TECHNICAL MEMORANDUM X-53354

LAUNCH WINDOWS FOR TWO TYPES OF ORBITS SYNCHRONOUS WITH THE LUNAR PERIOD

By

E. H. Bauer and L. D. Mullins

ABSTRACT

This report presents launch windows for two types of orbits designed to be synchronous with the lunar orbital period. One class of conic, the 1/8-class orbit, maintains a period one-eighth that of the lunar period and an apogee of approximately one-half the lunar distance. The second type, 1/2-class orbit, consists of a conic with one-half the lunar period and apogee radius approximately equal to the lunar distance, an Arenstorf Orbit. Launch windows are presented which reflect the assumptions and constraints applicable to the specific geometry of each class and to the S-IB/S-IVB/Centaur vehicle. The time period considered for the 1/2-class orbit is December 1967 through June 1968 where only discrete launch opportunities are found. The window for the 1/8-class is less constrained and is shown for each day of any year.

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SYMBOL AND NOMENCLATURE DEFINITION

MOP	Orbit plane of moon about the earth.
S-E Line	Line through center of sun and center of earth, piercing the earth at local noon.
NADIR	With reference to the S-E line, the nadir is the point where the extension of this line passes through the earth's center, exiting the surface at local midnight 180° away in right ascension and of opposite sign in declination.
RCA	Radius of close approach of conic; perigee.
Ecliptic	Plane of earth's rotation about the sun; locus of S-E line.
Inclination	Dihedral angle between two planes.
Declination	Space-fixed declination; angular distance north or south from earth's celestial equator; here synonymous with latitude.
Line of Apsides	Major axis of conic extending from perigee to apogee.
KSC	Kennedy Space Center, assumed at a latitude of 28.5°.
Cislunar	Space between earth and moon.
Right Ascension	Space-fixed right ascension; angular distance eastward along the celestial equator from the vernal equinox, or ascending node of ecliptic on the earth's celestial equator, to great circle passing through poles and point being defined.

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LAUNCH WINDOWS FOR TWO TYPES OF ORBITS SYNCHRONOUS WITH THE LUNAR PERIOD

SUMMARY

Launch windows are presented for two classes of orbits in the earth-moon space designed to have periods which are synchronous with the lunar orbital period. The windows reflect the constraints of a particular launch vehicle (the Saturn IB/S-IVB/Centaur), the geometrical constraints required to maintain at least one year of orbital stability, mission constraints requiring the orbits to lie in or near the moon's orbit plane (MOP), and range safety launch azimuth constraints.

For orbits generated with a period one-eighth that of the lunar period and oriented such that the conic's line of apsides lies in the MOP and near the sun-earth line, launch opportunities are found to occur twice daily, each of approximately 4 1/2 hours duration.

A launch window for orbits of one-half the lunar period which periodically pass near the earth and moon, referred to as Arenstorf orbits, is generated for the period of December 1967 to June 1968. These orbits achieve twice the apogee distance of the 1/8 class and are consequently much more affected by the moon's perturbing force. This in turn adds to the launch constraints, requiring that the orbits generated lie embedded in the moon's orbit plane. The resulting launch window is extremely small when compared with the 1/8 class. In fact, throughout the time period considered, only three days in May with a 2-hour ground launch window per day yielded opportunities for injecting into a conic of sufficient orbital stability. However, a trade-off study revealed that it is possible to lower the initial perigee attitude of the Arenstorf orbit, thus increasing vehicle performance capability and increasing the launch window. This was done for May 1968, and resulted in an increase in launch window to 10 days.

I. INTRODUCTION

Two classes of orbits in the earth-moon space designed to be synchronous with the lunar orbital period are surveyed with respect to their launch windows. One class of conic, designated as the 1/8-class orbit, maintains a period one-eighth that of the lunar period and reaches an apogee of approximately one-half the lunar distance. The other class investigated, the 1/2-class orbit, consists of a conic with one-half the lunar period and apogee radius approximately equal to the lunar distance. The 1/2-class orbits are periodic with respect to the earth and moon and are referred to as Arenstorf orbits. It is the purpose of this report to present the launch windows which reflect the assumptions and constraints applicable to the specific geometry of each class.

The most significant constraint difference between the two classes is the requirement to embed the orbits of the 1/2-class in the moon's orbit plane (MOP) about the earth, while only the line of apsides of the 1/8-class is constrained to lie in the MOP. Specifically, the 1/2-class must maintain a 0° relative inclination of the conic plane to the MOP while the 1/8-class orbits may be of any inclination. This constraint requires a different approach to the launch window problem for the two classes. It requires the 1/2-class to fly to a space-fixed plane. This in turn implies a powered plane change to produce a window of any appreciable width. The 1/8-class flies to a space-fixed perigee point which lies in the MOP. This may be achieved by the proper geometrical alignment of the launch site, launch azimuth, and perigee point without the necessity of any powered plane change.

The position of the earth relative to the sun greatly affects the launch window. To maintain orbital stability for at least one year, it is necessary for the line of apsides of the conics to be near the sun-earth line. As the 1/2-class conic is constrained to lie in a particular plane (the MOP), the launch window is severely limited when the orientation of the major axis of the conic is also constrained. Thus, the proper constellation of the earth, moon and sun necessary for launch is rare when compared to the daily launch opportunities available for the 1/8-class. The time period considered for the 1/2-class is December 1967 through June 1968 where only discrete opportunities are found. The window for the 1/8-class is less constrained and is shown for any day of any year.

