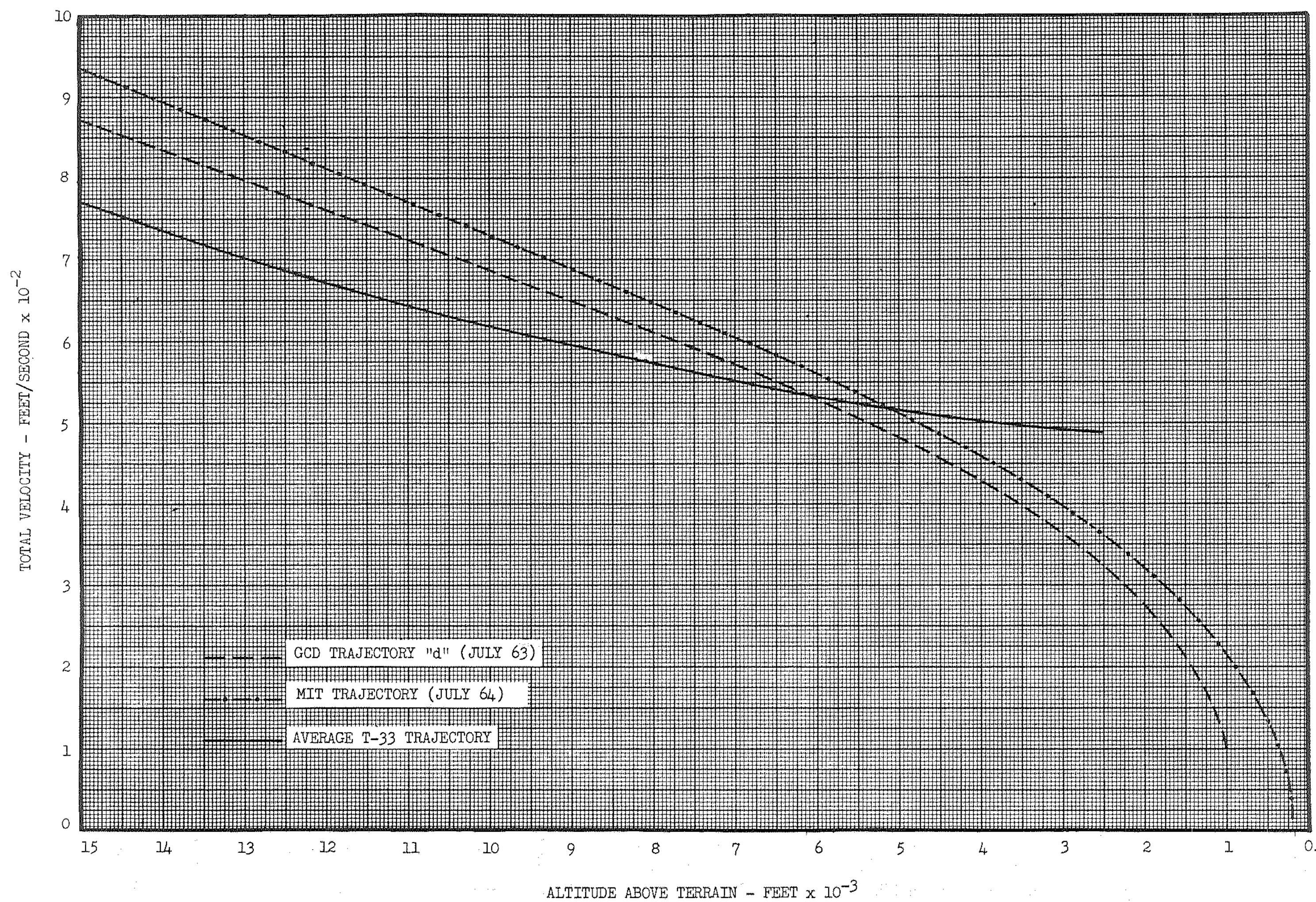


Figure 10.- Nominal trajectory velocity - altitude profiles.

