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PRELIMINARY INVESTIGATION OF THE ASTRONAUTICS OF EARTH - MOON TRANSITS

By Nolan J. Braud

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ABSTRACT

The objective of this report is to present preliminary results of investigations into the problems of earth-moon transits where particular emphasis was placed on the class of trajectories considered for Apollo and Support Vehicle flights. Flight profiles, velocity budgets and launch windows are among the areas which are given most attention. One of the primary points is a newly conceived method of establishing a flight mechanical classification of the transits. The classification is made by use of a simplified time invariant coordinate system. The results are empirical and are generated by the integration of the equations of motion by Cowell's method. Impact, as well as fly-by transits, are treated and results are extended to three dimensions.

Author

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FUTURE PROJECTS BRANCH
AEROBALLISTICS DIVISION

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GEORGE C. MARSHALL SPACE FLIGHT CENTER

MTP-AERO-63-7

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SUMMARY

Preliminary information on flight profiles, velocity budgets and launch windows for Apollo and Support Vehicle flights is presented in this report. A newly conceived method of establishing a flight mechanical classification of the earth-moon transits is discussed. The results are empirical and are designed to contribute to the mission mode selection.

SECTION I. INTRODUCTION

This report presents preliminary findings of an investigation of earth-moon transits which is being conducted at Marshall Space Flight Center. The investigation was motivated by a request from Office of Manned Space Flight to perform a trajectory analysis to answer certain questions associated with the problem of Lunar Logistics System mission mode selection.

It has been evident for some time that fundamental information in a single, integrated report which would provide knowledge of important aspects of trajectory behavior due to variations in injection conditions would be a significant help in the solution of problems associated with the selection of mission modes. Hence, the approach taken by MSFC was to attempt to form a useful classification of trajectory features which will serve to indicate trends in the behavior of earth-moon transits when injection conditions are varied over relatively wide ranges.

The treatment is expository and illustrative rather than mathematical and abstract. It is hoped that thereby the findings would be more easily and more widely understood. This report will be followed by further studies to be made to refine, corroborate, and modify the trends that have appeared as a consequence of the preliminary investigations.

SECTION II. FLIGHT PROFILES FOR EARTH-MOON TRANSITS

A. GEOMETRY OF THE SYSTEM

An understanding of the astronomical relationships in cislunar space is necessary to comprehend fully the significance of certain characteristics of Earth-Moon transits. To promote the requisite understanding, this section will set forth a brief discussion of these relationships.

First, let it be noted that the plane of the moon's motion about the earth lies at a constant inclination of about 5.1° to the ecliptic, (the plane of the earth's motion about the sun) and has a precessional rate of one cycle per 18.6 years. The earth's equator is inclined by about 23° to the ecliptic and has such a slow precessional rate that it may be assumed to be space-fixed. These relationships are depicted in Figure 1 at the time of the winter solstice 1960. In connection with this figure, it may be pointed out that the 18.6 year period of precessional motion of the moon's plane causes the inclination between the moon's plane and the earth's equator to vary between the values of about 18 and 28.5 degrees. This has significance when considering a fixed launch site (such as the Atlantic Missile Range), and will be discussed later.

The next relationship that may be noted is that the moon's equator maintains a nearly constant inclination of about 7° to the moon's plane of motion. This is depicted in more detail in Figure 2, "The Moon-Earth Plane"; however, due to the 18.6 year precessional cycle and the monthly revolution of the moon about the earth, the alignment of the lunar equator as viewed from the earth is constantly changing.

The Moon-Earth Plane (abbreviated MEP) is used as a reference system and has proven to be a valuable tool in the study of Earth-Moon transits. The selection of this reference system was influenced by the desire to operate with a time invariant set of coordinates. The resultant MEP-Related System Coordinates are indicated on Figure 3. From the figure, by referring to the earth, it is seen that longitude is measured easterly in the MEP-earth equator from the translunar point. Latitude is measured positive north where north has the same sense as the angular velocity vector of the system. Azimuth is measured positively clockwise east from north. The corresponding MEP-selenographic coordinates are similarly measured. The sub-earth point on the moon is used as the origin for longitude reference.

In addition to this reference system, some of the investigation was made by use of the ephemeris related coordinate system, a sophisticated mathematical model of the Earth-Moon system constructed by JPL. In taking the dual approach of using the simplified MEP system and the JPL Ephemeris Model, it was found that each served to compliment the other. The simplified MEP model is quite useful in developing characteristic patterns whereas the realistic JPL model serves to illustrate how the perturbations, due to various causes, affect the patterns.

The next chapter introduces the analysis of Earth-Moon transits in the simplified MEP model.

B. COPLANAR TRANSIT CHARACTERISTICS

The terminology, "Coplanar Transit," as used in this report, is understood to mean a flight whose path is for all time imbedded within the Moon-Earth Plane. These transits are of a specialized nature and can only exist under certain rigid circumstances; however, they display characteristics which provide a great deal of inslight into the understanding of the more general three-dimensional transits.

The assumption is made that 185 km perigee altitude would be used for all transits, and this will be the case in all further discussions unless it is otherwise indicated. Therefore, for the coplanar analysis, only velocity magnitude and MEP-longitude are open initial parameters. For appropriately chosen velocity magnitudes, Figure 4 shows the longitude variation required to generate a family of transits that completely envelops the moon. As it turns out the width of this variation is about 2°. The behavior of a family of coplanar transits as they define the ballistic impact pattern on the moon is depicted on Figure 5. Also, on this figure there is shown the impact flight path angle measured against the local vertical, and the deviation of injection longitudes about the 60 hour transit perpendicular impact conditions that result in tangential or limiting impact flights.

The characteristic features of coplanar Earth-Moon Transits at the moon can be seen in more detail in Figure 6. Note first that when injection velocity is kept constant, there is a unique MEP-longitude for the injection point that results in perpendicular impact on the moon. Varying the injection longitude to both sides results in impacts on the moon with increasingly shallower impact direction. The area of impact terminates on both ends with "grazing impacts," i.e., horizontal impact velocity. If these fly-by transits are extended past their periselenum loci, they intersect on a line of vertices as illustrated in Figure 6.

As was previously indicated, there is a unique location for the perpendicular impact flight of a given transit time. To contribute information to this area, a study was made of the perpendicular impact transits where total flight times of fairly large magnitudes were considered. The results of that investigation are shown on Figure 7 for transit times of 60, 84, 167 and 350 hours. The moon is traveling in the direction of the y axis and it is seen that all of the perpendicular impacts occur on its leading half. Situated in a symmetric fashion around the moon from the respective perpendicular impact is the retrograde and direct periselenum loci for the 60 hour transit family and the 350 hour family. Remembering that the short arc length area between the associated periselenum loci is not accessible by ballistic transits, the figure shows that when transit time is open, transits can be designed which result in the full area of the moon being covered by ballistic impacts.

The family of perpendicular impact transits is shown in a space-fixed reference system in Figure 8. From the figure it can be seen that the longer transits have the feature of crossing the moon's path prior to the arrival at the moon and have their resulting perpendicular impacts on their return path. In transits of this nature, injection velocity and impact velocity are significant. On Figure 9 are shown these parameters as functions of transit time. There are two features here that are worthy of note. The first is that as injection velocity varies, the impact velocity varies in the same direction; the second is that for transit times longer than about 110 hours, the requirement on injection velocity increases. This last point would seem to indicate that, from a performance standpoint, the velocity of injection should be chosen so that transit times near to 110 hours result.

This material essentially concludes the section on coplanar transits. The emphasis will now be shifted to three-dimensional transits where some of the coplanar characteristics will be extended.

C. THREE DIMENSIONAL TRANSIT CHARACTERISTICS

In Figure 10 terminal patterns for constant transit times with various injection longitudes and azimuths are shown. Assuming departure from zero MEP-latitude, two coplanar transits approach the moon in a retrograde and direct sense and intersect at the vertex. As previously stated these two flights have about a 2 degree difference in initial longitude. Now if an azimuth variation which introduces three-dimensionality is made, it is found that only about a 3 degree variation is needed to generate all fly-by transits that completely envelop the moon with maintaining 185 km distance from the surface. Near earth such a family forms a "horn" as indicated in the figure. At the moon, there is again a collection of these flights within a "horn," the point of the horn being located at the vertex line. The vertex line intersects the moon approximately opposite to the point of perpendicular impact. Thus, there appears to be a tube-like volume containing all trajectories injected from a given latitude, which impacts over the maximum accessible area of the moon and also containing those flights which define all possible fly-by directions. The variable directions of fly-by transits permits the establishment of parking orbits of different inclinations in retrograde and direct senses.

If, now, initial conditions starting from some non-zero latitude are considered then, as the inset shows, a similar horn results. In this case the end near the earth maintains a departure direction which is nearly orthogonal to a circular ring on the earth's surface. The geometry of this family at the moon is similar to that discussed before with the exception that the line of vertices (and also the perpendicular impact point) is rotated out of the Moon-Earth Plane.

The circular ring of injection loci is actually an area of latitude and longitude combinations from which given transits to the moon may be started. The behavior of this circular ring for varying transit time is such that it gets larger in diameter and its center moves eastward with shorter transit times. A further elaboration of the pattern of earth injection locations is shown in Figure 11 where the "ring" has been projected onto the earth's surface. One of the significant points to be made here is that even though all transit flights are started at perigee with flight path angles of 90 degrees against local vertical, a propelled phase could be assumed to be merged into the free flight path at any point along its path. This is shown in Figure 11 where injection rings for 90, 80, and 70 degree flight path angles are indicated. The arrows signify some of the departure azimuths for the horns that contain the families of fly-by trajectories that envelope the moon.

Because the Earth-Moon system rotates with a certain angular velocity around its barycenter, this velocity component enters the requirement on injection velocity in that as the injection conic is inclined to a greater degree to the MEP, more injection velocity is needed to make up for that lost by not utilizing the rotation of the system.

Figure 12 provides some illustrative information on the variation of impact points for constant impact path angles, constant injection velocity, and various injection longitudes and azimuths. This pattern is built around the perpendicular impact transit (launched from zero latitude) and shows how the loci of impact points for constant impact path angles form concentric circles about a line through the normal approach direction. Figure 13 shows the corresponding pattern for the former family as well as for a family of trajectories launched from 5 degrees MEP-latitude within the injection ring on the earth's surface.

The behavior of the locations of perpendicular impacts as the injection position is varied throughout the injection ring is shown on Figure 14. The ring of injection locations was shown to be essentially circular; however, the pattern of perpendicular impacts is rather more elliptical with its major axis in an almost north-south line. The perpendicular impact pattern lies on the leading half of the moon as shown in this figure. Periselenum loci and the locus of their vertices is the subject of Figure 15. One periselenum loci shown in the figure is that for zero latitude of injection; the other is for 5 degree injection latitude. The actual loci have been projected to the lunar surface. Each periselenum has an altitude of 185 km and when all flights are extended they meet at the vertex point. The elliptic nature of the locus of vertices is also shown projected onto the lunar surface. It is the small ellipse in Figure 15. For any given vertex point on the locus of vertices, it is to be understood that conics of approach may have any direction. Figure 16 depicts a family of fly-by trajectories which were generated by use of the ephemeris program. The fact that all members of this family go through a common point (the vertex) implies that when using the orbital mode there are only two azimuths of approach to any specified landing site that is not at the vertex line or diametrically opposite. This situation will be discussed more in the next section.

The results presented up to now have been through use of the MEP-Related System Coordinates. A transition to the geographical coordinates has been performed but will not be presented here because of the detailed description involved. By way of a summary, the "Salient Features" or characteristics that have been brought out in this section are shown on Figure 17.

SECTION III. VELOCITY BUDGET AND OTHER CHARACTERISTIC FEATURES

The laying out of a velocity budget for lunar missions requires the consideration of many influence factors. One of these involves the inclination of the flight plane to the MEP. To understand how this variation of inclination occurs, the launch situation has to be investigated. If, for simplicity's sake, a due east launch from AMR (28.5 latitude) is assumed, it is found that for most locations of the moon in its orbit there are two launch opportunities per day. These are indicated in views (a) and (b) of Figure 18 for the moon at maximal and nodal declinations. One notes that in view (a), with the moon at maximal declination, the two transit conditions have equal inclinations to the lunar plane; however, when the moon is at a nodal point, for instance, (view (b)), the two opportunities have vastly different inclinations.

Whenever possible it would be desirable to select the solution which results in the smaller inclination, because of the increase in velocity required as the plane of the injection conic becomes more inclined to the MEP. A direct demonstration of this effect is shown on Figure 19. In this figure, the velocity at periselenum resulting from inclination of the injection conic to the MEP is indicated. This situation results because of the increase in injection velocity required as the injection conic is increasingly inclined to the MEP. This increase in injection velocity is reflected by a ratio of about four to one in an increase of periselenum velocity. From the figure it is seen that for a 57 degree injection inclination there is an increase of about 40 m/s in periselenum arrival velocity. This same example required an increase of about 10 m/s in injection velocity.

If launch azimuth variations between 70 and 110 degrees are assumed, it is found that the situation is as depicted on Figure 20. This figure gives information on launch windows as a function of the declination of the moon. To understand the figure, it must be remembered that a launch azimuth variation from 70 to 110 degrees will allow a continuous launch opportunity over a relatively long period. In this case the launch window width is about 5 hours and since there are two such opportunities equally distanced on each side of the reference injection meridian, time referenced from it is used. Looking at the zero declination point one finds the launch window extending from three to eight hours on both sides of this reference time. As the lunar declination at arrival increases, the distance or time between the two launch windows decreases to the point where for a lunar declination equivalent to the AMR latitude the launch window is ten hours in width.

Now, considering the elliptic nature of the lunar orbit, it is interesting to observe its effect on injection velocity requirements. For this purpose refer to Figure 21 where, as a function of transit time from injection to periselenum, the injection velocity at a 400 km injection altitude is depicted. The shaded portion represents requirements for varied Earth-Moon positions. The upper limit is that resulting when the moon is near its apogee distance whereas the lower limit has the moon near its perigee distance. This area provides definite bounds for planning the energy requirement of transits from 66 to 90 hours. It is to be noted here that the required velocity seems to be achieving a minimum near 90 hours which is slightly a shifted variation of the trend indicated on Figure 9. It may also be pointed out that if, from performance viewpoints, the payload restricts the maximum achievable injection energy, that energy level prescribes a range of transit times which can be accommodated. An example is that the velocity of 10,770 m/s allows transits from 69 to more than 90 hours.

Similar information on the periselenum arrival velocity for a 185 km altitude of periselenum is shown on Figure 22. Again the upper and lower bounds correspond to the moon near apogee and perigee, respectively.

The sensitivity to midcourse corrections of these Earth-Moon transits is considered next. In this respect an investigation was conducted on midcourse velocity requirements to enforce the attainment of the reference time and position of periselenum. Various transits were investigated where three-sigma injection errors were assumed. The procedure was to determine the required correction at various times of flight on transits ranging from 60 to 90 hours. The results are shown on Figure 23 where the parameter indicated is the percentage of flight time elapsed versus the total reference transit time when correction is made. The figure indicates that the earlier the correction is made the cheaper it is and that more correction velocity is needed at the same relative point for longer transit times.