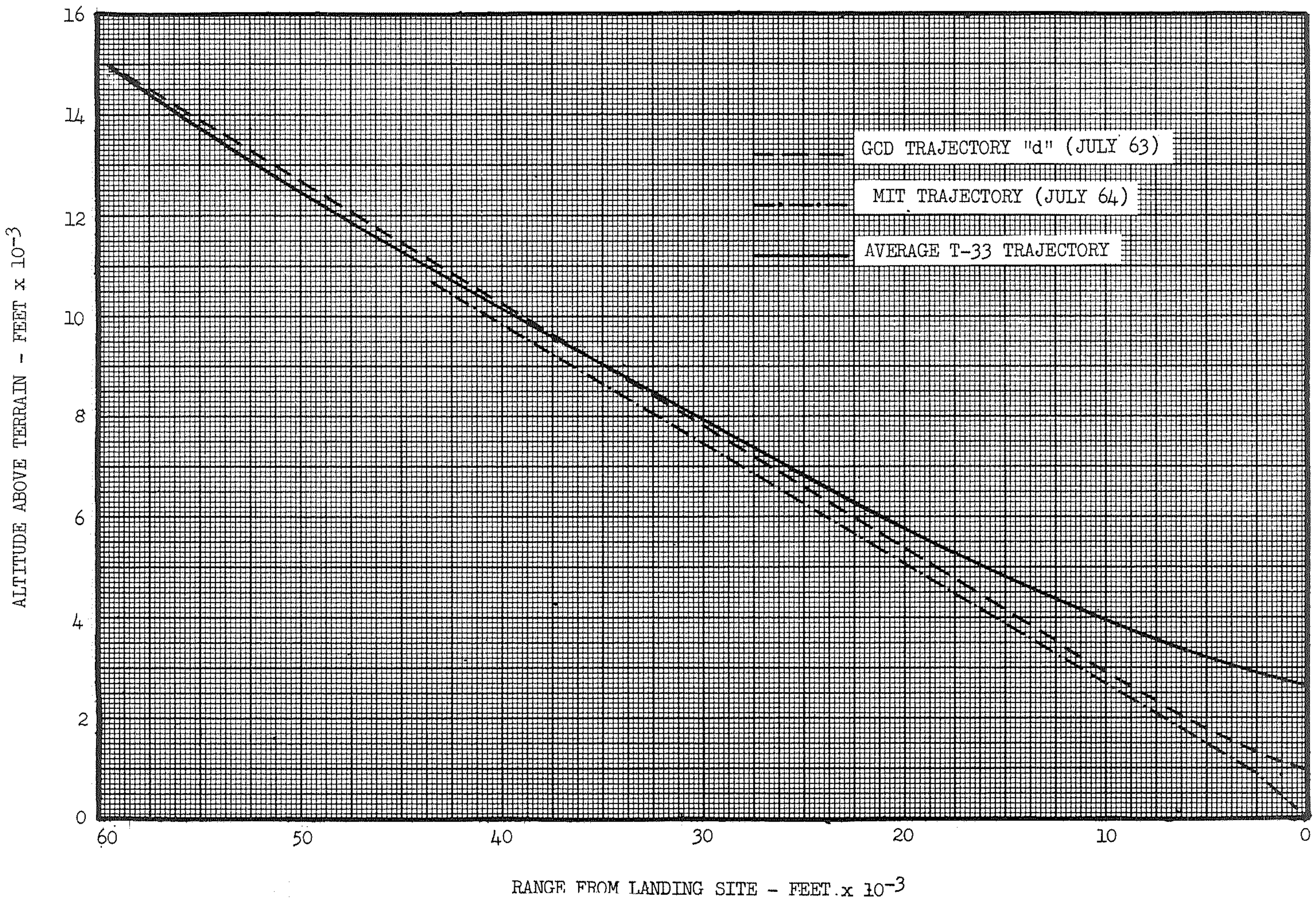


Figure 11.- Nominal trajectory altitude - range profiles.

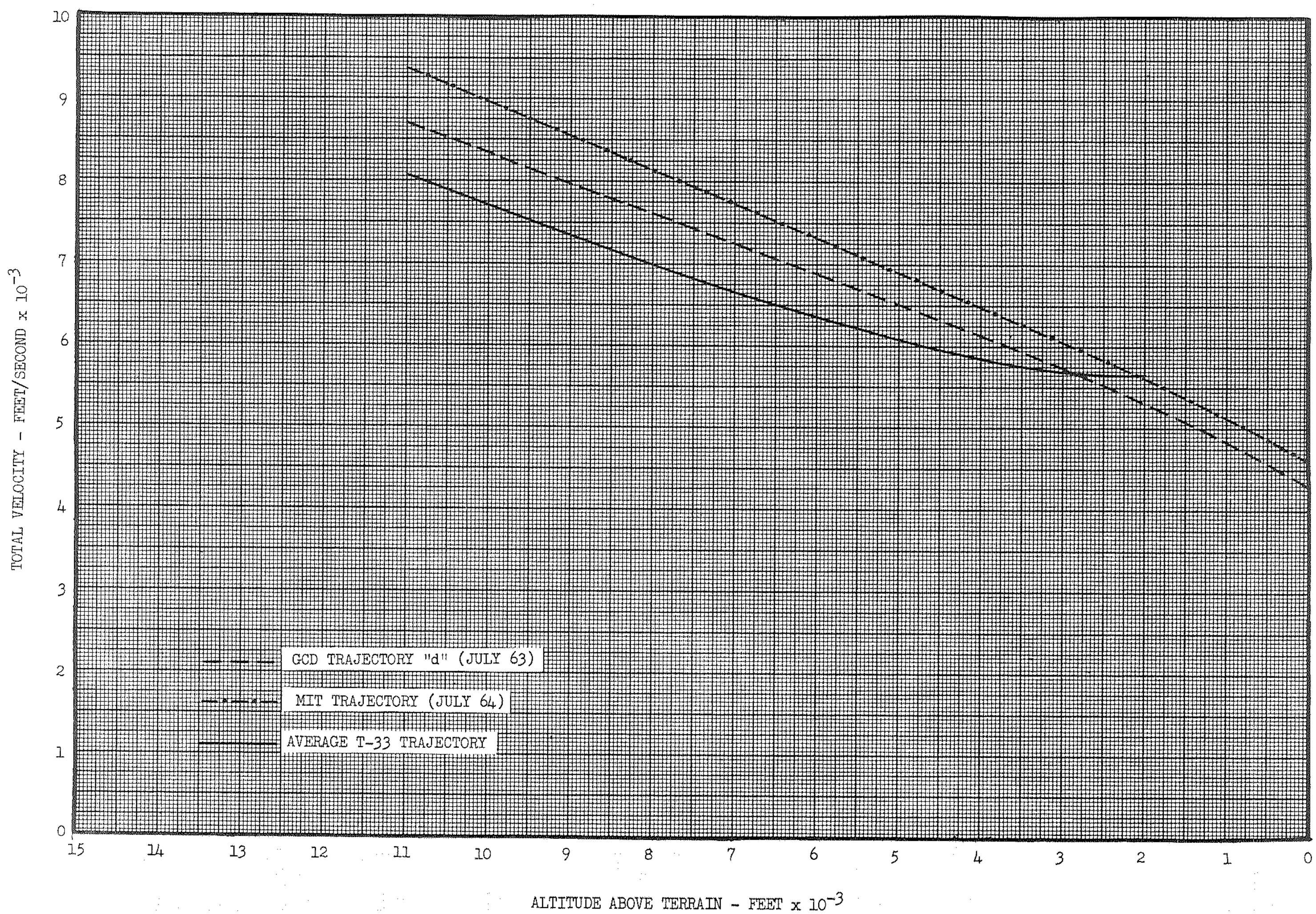


Figure 12.- Low trajectory velocity - altitude profiles.