To summarize some of the velocity inputs which have been discussed, reference is made to Figure 24. The requirements for a 90 hour transit are used as reference where injection velocity, periselenum arrival velocity and midcourse velocity requirements are weighed against one another and a comparative figure is quoted. As it turns out, the 66 hour transit requires 128 m/s more velocity than the 90 hour transit while the 72 hour transit requires 69 m/s more velocity than the 90 hour transit. So from a pure performance standpoint the longer transit times up to about 90 or 100 hours are favored because of a smaller burden on the velocity budget.

It was stated in Section I that the moon's equator has a constant inclination of about 7 degrees to the MEP and that its alignment as viewed from the earth is constantly changing. Figure 25 shows the monthly cycle for a particular alignment of the line of nodes between lunar equator and the Moon-Earth plane. From this figure it may be noted that the lunar equator appears to precess through 360 degrees during a single month as seen by a viewer on Earth. If Earth-Moon transits are referenced to the moon's plane of motion, it can be shown that the selenographic coordinates upon arrival at the moon are quite dependent upon the particular position of the moon within its orbit. If, in addition to this phenomenon, the librational motion of the moon is considered the locus of vertices as shown in Figure 15 is somewhat perturbed. This is depicted in Figure 26 for the two daily launch opportunities departing from AMR in a due east direction. The note on the moon's radial distance and declination refers to the fact that for the month under investigation the moon is at its perigee distance when it has its maximum declination.

It was stated earlier that in the orbital approach the vertex location determines fully the azimuth of approach to any landing site. A brief description of this situation is provided with reference to Figure 27. Attention is brought to the vertex motion during a month in March-April 1969 for due east launches from AMR. Along with this, the assumed landing site is in the Sea of Tranquility which is at about 30 degrees longitude and 2 degrees latitude. Noting that on a given day the vertex has a fixed location, it is easily seen that for each vertex location there is only the pair of transits which pass over the desired landing site. So if there is any desire to have a variable azimuth of approach to a given landing site, it would mean designing the transit from an envelope which has its vertex at another location. This would mean waiting until the day of the month when the vertex is properly placed. The geometry cited here allows a variation of some 30 degrees in azimuth of approach as the vertex location goes from its maximum to minimum latitude. In this case the chosen landing site is about 90 degrees away from the vertex pattern. As the site moves either to the vertex point or away by 180 degrees, the available azimuth of approach widens to 360 degrees, or the approach can be made from any direction. These considerations are very important if a beacon is considered for use in the landing procedure of the orbital approach.

Some consideration was given to the requirements on velocity for direct landing on the moon. This problem was treated for 72 hour coplanar transits and the results are illustrated in Figure 28. The performance assumptions made were that of 30,000 lb thrust, 90,000 lb (Earth) weight, and an engine specific impulse of 425 seconds. The parameters of interest are the altitude of ignition of the braking stage and the velocity required to touchdown with zero velocity. They are presented as a function of the central angle at impact measured from the perpendicular impact location. It is seen that the normal approach requires a total braking velocity of about 3000 m/s with the stage igniting at about 800 km. As the approach moves out to the edge of the moon both ignition altitude and total velocity decrease to a point and then the velocity starts increasing while the ignition altitude is constrained to above 100 km. What is actually taking place here is that what would normally have been near moon fly-by transits are being braked so that they are in a sense direct landing approaches. From this it can be seen that near tangential approaches are most economical and that fly-bys up to a certain altitude can be accommodated and still not exceed the velocity required by the direct in or normal approach. Also of note is the fact that by this method the area that can be reached on the moon by direct approach is greatly extended.

In conclusion, information which would influence a launch window selection is given on Figure 29. It shows the velocity magnitudes at injection and arrival at the moon for the two launch opportunities within a month for 66 hour transits. The two upper parameters are those of injection whereas the lower pair are for periselenum arrival velocity. An example might cite how this could be used for launch window (number of days in a month) determination. If it is assumed that the maximum achievable energy or velocity is 10,780 m/s then launch opportunities would occur between March 6 - 18 and April 3 - 12, approximately. Of course, there are related areas of velocity magnitude at periselenum. So by such a consideration, the availability of days suitable for launch in a given month can be found.

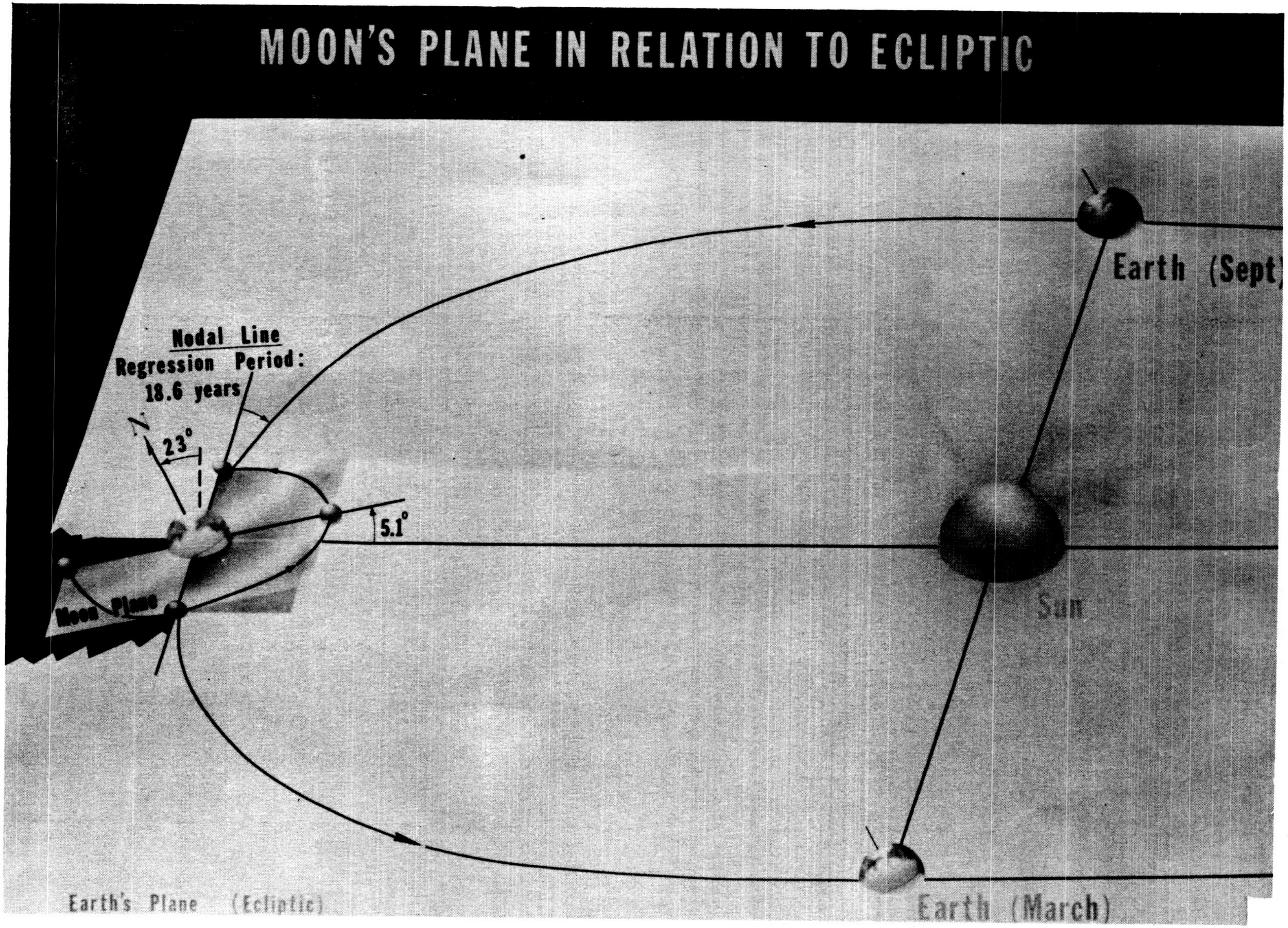

MOON'S PLANE IN RELATION TO ECLIPTIC
Nodal Line
Regression Period:
18.6 years
N
23°
5.1°
Moon Plane
Earth (Sept
Sun
Earth (March)
Earth's Plane (Ecliptic)

Figure 1

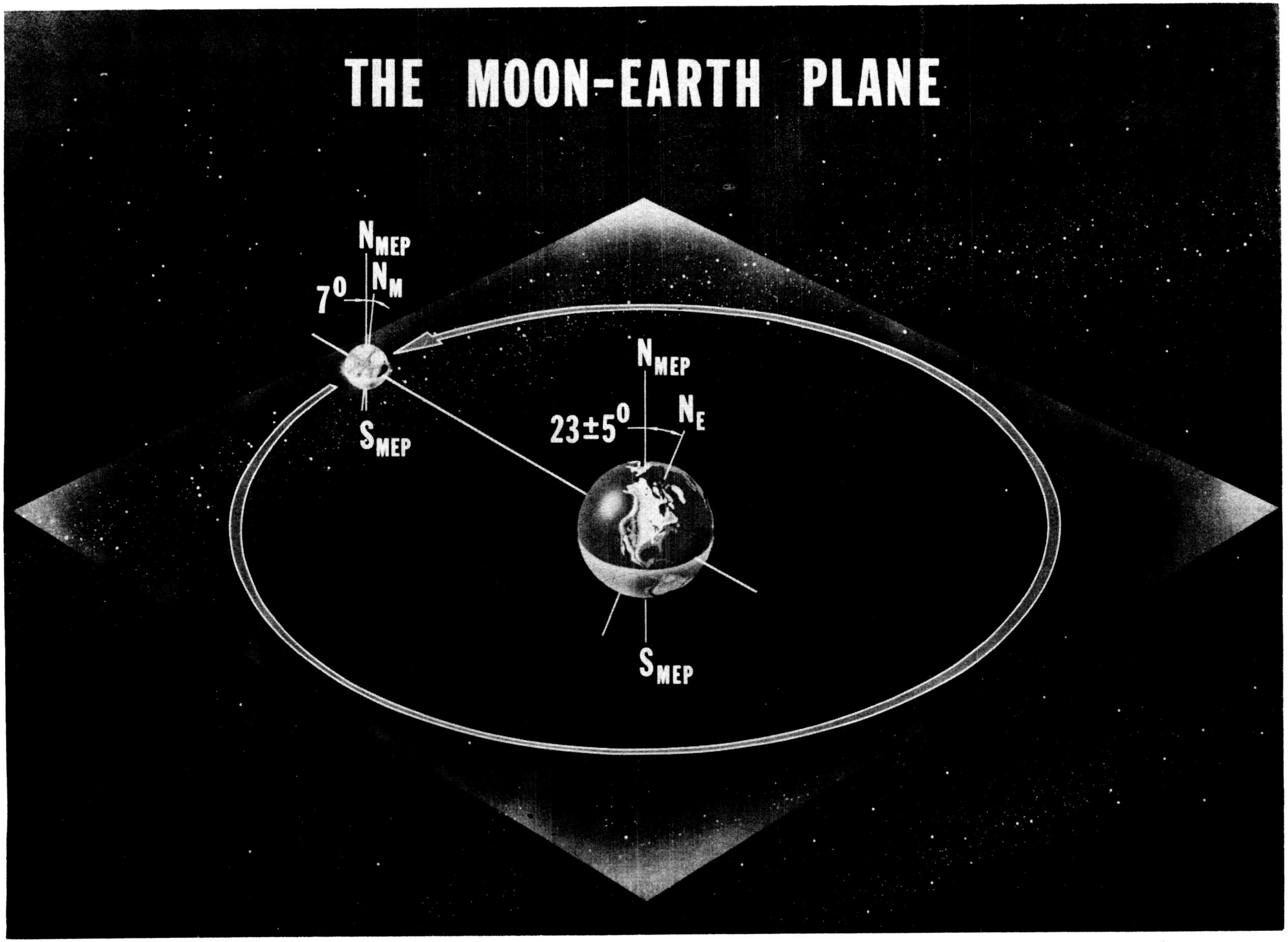
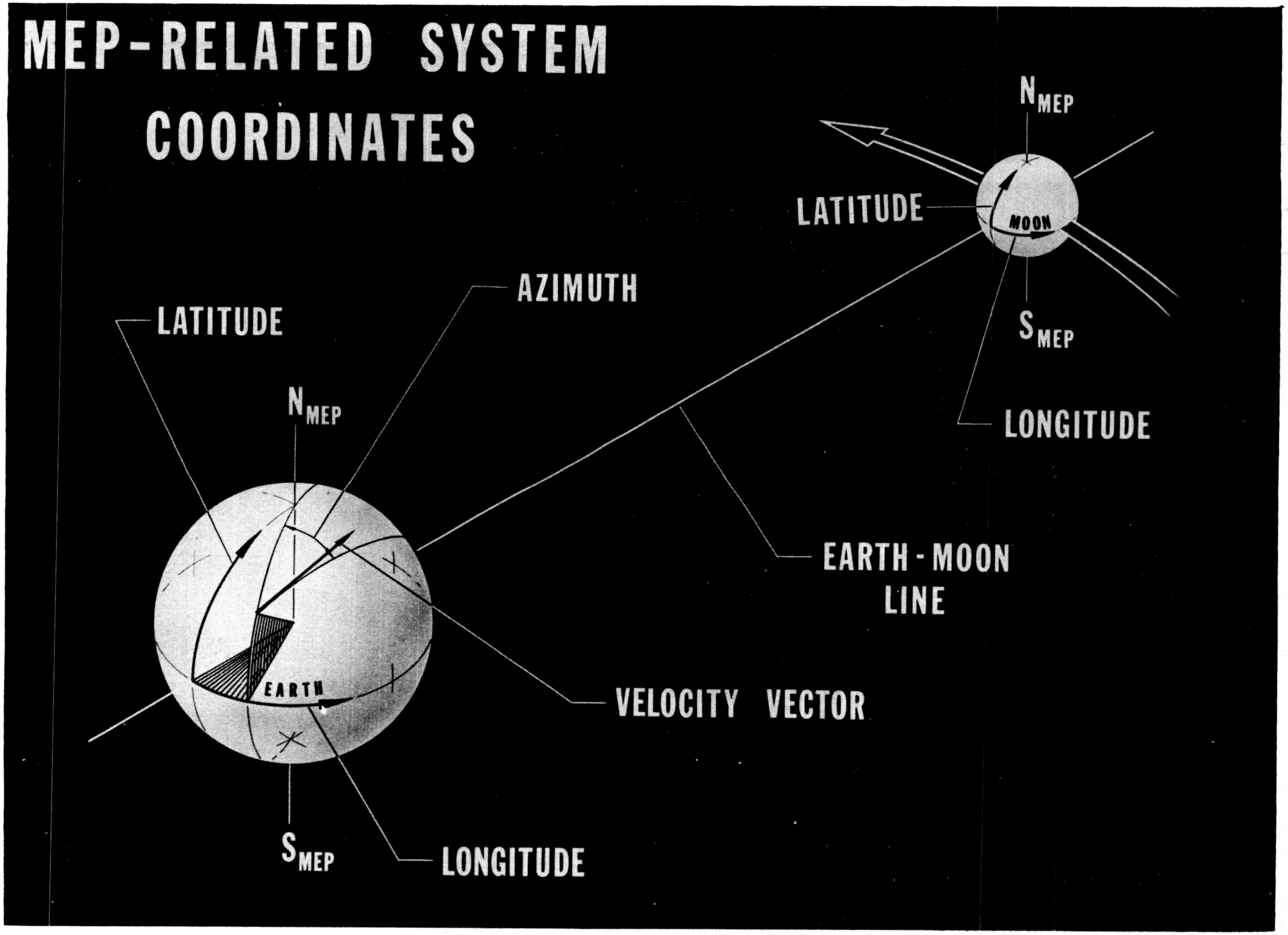