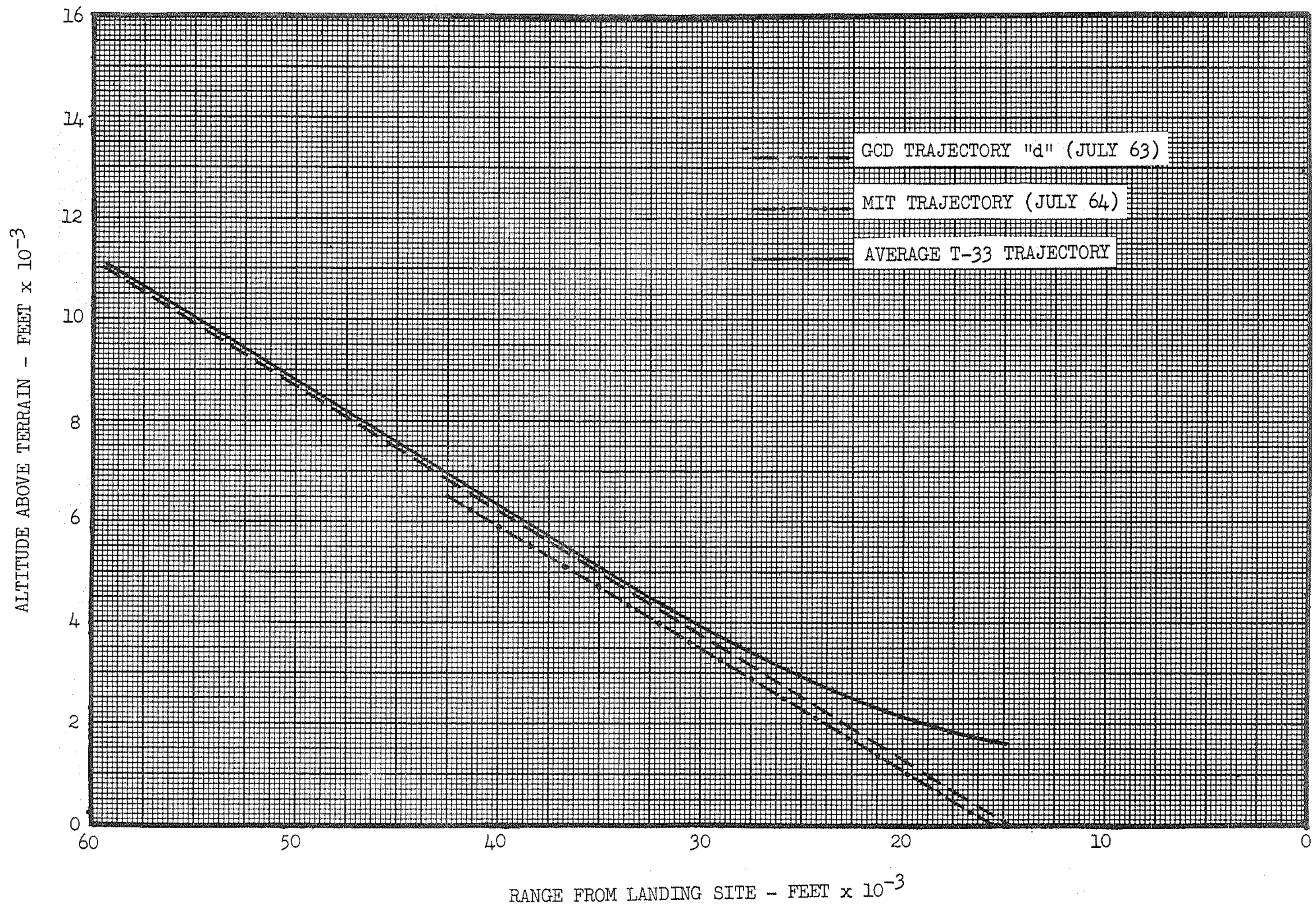


Figure 13.- Low trajectory altitude - range profiles.

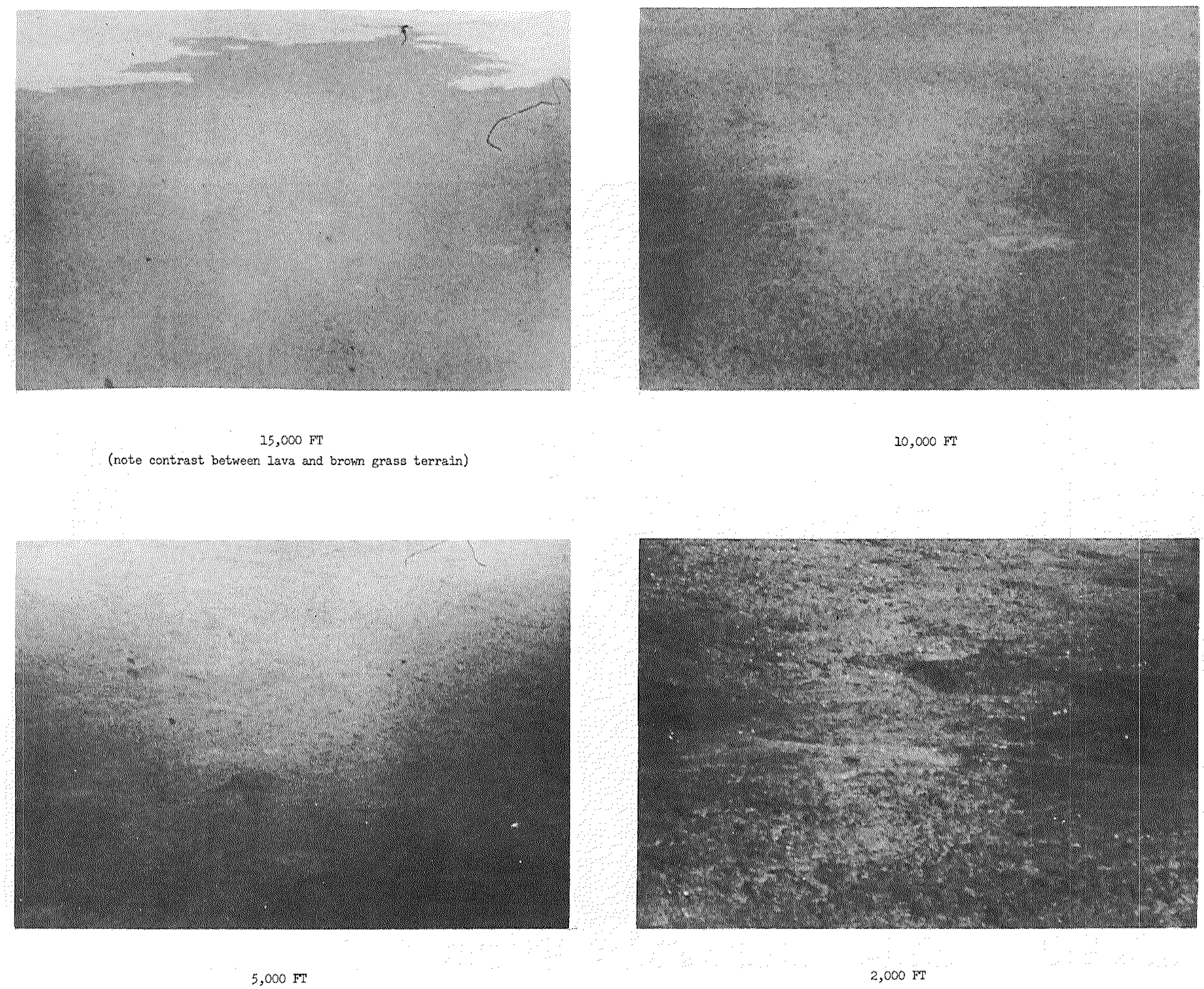


Figure 14.- Nose camera photographs of terrain ahead at four altitudes.