Figure 2



MEP-RELATED SYSTEM COORDINATES

Figure 3

FEATURES OF EARTH-MOON TRANSITS AT EARTH (COPLANAR FLIGHT)

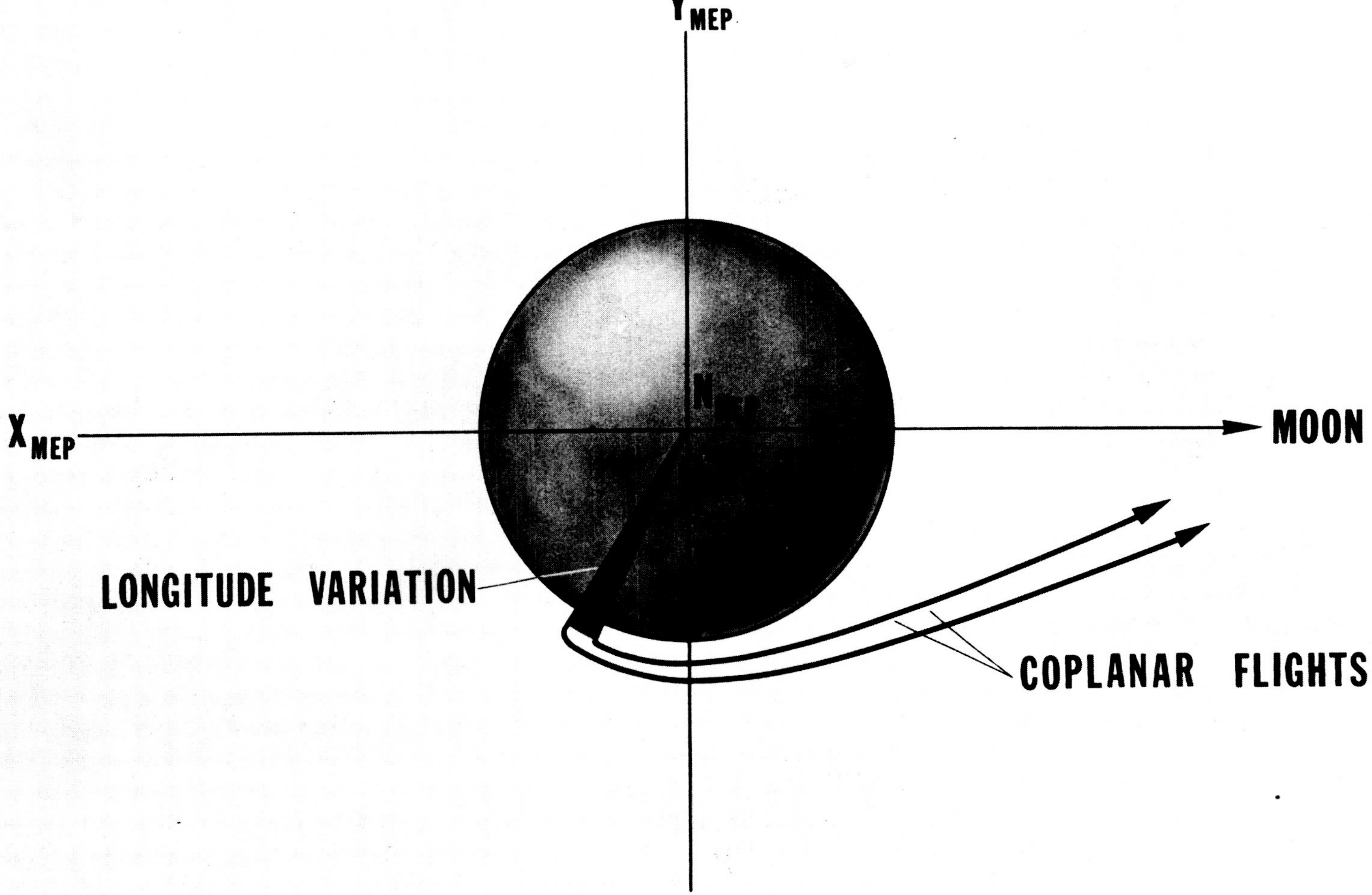


Figure 4

COPLANAR FLIGHTS

IMPACTS FOR VARIED INJECTION LONGITUDE

60 HOUR TRANSIT TIME

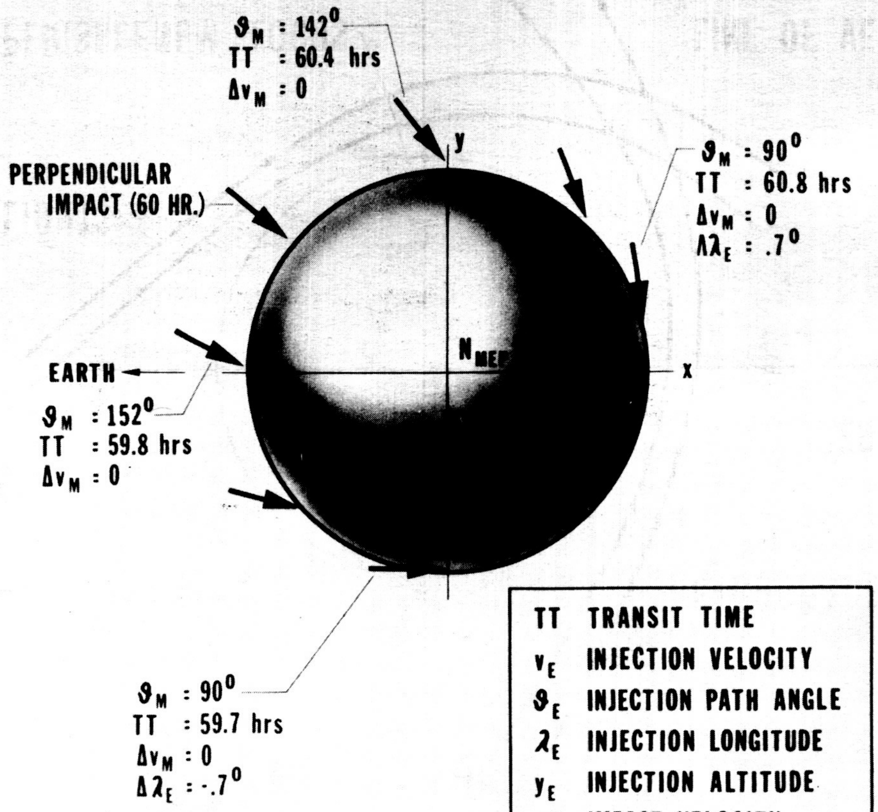
v_E = 10,898 m/sec

ϑ_E = 90°

λ_E = 44.4°

y_E = 185 km

v_M = 2,685 m/sec



TT	TRANSIT TIME
v_E	INJECTION VELOCITY
ϑ_E	INJECTION PATH ANGLE
λ_E	INJECTION LONGITUDE
y_E	INJECTION ALTITUDE
v_M	IMPACT VELOCITY
ϑ_M	IMPACT PATH ANGLE

Figure 5

FEATURES OF EARTH - MOON TRANSITS AT MOON
(COPLANAR FLIGHTS)

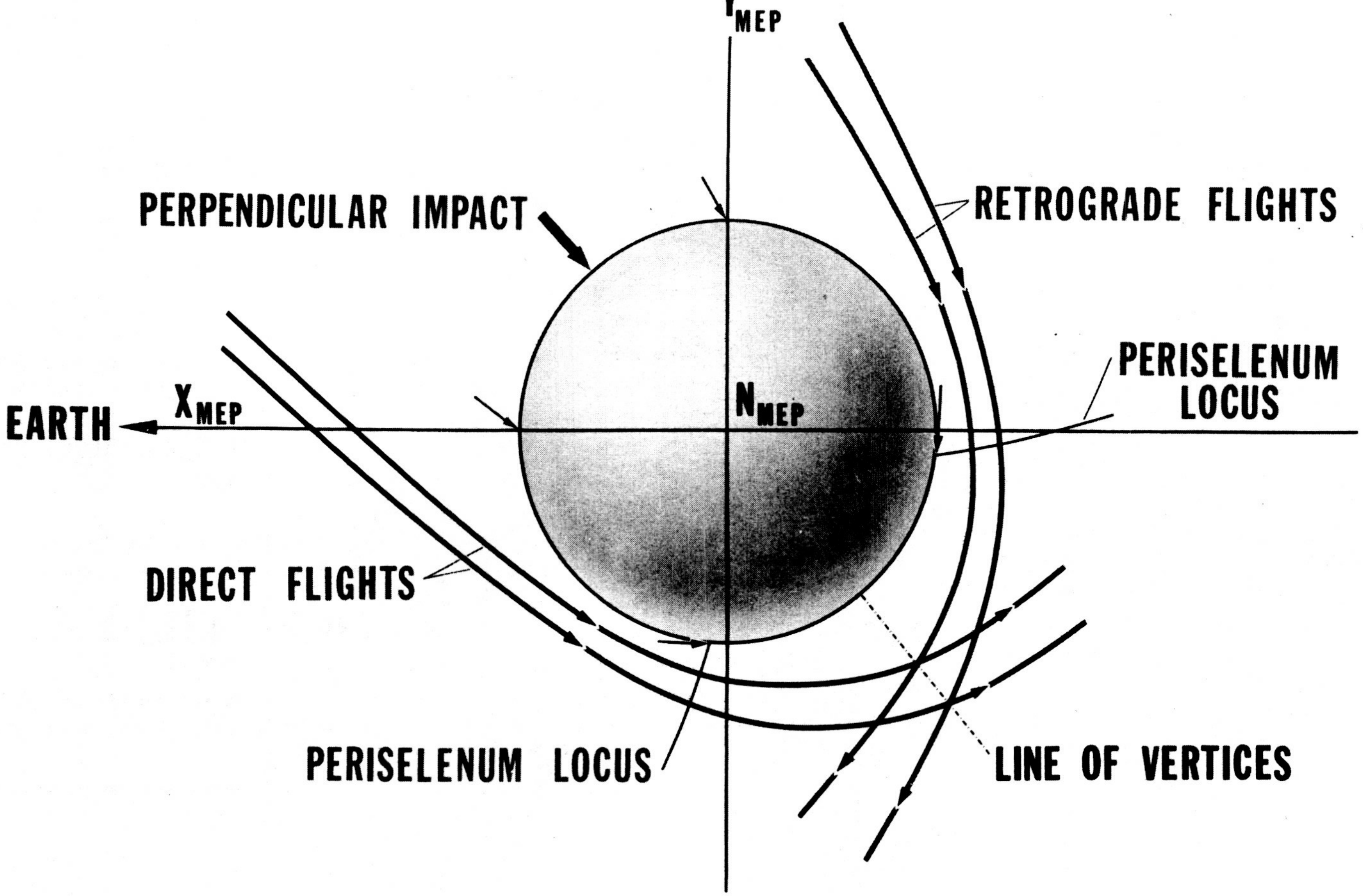
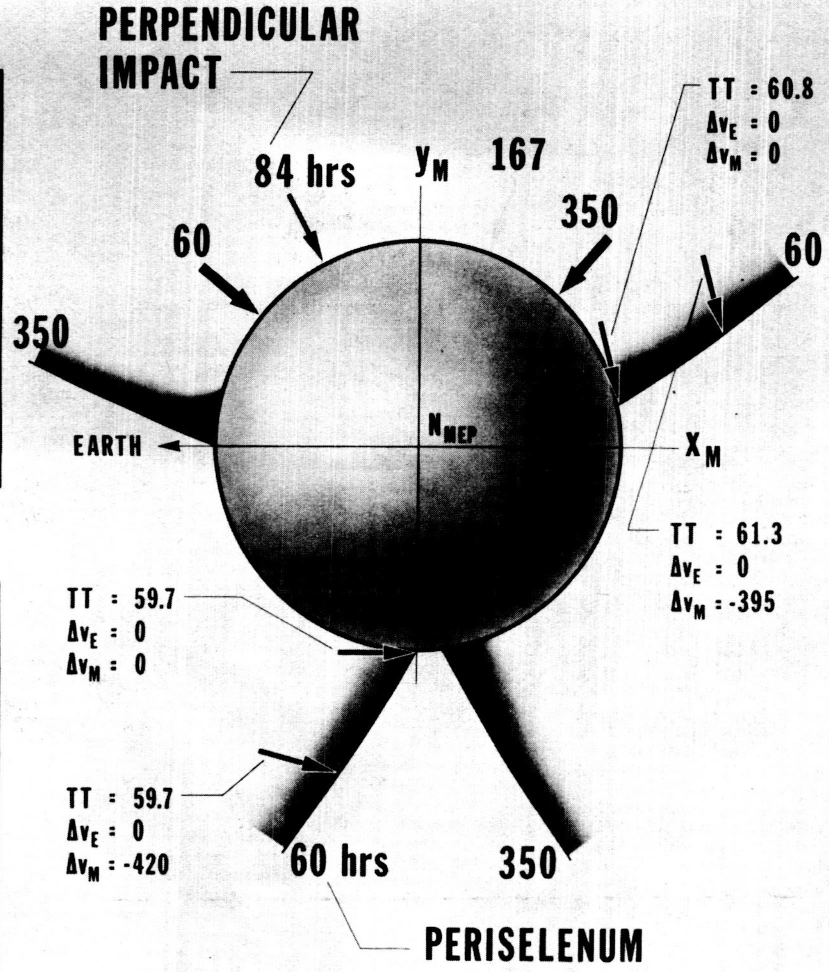


Figure 6

ARRIVAL CONDITIONS AT THE MOON FOR VARIOUS TRANSIT TIMES

TT = 60 hrs
v_E = 10,898 m/sec
ϑ_E = 90 deg
λ_E = 44.4 deg
y_E = 185 km
v_M = 2,685 m/sec

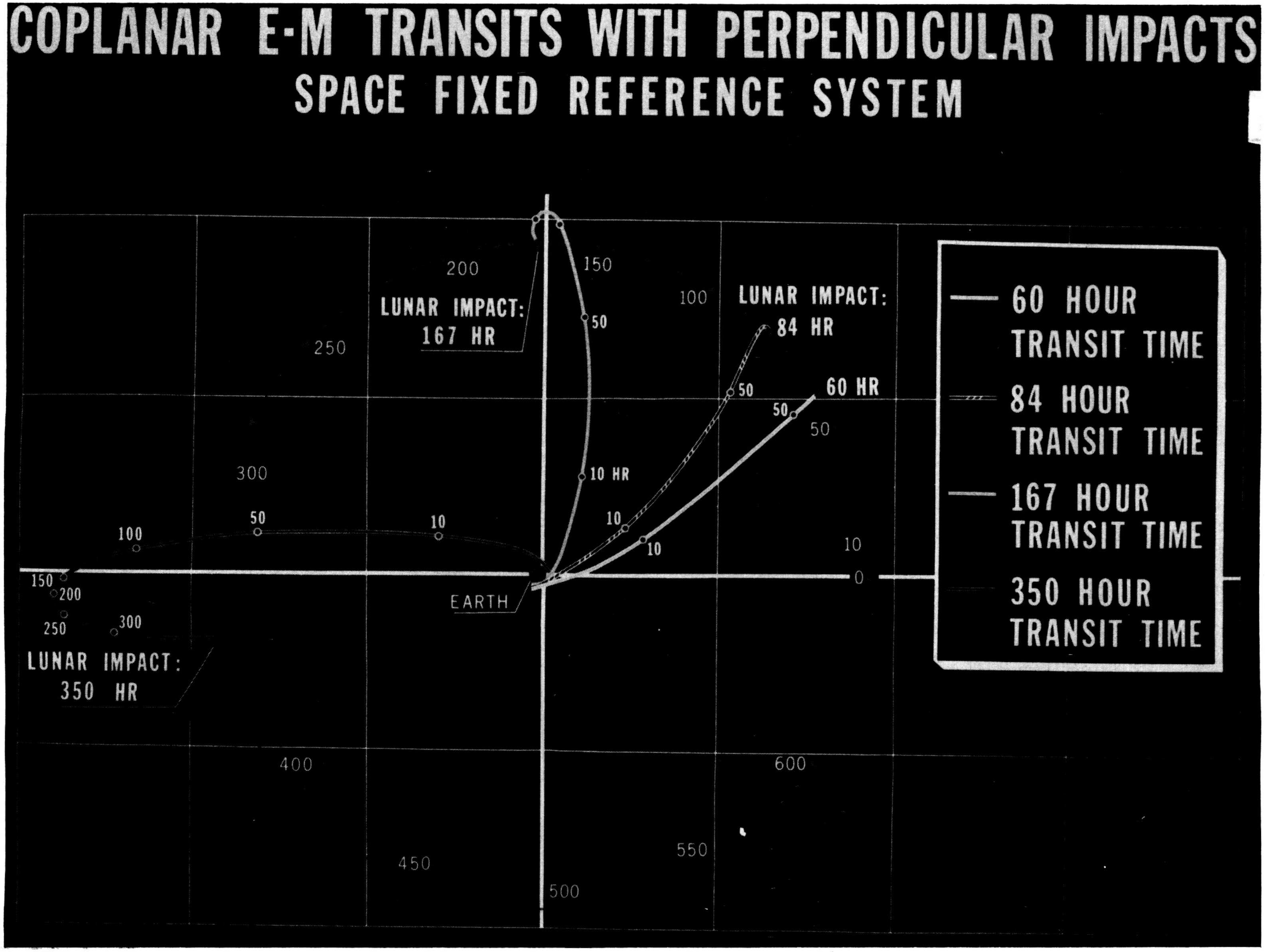


TT = 167 hrs
v_E = 10,858 m/sec
ϑ_E = 90 deg
λ_E = 90.4 deg
y_E = 185 km
v_M = 2,520 m/sec

TT = 84 hrs
v_E = 10,859 m/sec
ϑ_E = 90 deg
λ_E = 52.4 deg
y_E = 185 km
v_M = 2,523 m/sec

TT = 350 hrs
v_E = 10,880 m/sec
ϑ_E = 90 deg
λ_E = 182.5 deg
y_E = 185 km
v_M = 2,613 m/sec

Figure 7



COPLANAR E-M TRANSITS WITH PERPENDICULAR IMPACTS
SPACE FIXED REFERENCE SYSTEM

Figure 8

TERMINAL VELOCITIES FOR EARTH-MOON TRANSITS
PERPENDICULAR IMPACT FLIGHTS

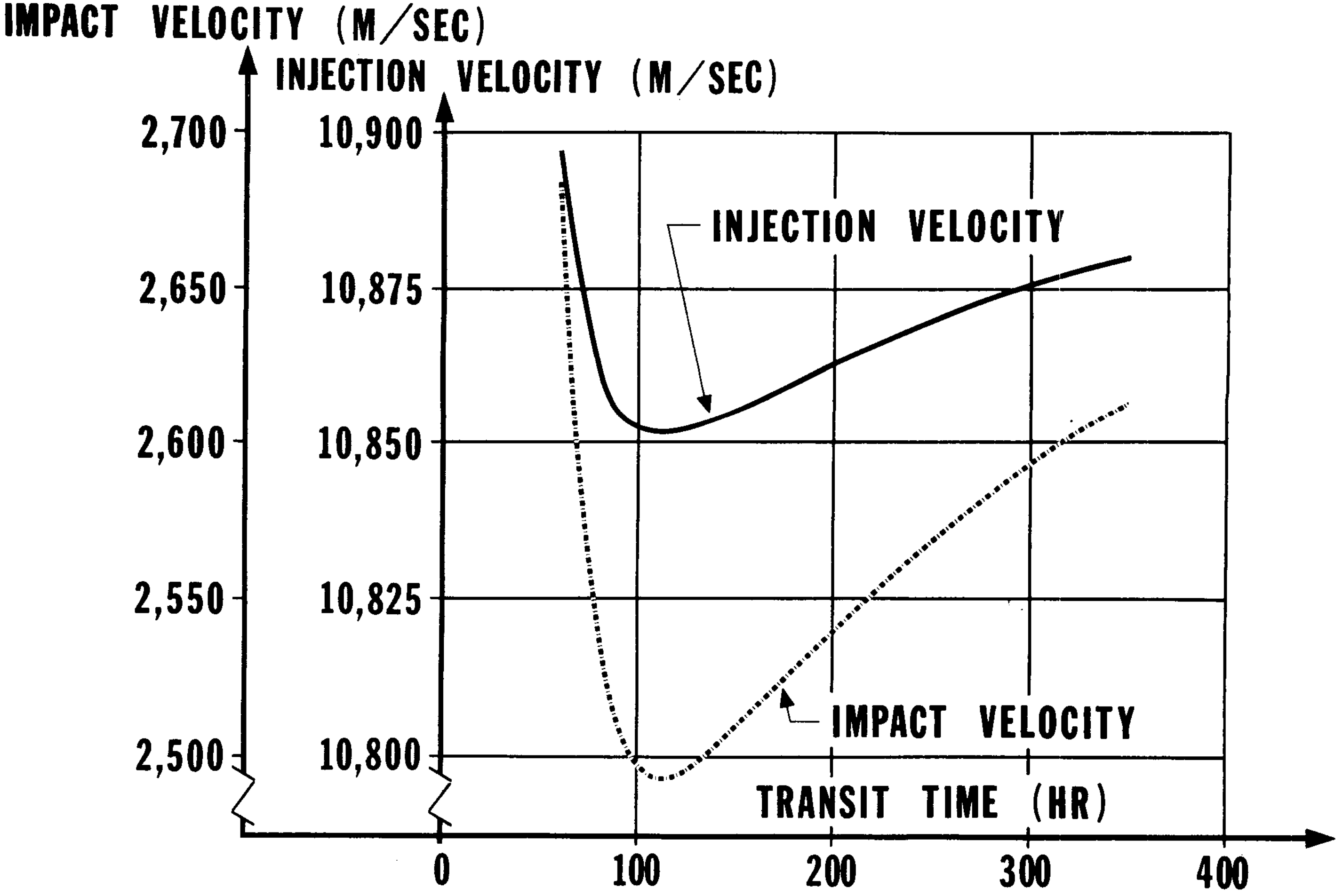
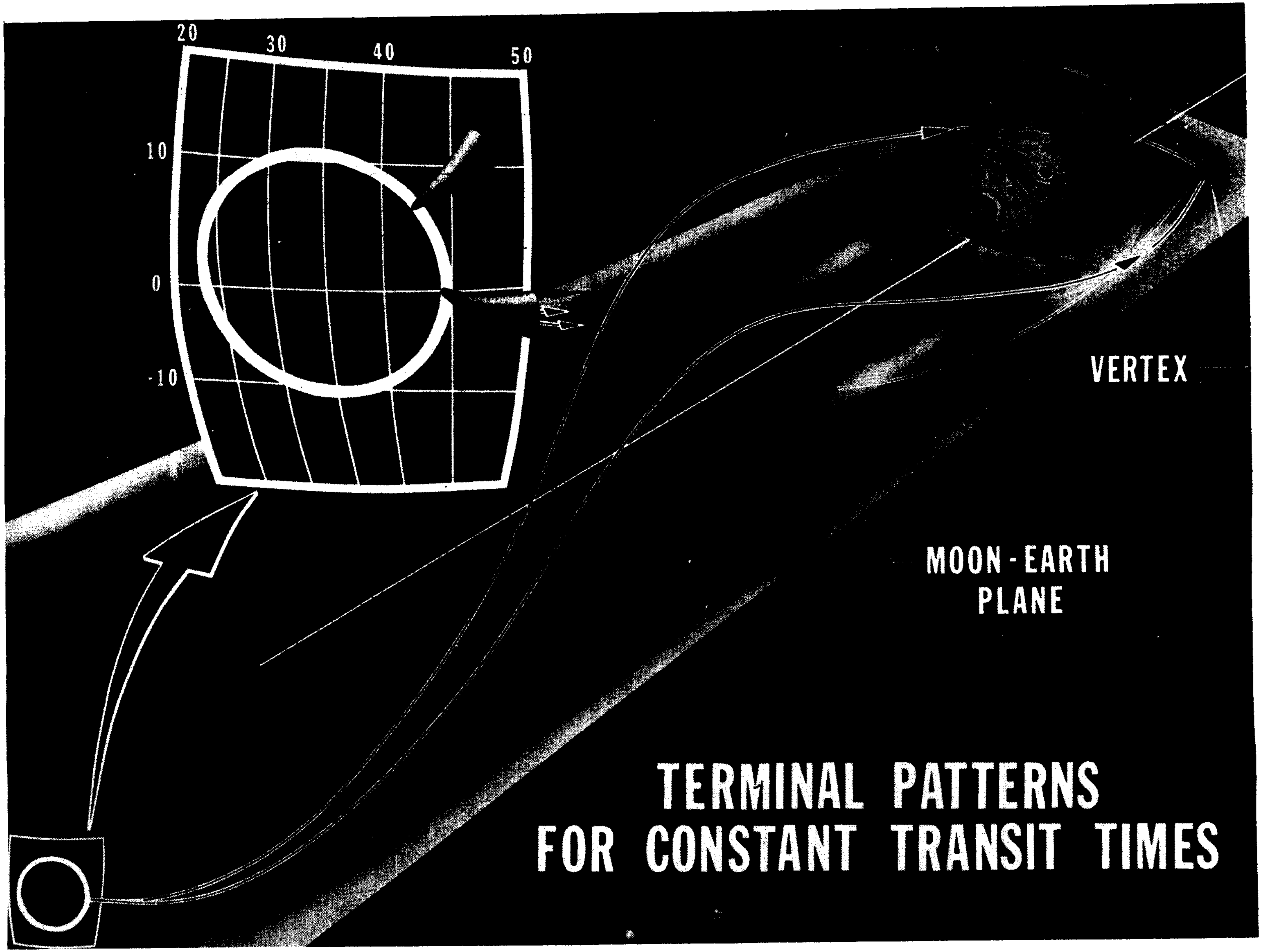


Figure 9



TERMINAL PATTERNS
FOR CONSTANT TRANSIT TIMES

Figure 10

PATTERN OF EARTH INJECTION LOCATIONS FOR CONSTANT TRANSIT TIME

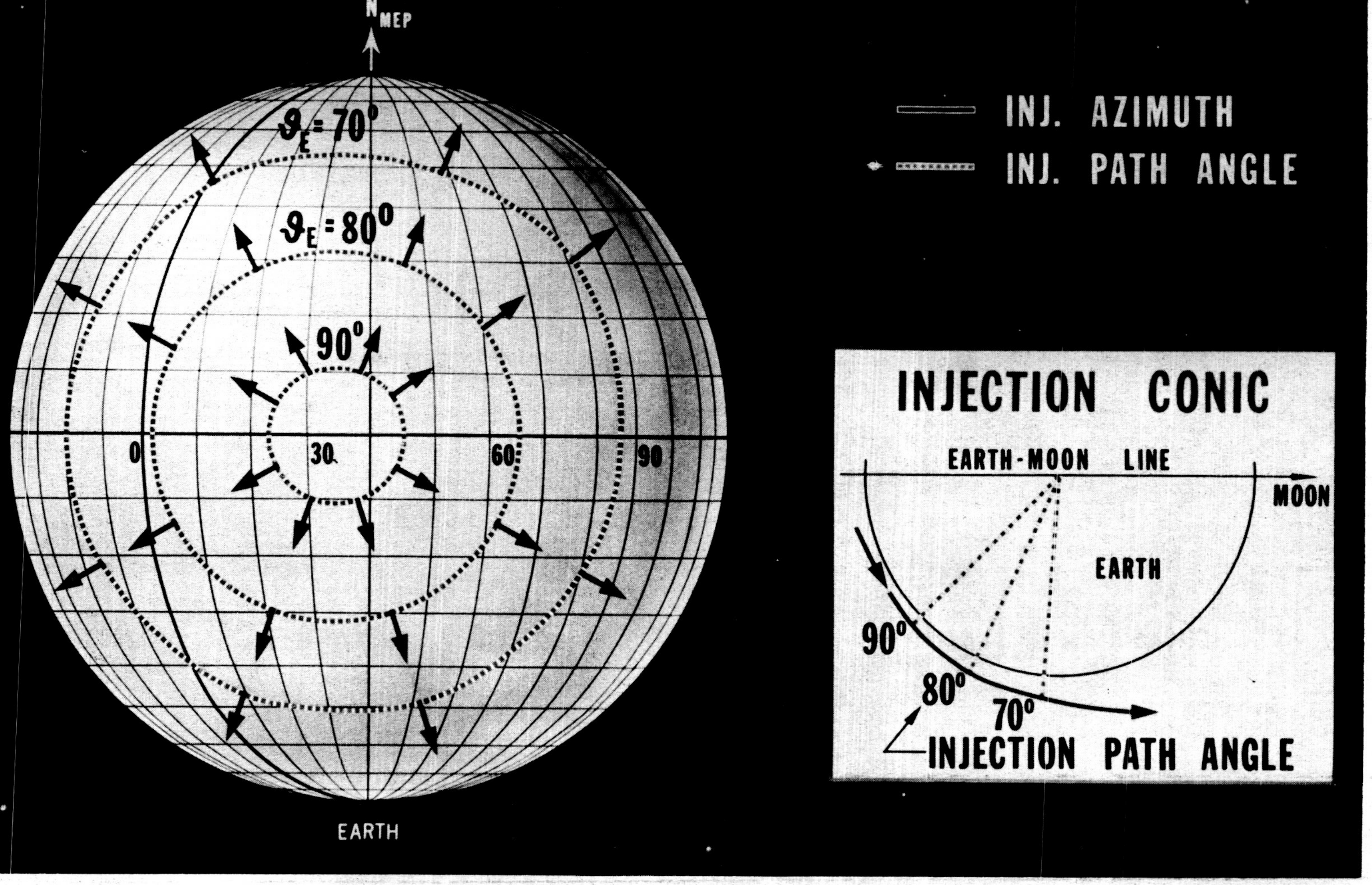
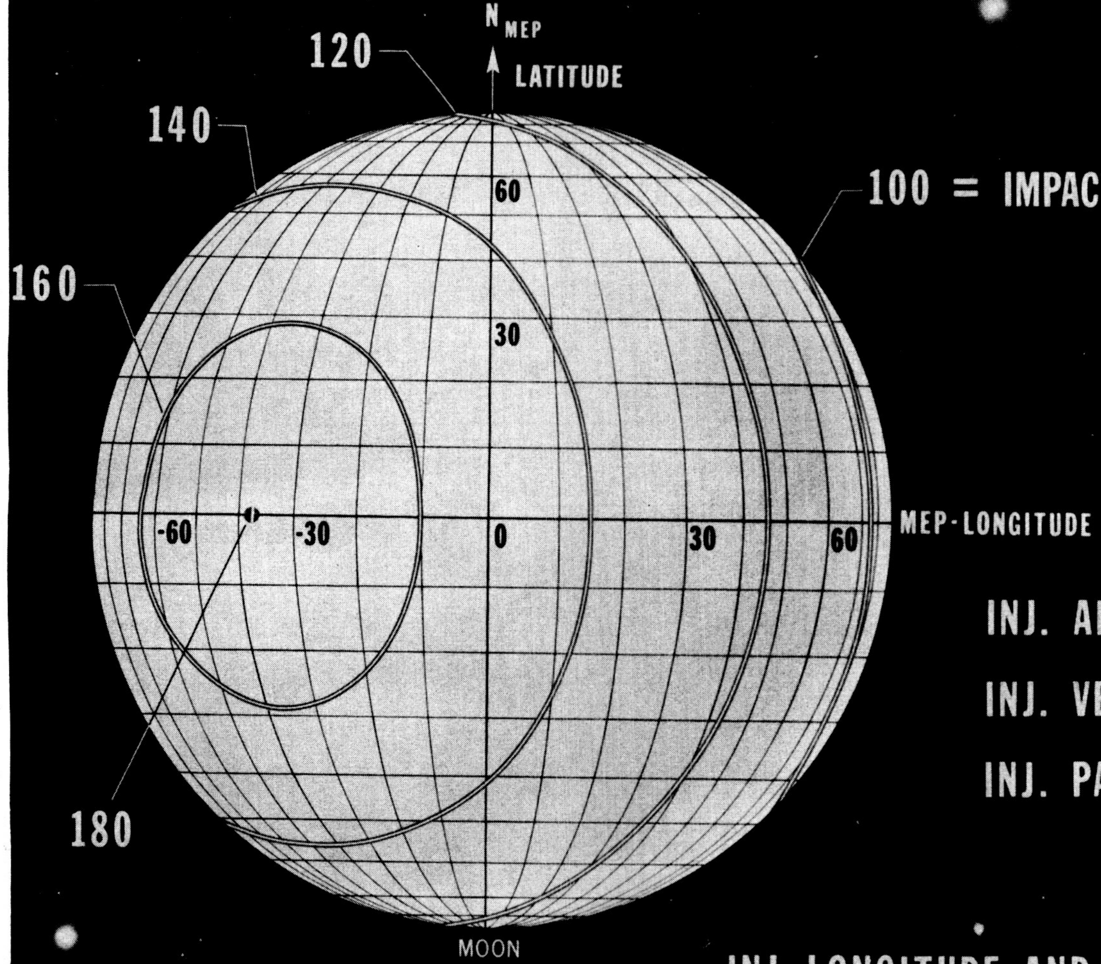