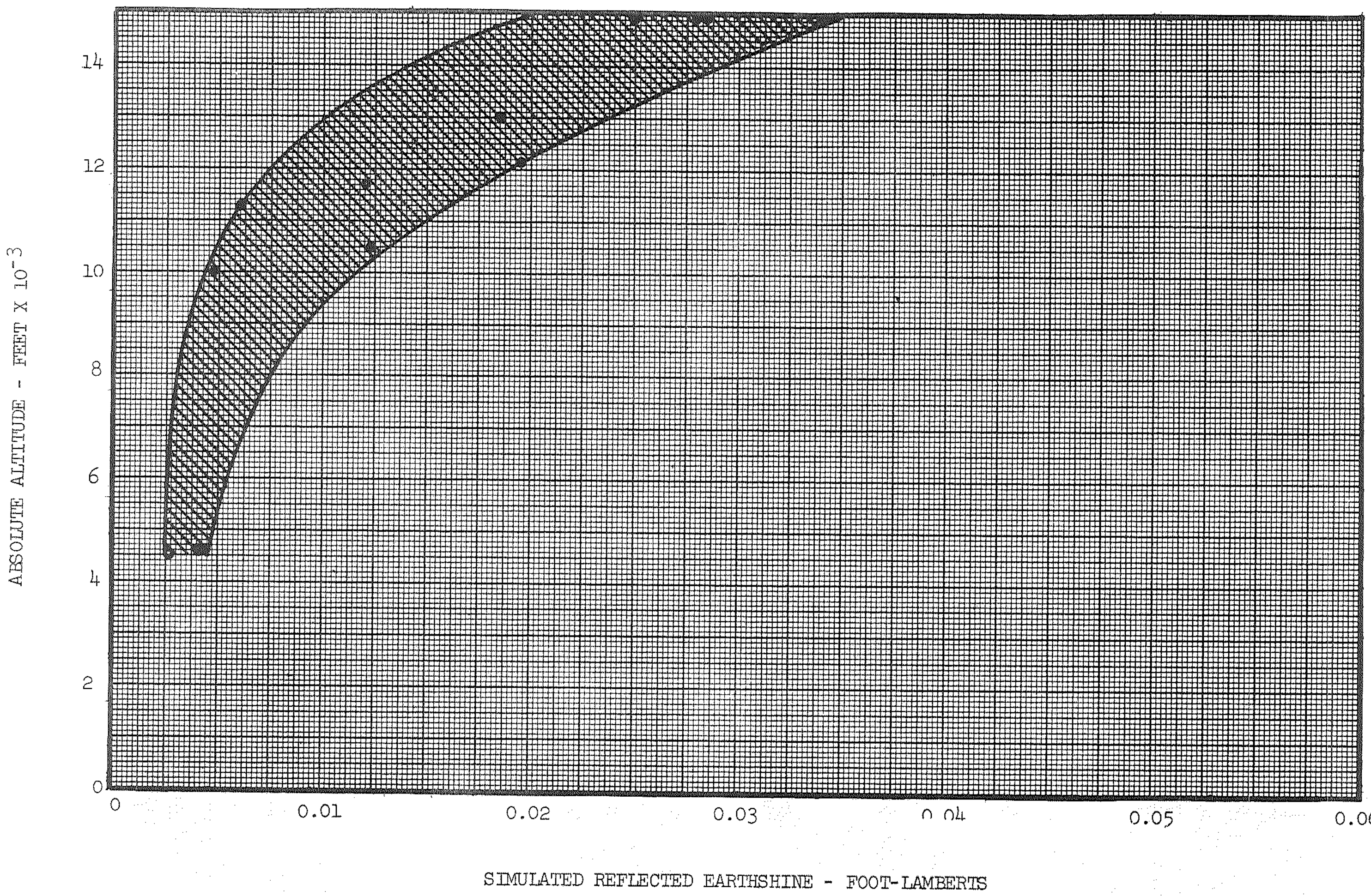


Figure 15.- Relationship between simulated earthshine environment and estimated capability to take terrain avoidance action (four pilots).