Figure 21

LOCATIONS OF CONSTANT IMPACT PATH ANGLES



100 = IMPACT PATH ANGLE (DEGREES)

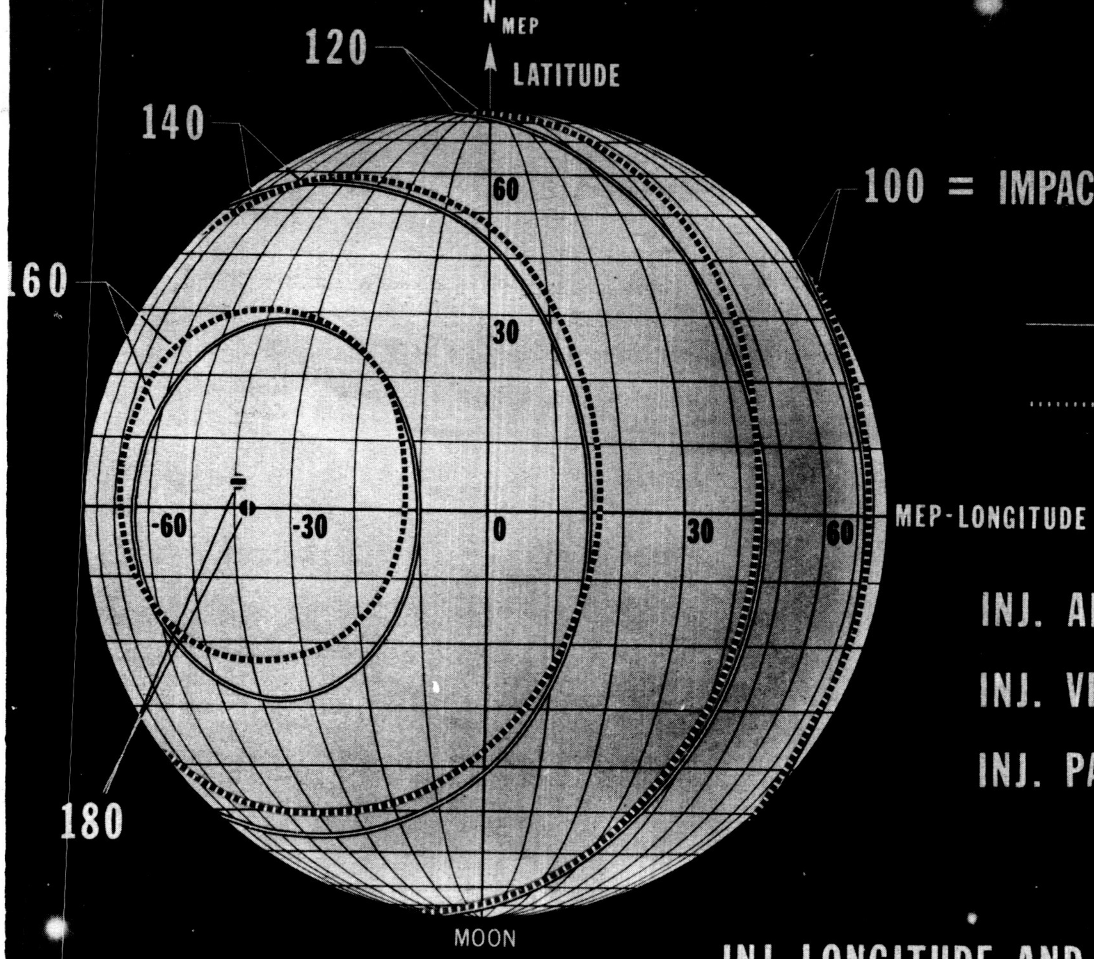
INJ. LATITUDE = 0 DEG

INJ. ALTITUDE = 185 KM
INJ. VELOCITY = 10,897 M/S
INJ. PATH ANGLE = 90 DEG

INJ. LONGITUDE AND INJ. AZIMUTH ARE VARIED

Figure 12

LOCATIONS OF CONSTANT IMPACT PATH ANGLES



100 = IMPACT PATH ANGLE (DEGREES)

—— INJ. LATITUDE = 0 DEG

······· INJ. LATITUDE = 5 DEG

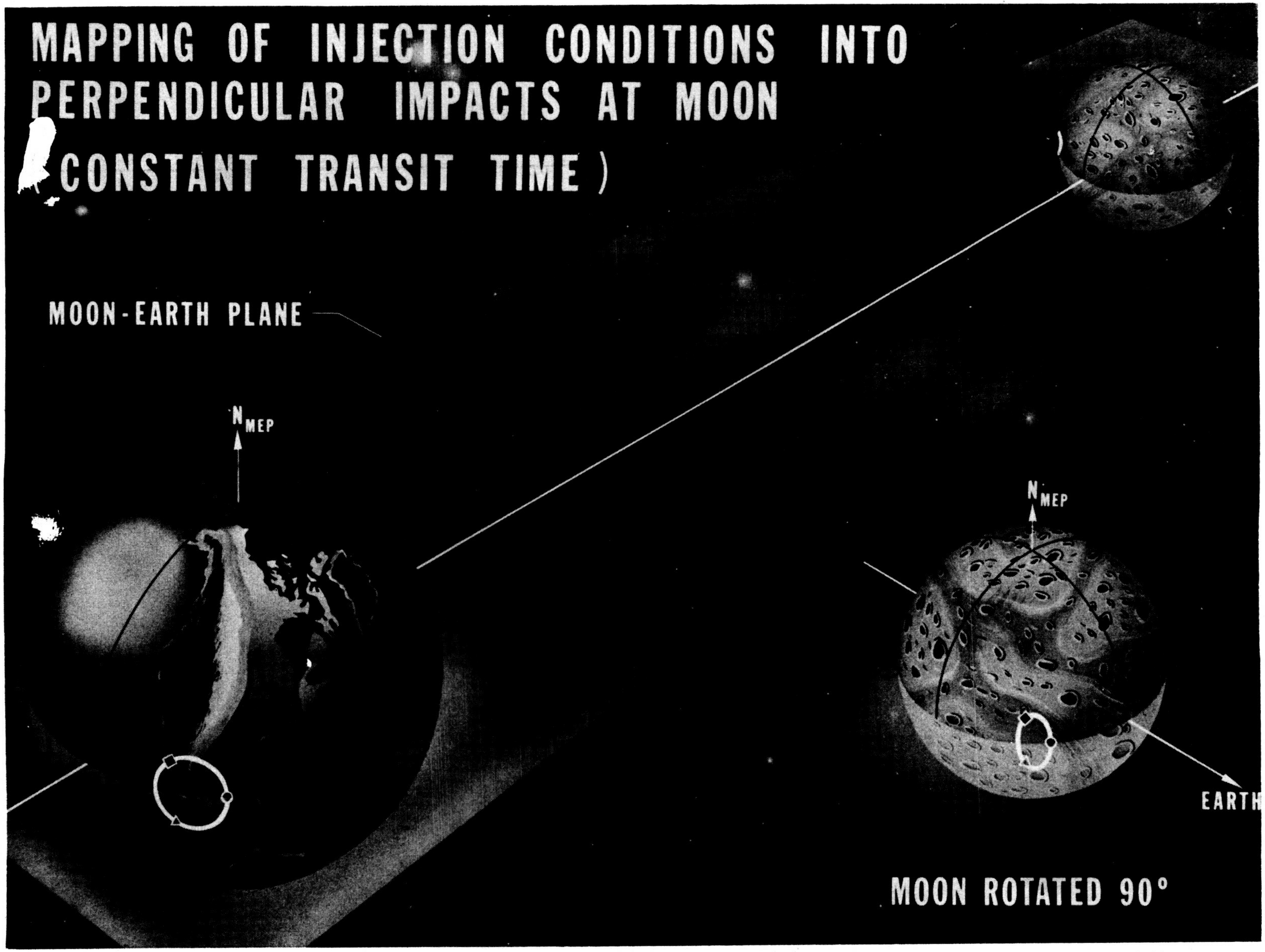
INJ. ALTITUDE = 185 KM

INJ. VELOCITY = 10,897 M/S

INJ. PATH ANGLE = 90 DEG

INJ. LONGITUDE AND INJ. AZIMUTH ARE VARIED

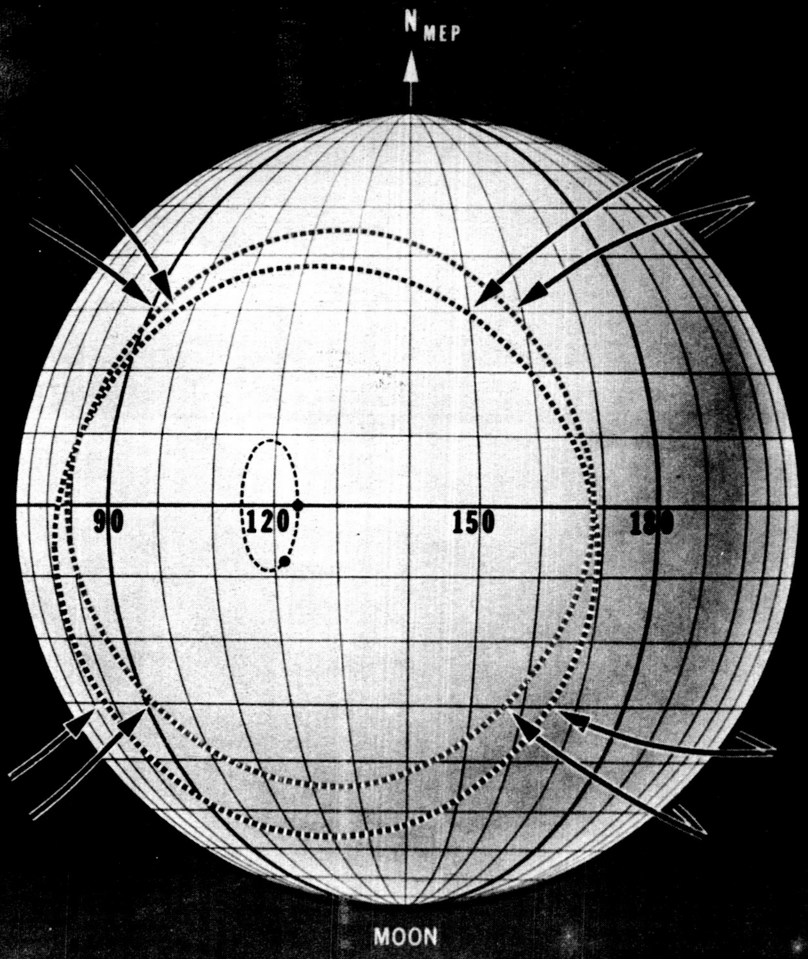
Figure 13



MAPPING OF INJECTION CONDITIONS INTO PERPENDICULAR IMPACTS AT MOON (CONSTANT TRANSIT TIME)

Figure 14

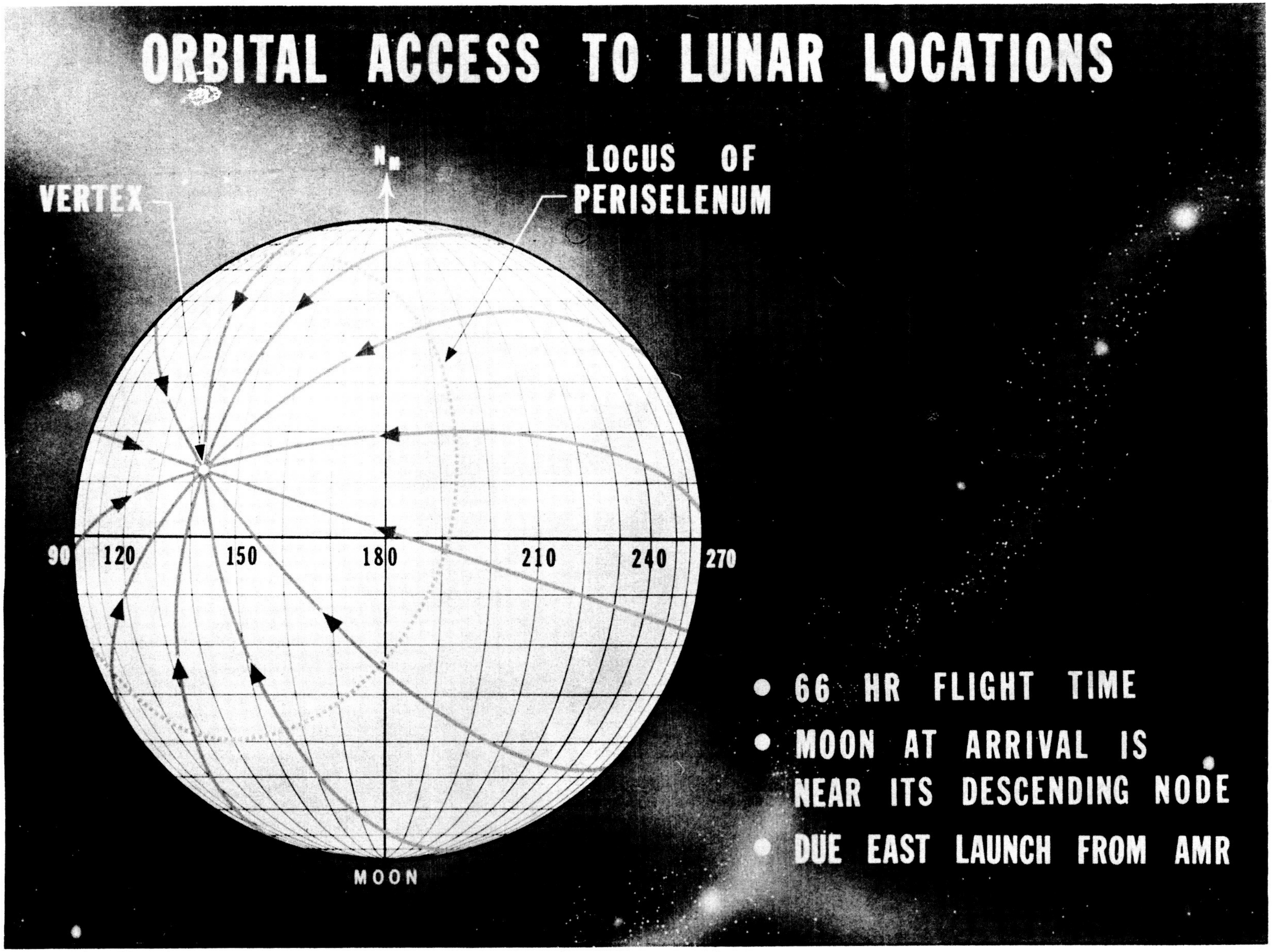
PERISELENUM LOCI AND LOCUS OF THEIR VERTICES



FAR SIDE
OF MOON

·········· INJ. LATITUDE = 0 DEG
·········· INJ. LATITUDE = 5 DEG

Figure 15



ORBITAL ACCESS TO LUNAR LOCATIONS

- 66 HR FLIGHT TIME
- MOON AT ARRIVAL IS NEAR ITS DESCENDING NODE
- DUE EAST LAUNCH FROM AMR

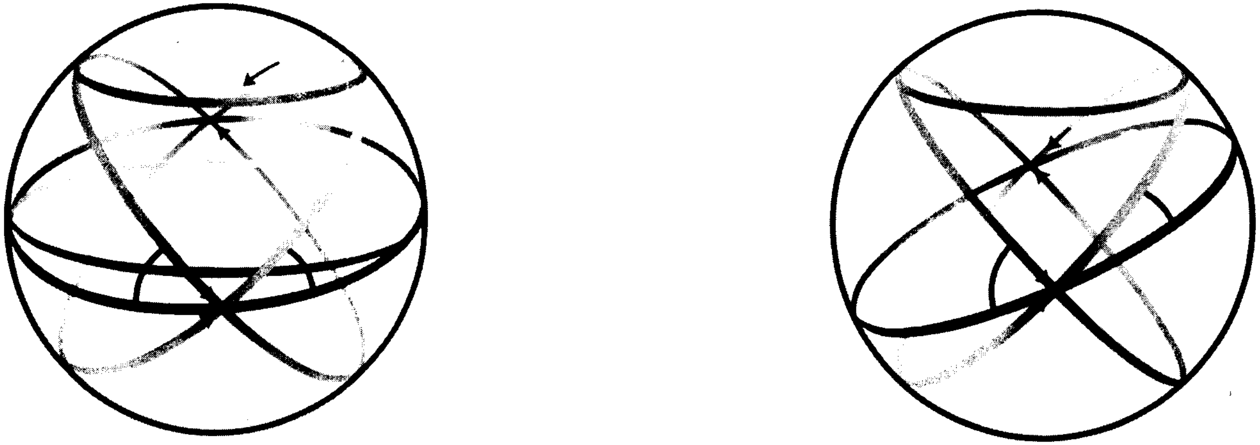
Figure 16

SALIENT FEATURES

1. Perigee locations of transit of constant time form a nearly circular belt.
2. Each element of the belt is the origin of a family of transits that covers and envelops the moon and passes through a unique vertex.
3. The vertical impact transit of a family is diametrically opposite to the vertex.
4. Vertex coordinates are functions of coordinates of departure element.
5. The higher the latitude of departure element the larger the inclination of all associated transits to M-E Plane.
6. Vertex location determines fully the azimuth of approach to any landing site.

Figure 17

DIRECTION OF APPROACHING THE MOON FOR TRANSITS LAUNCHED FROM ORBITS OF 28.5 DEG INCLINATION



(a) for Moon at Highest and Lowest Declination

(b) for Moon at Ascending and Descending Nodes

Figure 18

VELOCITY AT PERISELENUM AS FUNCTION OF INCLINATION OF INJECTION CONIC

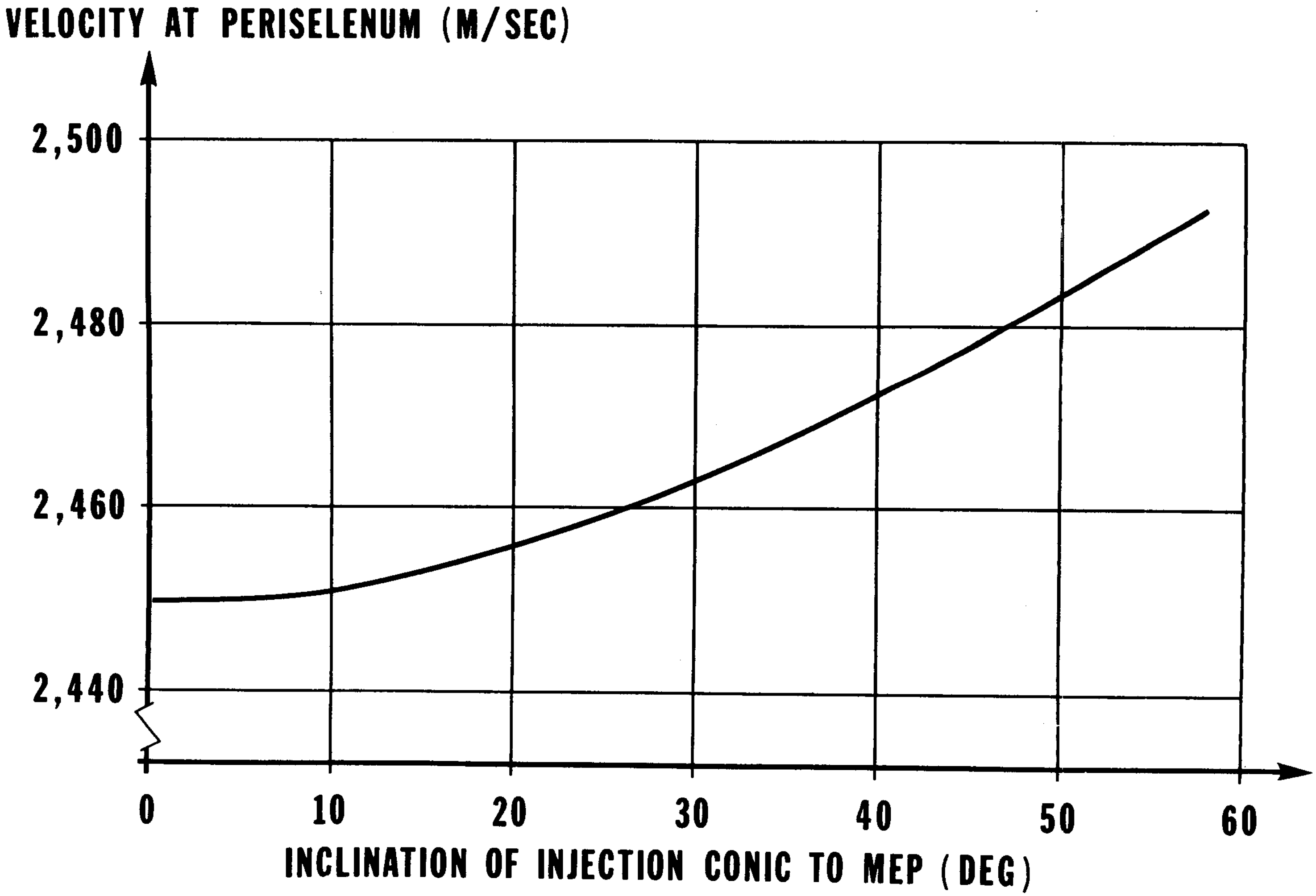
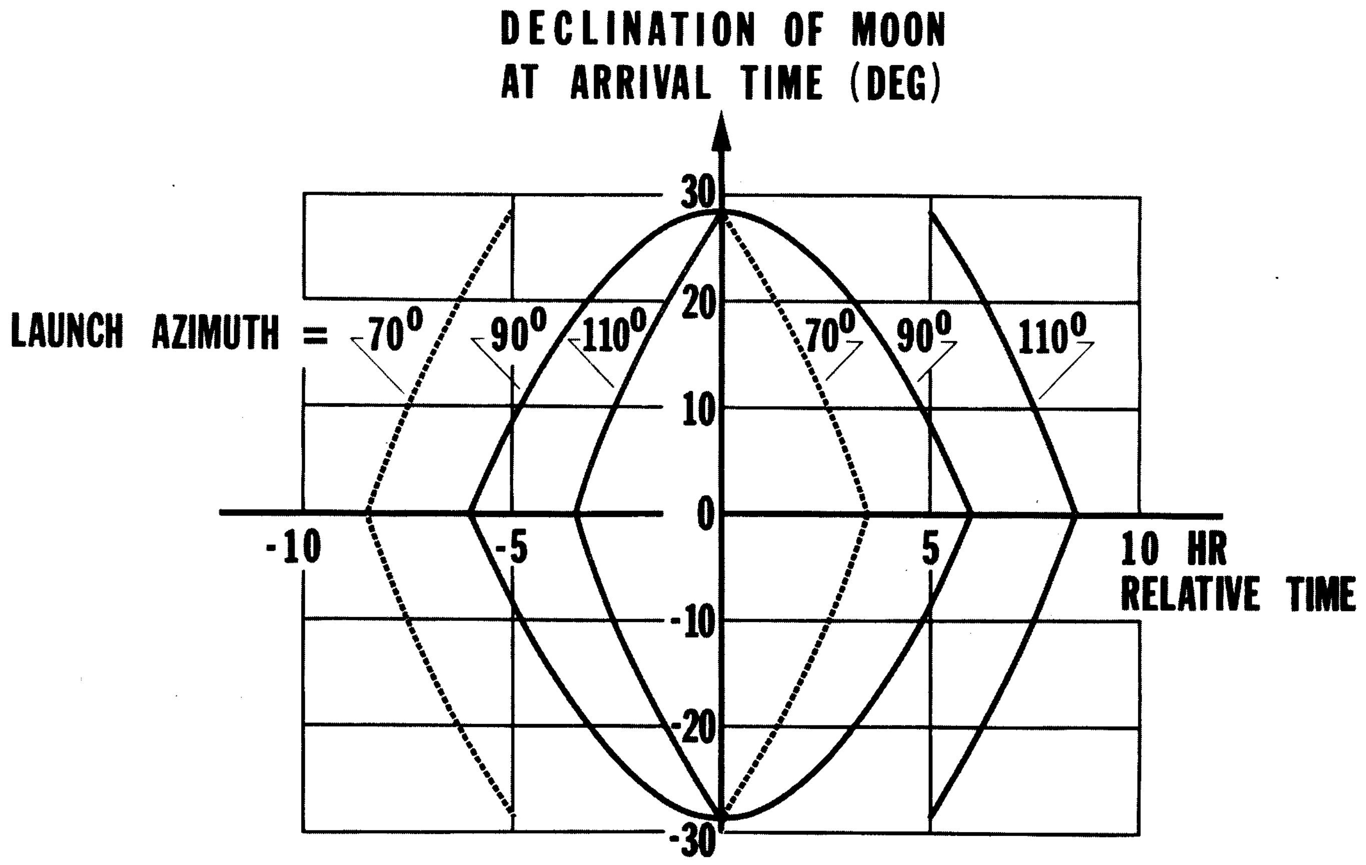