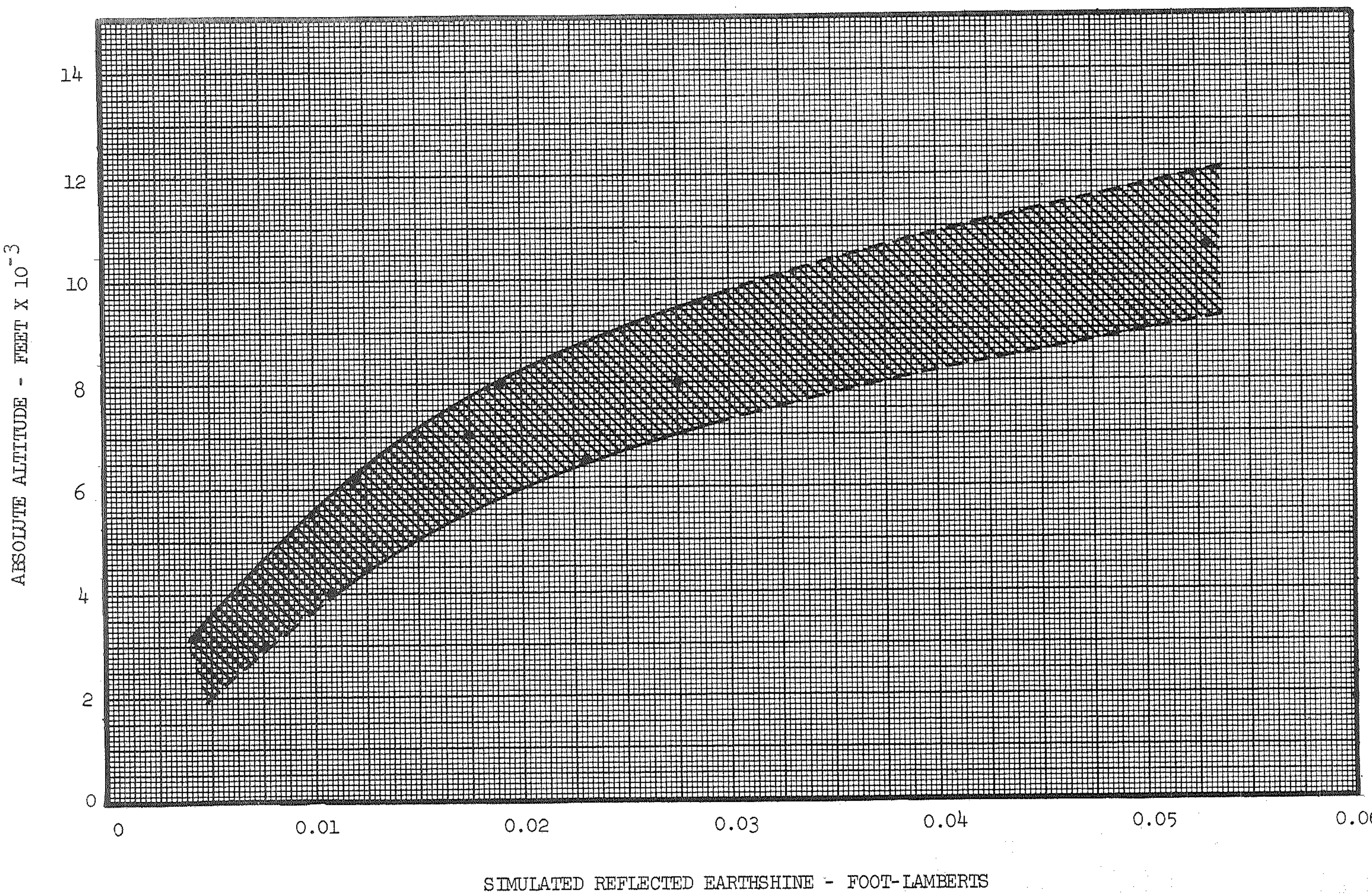


Figure 16.- Relationship between simulated reflected earthshine environment and one pilot's estimated capability to take terrain avoidance action.

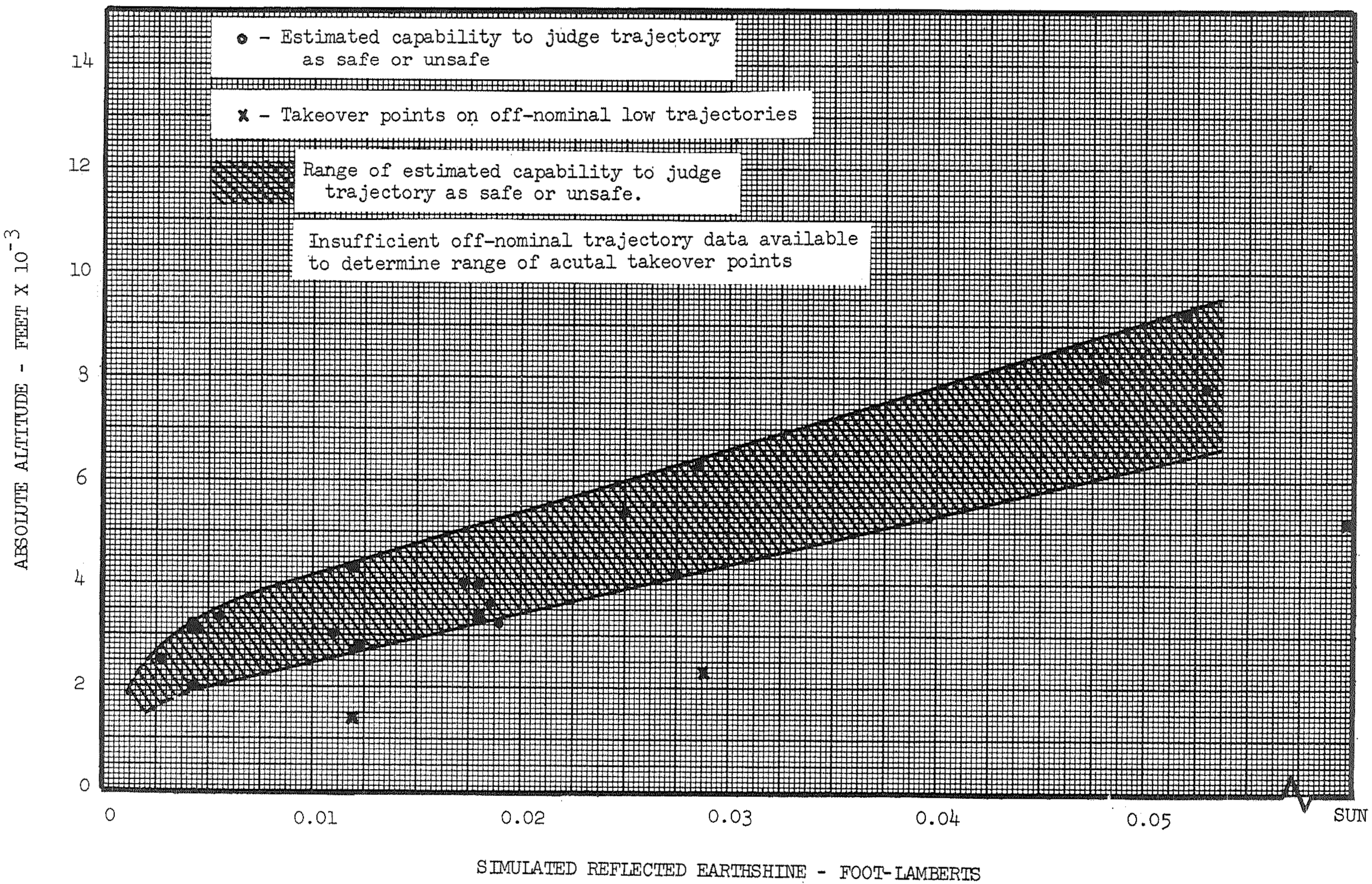


Figure 17.- Relationship between earthshine environment and capability to judge trajectory as safe or unsafe.