Figure 19

LAUNCH WINDOW FROM AMR AT VARIOUS AZIMUTHS FOR EARTH-MOON TRANSIT



REFERENCE TIME CHOSEN MIDWAY BETWEEN DUE EAST LAUNCH OPPORTUNITIES

Figure 20

DEPARTURE VELOCITY FOR VARIOUS FLIGHT TIMES AND EARTH-MOON POSITIONS AT ARRIVAL

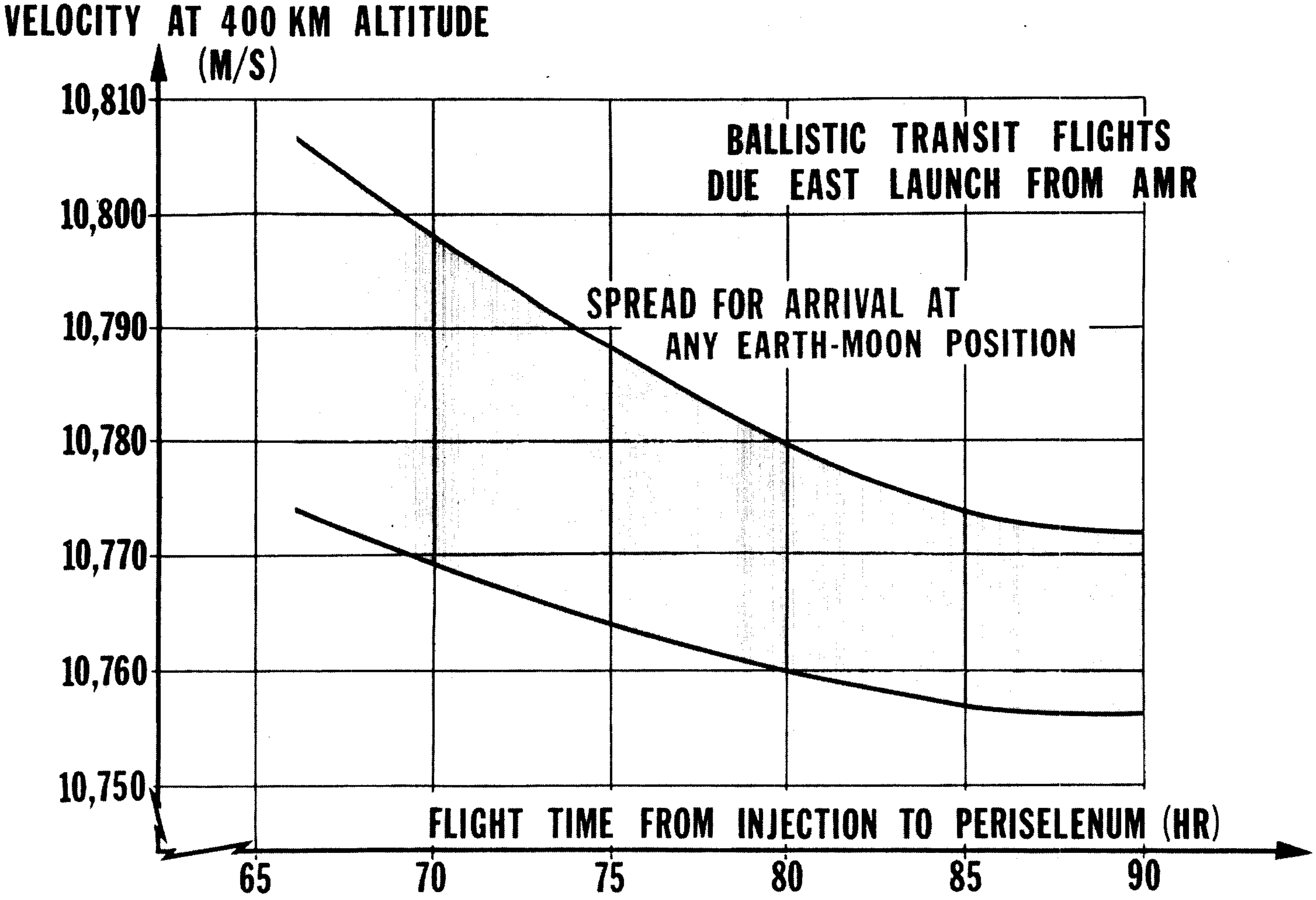


Figure 21

VELOCITY FOR ARRIVAL AT 185 KM PERISELENUM ALTITUDE FOR VARIOUS TRIP TIME AND EARTH - MOON EPHEMERIS SAMPLINGS

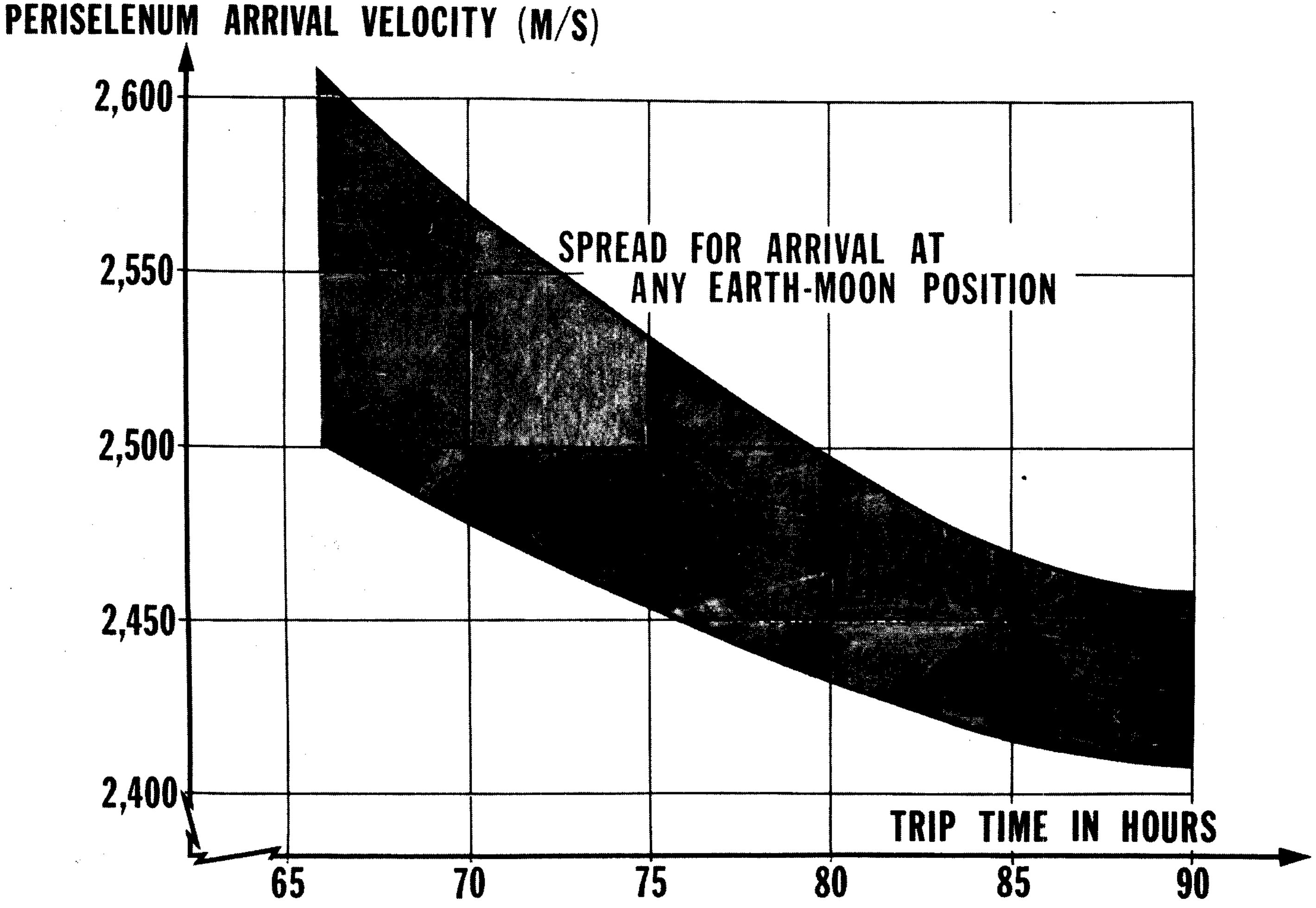


Figure 22

MIDCOURSE VELOCITY REQUIRED TO ENFORCE TIME AND POSITION OF PERISELENUM AS FUNCTION OF FLIGHT TIME

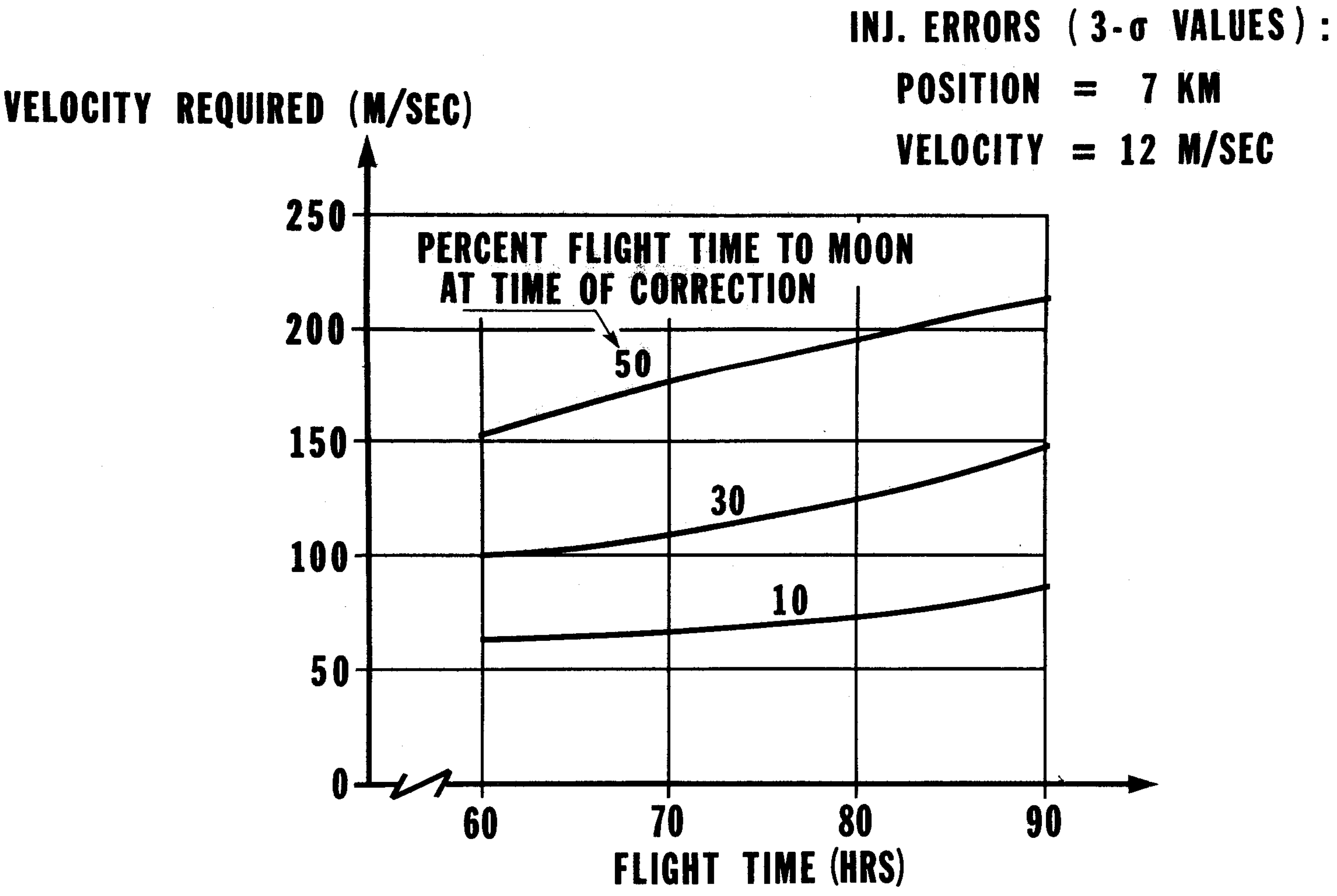


Figure 23

COMPARISON OF VELOCITY REQUIRED FOR THREE DIFFERENT TRANSIT TIMES

	VELOCITY REQUIREMENT (REFERENCED TO 90 HR TRANSIT TIME)		
	66 HR	72 HR	90 HR
INJECTION VELOCITY (M/S)	34	22	0
PERISELENUM ARRIVAL VELOCITY (M/S)	142	82	0
MIDCOURSE CORRECTION REQUIREMENT (M/S) EXECUTED AT 30% OF TRANSIT TIME	-48	-35	0
COMPARATIVE VELOCITY REQUIREMENT (M/S)	128	69	0

Figure 24

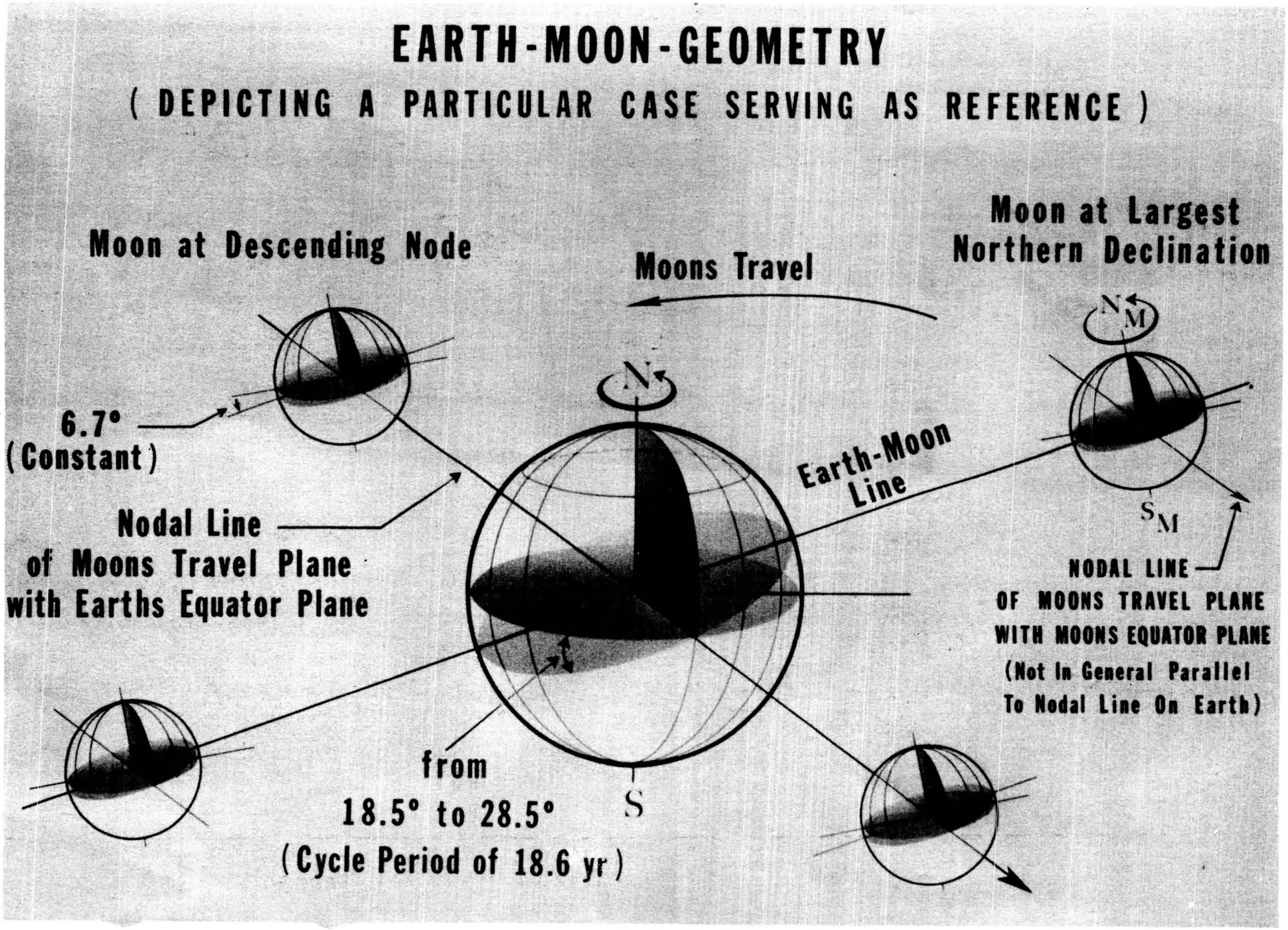
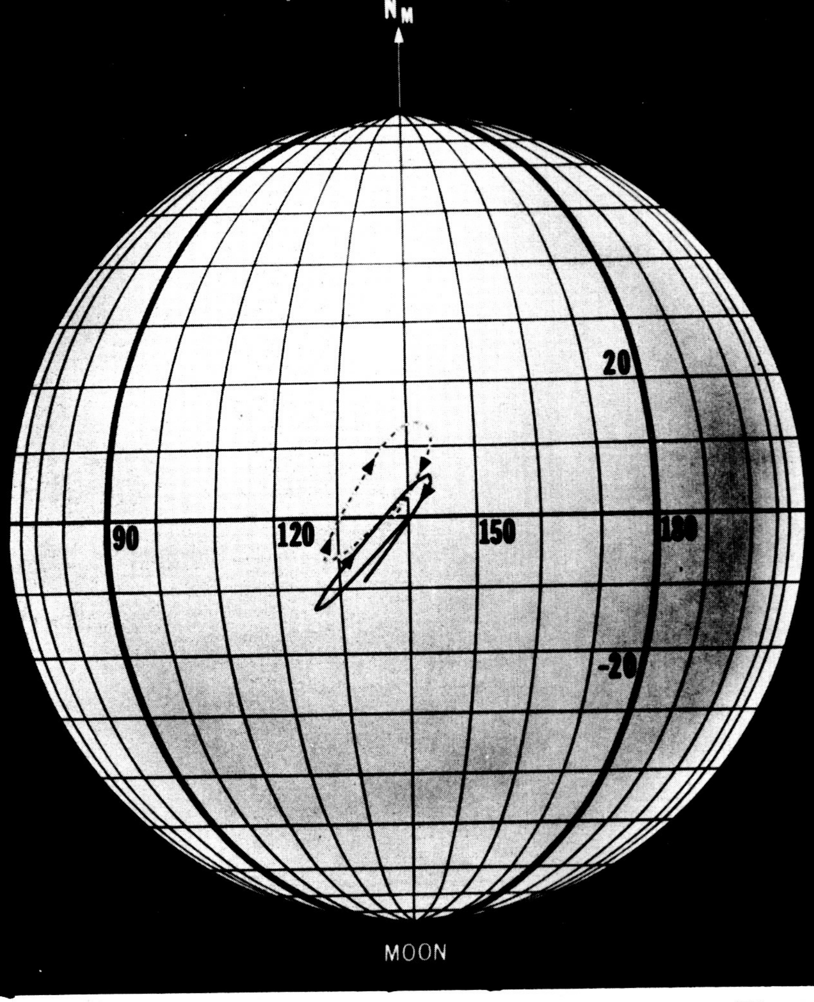