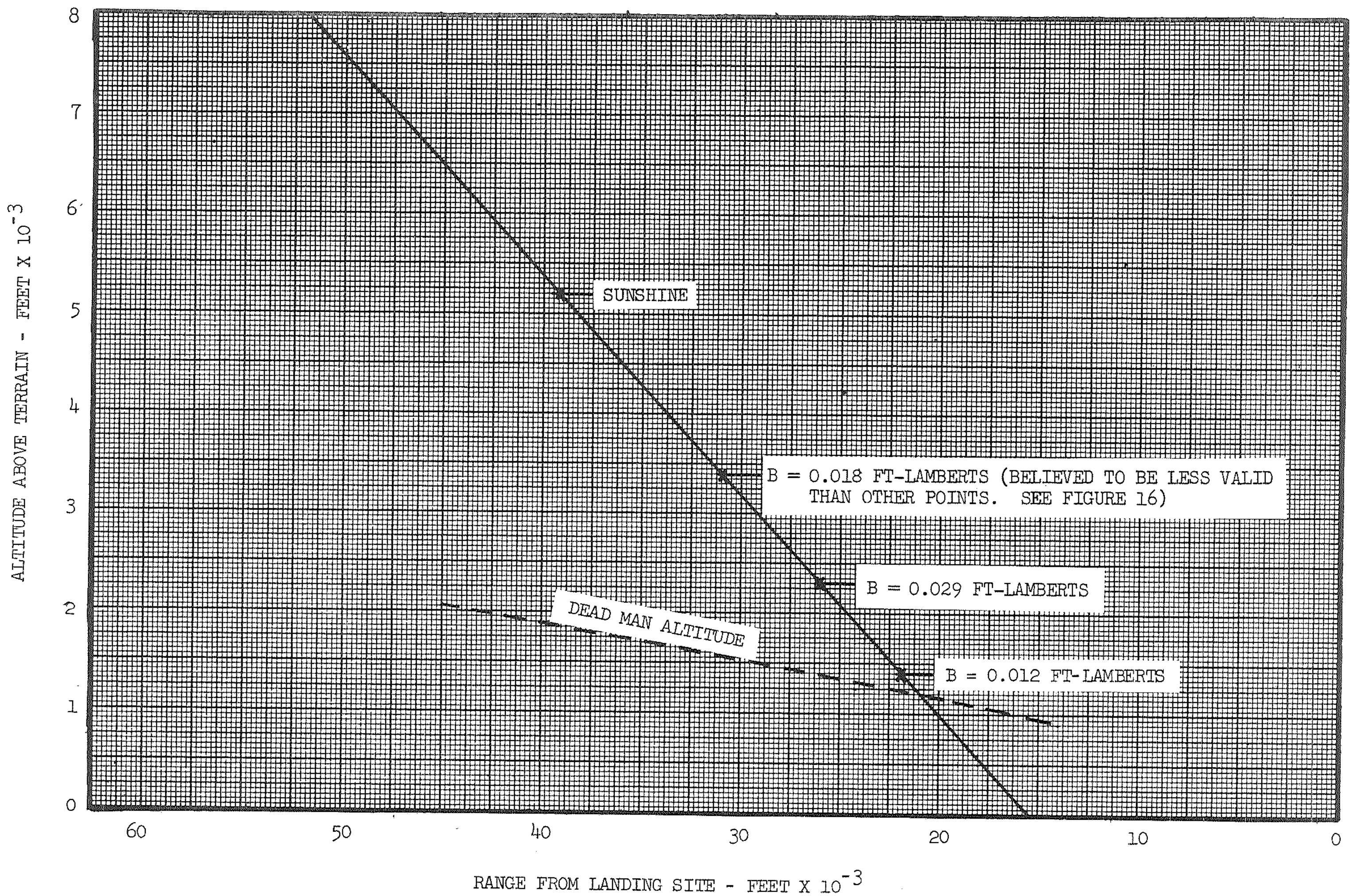


Figure 18.- MIT low trajectory altitude-range profile with "dead man curve" and pilot takeover points under sunshine and simulated earthshine environments.