EARTH-MOON-GEOMETRY
(DEPICTING A PARTICULAR CASE SERVING AS REFERENCE)
Moon at Descending Node
Moons Travel
Moon at Largest Northern Declination
N_M
N
6.7° (Constant)
Nodal Line of Moons Travel Plane with Earths Equator Plane
Earth-Moon Line
S_M
NODAL LINE OF MOONS TRAVEL PLANE WITH MOONS EQUATOR PLANE
(Not In General Parallel To Nodal Line On Earth)
from 18.5° to 28.5°
(Cycle Period of 18.6 yr)
S

Figure 25

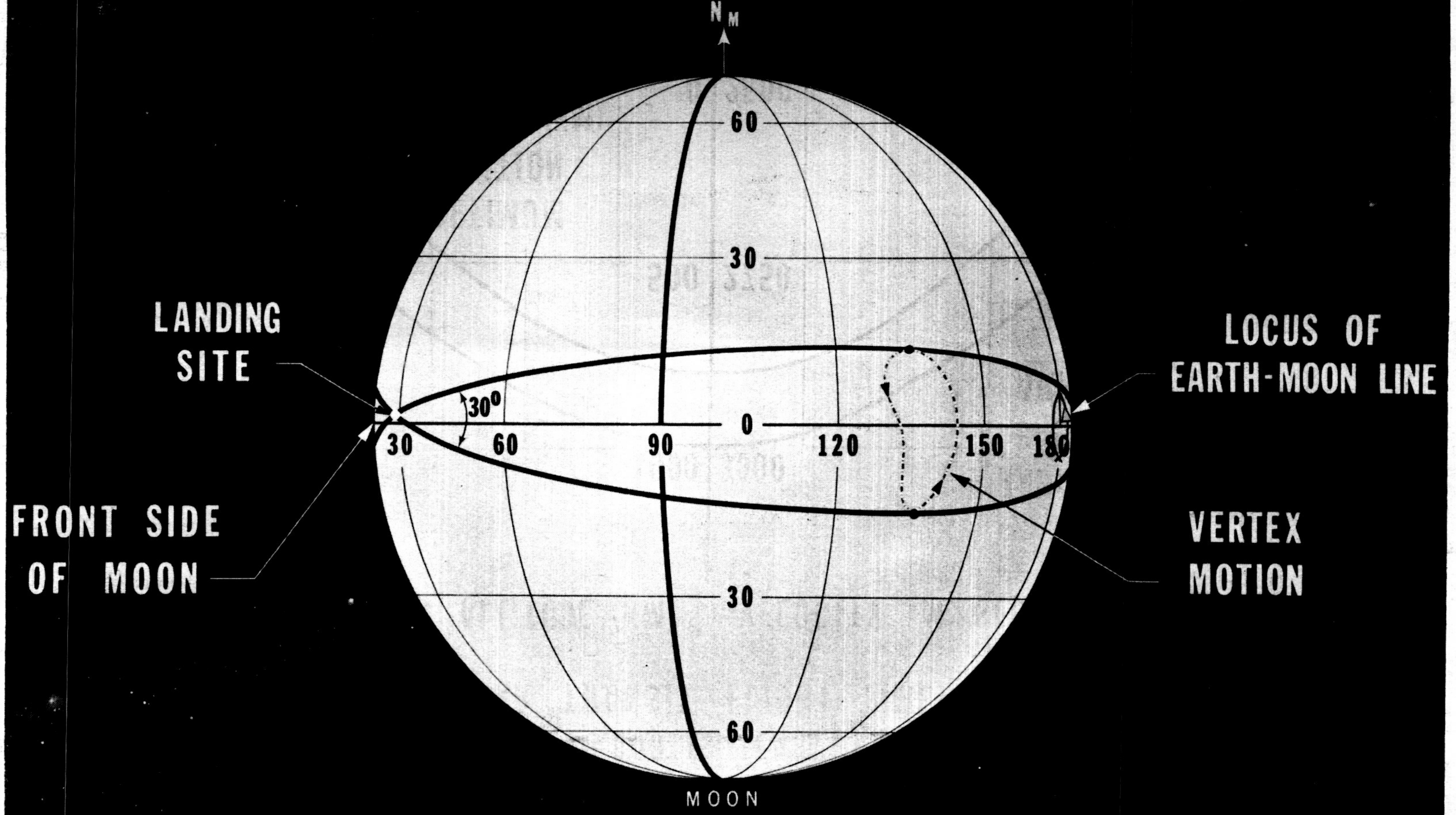
VERTEX MOTION DURING A MONTH FOR BOTH DAILY LAUNCH OPPORTUNITIES



- DUE EAST LAUNCH FROM AMR
- NO POWERED PLANE CHANGES
- MOON RADIAL DISTANCE AND DECLINATION OUT-OF-PHASE BY 180°
- NOV. - DEC. 1964

Figure 26

VARIATION IN APPROACH AZIMUTH FOR BALLISTIC FLIGHT OVER LANDING SITE



LANDING SITE

FRONT SIDE OF MOON

LOCUS OF EARTH-MOON LINE

VERTEX MOTION

- MARCH-APRIL 1969
- DUE EAST LAUNCH FROM AMR

Figure 27

VELOCITY REQUIRED FOR DIRECT LANDING AT ANY POINT ON LUNAR MEP EQUATOR

THRUST = 30,000 LB; WEIGHT = 90,000 LB (EARTH); SPECIFIC IMPULSE = 425 SEC
COPLANAR TRANSIT FLIGHT TIME = 72 HR

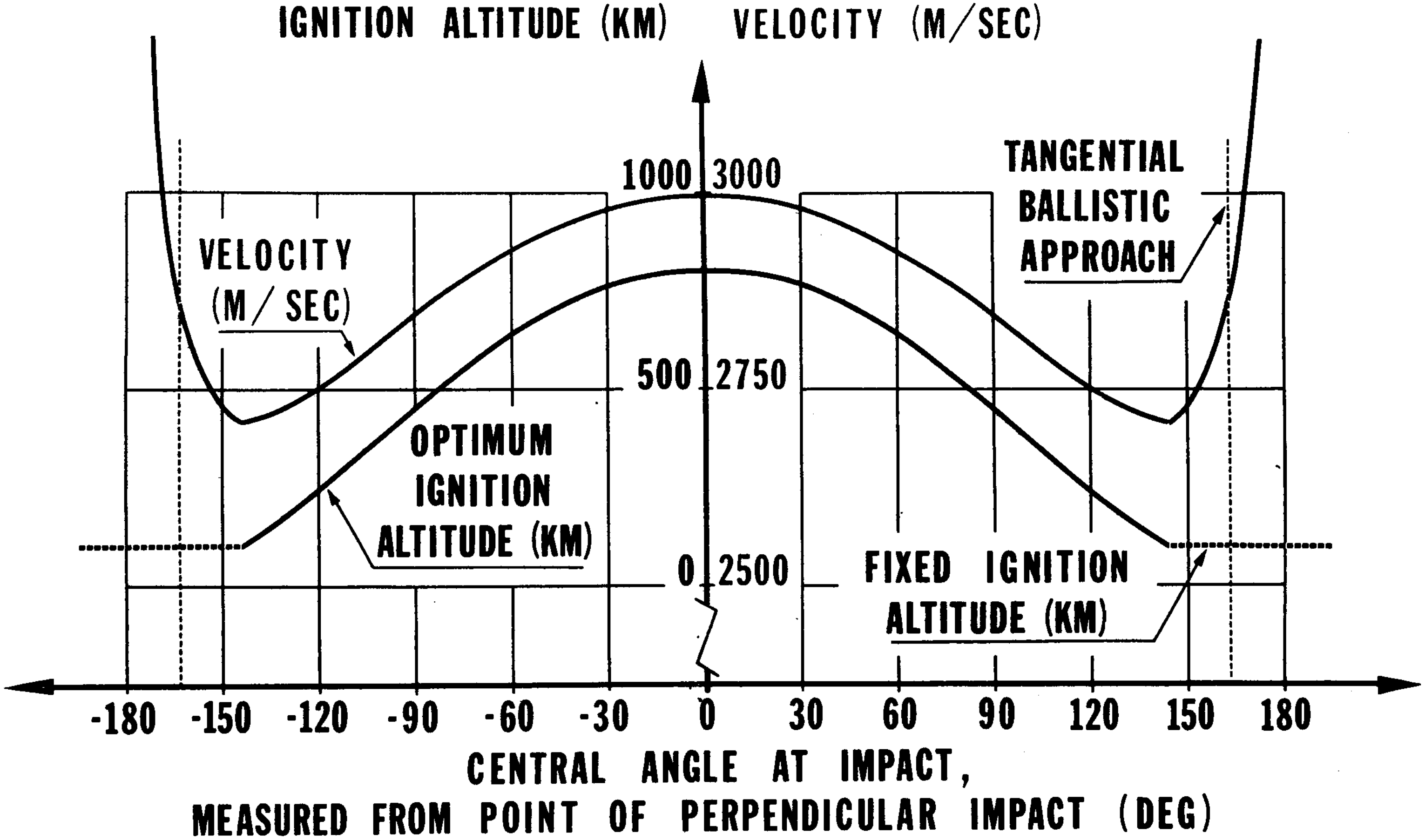
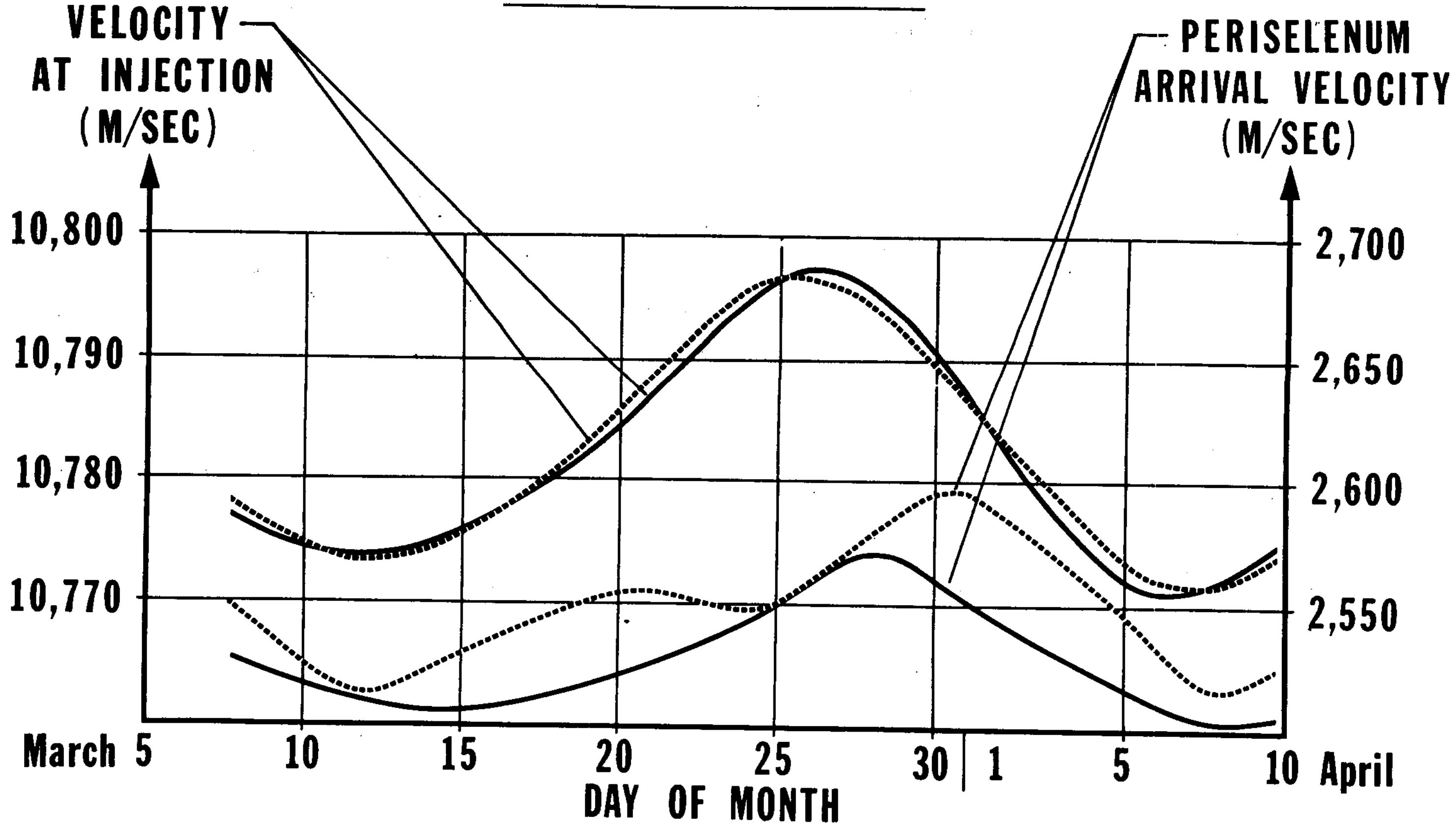


Figure 28

VELOCITY BUDGET FOR MARCH-APRIL 1969
(TWO SOLUTIONS PER DAY; DUE EAST)

66 HOUR TRANSIT TIME



NOTE: Add about 20 m/s at earth and 8 m/s at moon for daily launch window of 5 hrs. (Allows 10 hrs during part of month)

Figure 29

APPROVAL

PRELIMINARY INVESTIGATIONS OF THE ASTRONAUTICS OF EARTH - MOON TRANSITS

By Nolan J. Braud

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be Unclassified.

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