Both classes reflect the constraints of one particular launch vehicle, the S-IB/S-IVB/Centaur, which is defined by the control weights and described explicitly in Table I. The flight profile consists of a Saturn IB, S-IVB, and Centaur burn into a parking orbit. After an appropriate coast period designed to place the perigee of the injection conic in the proper position under the imposed constraints, the Centaur is restarted, cutting off on the energy that produces the desired orbital period. The most limiting restriction of this particular vehicle with reference to the launch window is the maximum parking orbit coast time allowed the Centaur. To insure restart reliability of the Centaur, a maximum of 30 minutes is allowed from first cutoff at injection into the parking orbit to second ignition which initiates the injection maneuver into the desired conic.

II. ONE-EIGHTH CLASS ORBIT

A. GEOMETRY AND WINDOW

The 1/8-class orbit is characterized by a trajectory with free flight elliptical orbits of approximately one-half the lunar distance and synchronous orbital periods of one-eighth lunar month. The line of apsides of the injection conic is specified to lie in the moon's orbit plane about the earth (MOP), or earth-moon plane. However, the orbits are not required to be embedded in this plane and may be of any inclination. The flight profile consists of a Saturn IB, S-IVB, and Centaur burn into a 555.5 km (300 n. mi.) altitude circular parking orbit. After an appropriate coast period designed to place perigee in the MOP, the Centaur is restarted, cutting off on the energy (C_3 = - 4.161 km^2/sec^2) that produces the desired orbital period. No powered plane changes are made in this study, and the orbits generated have lifetimes exceeding one year.

Vehicle, range safety, mission, and orbital stability constraints introduce limitations on the launch opportunities. The constraints applicable to the 1/8-class orbit include the following:

1. Launch azimuth between 72° and 108°, a range safety restriction.

2. Parking orbit coast not to exceed 30 minutes. This is a vehicle constraint to insure Centaur restart reliability.

3. Line of apsides in the MOP. This mission constraint places the major axis of the orbit in the moon's orbit plane, affording slightly better orbital stability. More importantly, this constraint places a greater portion of the conic near the plane of major interest, the MOP, the nearness being dependent upon the relative inclination of the two planes.

4. Vertical projection of the sun-earth line (hereafter referred to as the S-E line) onto the MOP near the line of apsides. This constraint requires perigee, which is constrained in 3. above to lie in the MOP and to also lie as near as possible to the S-E line. The positioning of perigee relative to the S-E line is a prime factor in determining orbital lifetime. This effect is shown in Figure 1, where perigee radius time histories are presented for various initial angular distances of the perigee radius from the S-E line. Where the initial perigee lies on the S-E line (0° case), over one year of orbital stability is maintained.

The major sinusoidal motion of the perigee radius (RCA), Figure 1, is attributed to the sun's perturbing force; the small oscillations, as shown in the 0° case, are due to the moon's perturbing force. The moon's effect is relatively minor and only the average motion is presented for the remaining cases.

The altitude of the initial perigee is determined primarily by the parking orbit altitude and the requirement to fly optimized powered trajectories from the parking orbit to mission injection. Since the parking orbit altitude is fixed, initial perigee altitude also remains relatively fixed regardless of the angle between perigee and the S-E line. However, this angle, or the position of the sun relative to the initial perigee vector, does affect the altitude of subsequent perigees. Perigees that begin on the S-E line (0°) are perturbed upward in altitude for three months then downward for three months until the major axis is again aligned with the S-E line. Placing perigee of the injection conic at some angle away from the S-E line produces the same initial altitude as the nominal 0° case, but the sun is now at a different relative position and its effect is shifted by the amount of time it would take to align the line of apsides of the space-fixed conic with the S-E line. The line of apsides of the conic moves with the earth's rotation about the sun at the rate of 90° each three months. This phase shift of the sinusoidal solar perturbations as a function of the dihedral angle from the perigee vector to S-E line is shown in the 15° - 135° cases of Figure 1. For example, if the injection conic were oriented in space such that the perigee vector was 90° behind the S-E line, it would take three months for the earth to rotate 90° in the ecliptic plane; the sun's effect would be shifted by three months, with the result of perturbing subsequent perigees downward causing earth impact. The amplitude of the sun's perturbing effect remains constant, $\approx$ 1300 km, such that placement of the conic's line of apsides anywhere other than on the S-E line would lower the minimum RCA (radius of close approach). Initial perigee altitude, directly dependent upon the parking orbit attitude, would therefore limit the amount which the initial perigee vector could deviate from the S-E line.

It can be seen that perigees offset 180° are again acceptable, as the line of apsides is once again aligned with the S-E line. This six-month cycle of sun-dominated perturbations allows perigees to be placed either near the incoming S-E line or 180° away near the nadir, or extension of the incoming S-E line through the center of the earth in the opposite hemisphere. Thus, a desirable initial perigee could occur near either local noon or midnight, and launch windows would become available twice daily.

Placing perigee in the MOP and exactly on the S-E line could occur only at the nodes of the two planes, the ecliptic and the MOP, thereby restricting launches to two periods yearly. However, referencing the 15° case of Figure 1, we see that minimum RCA, and consequently orbital lifetime, is not significantly reduced by small angular variations of the perigee radius. Since the MOP lies nearly in the ecliptic, having an almost constant inclination of 5.1°, each entire year is made available for launch by placing perigee closest to the S-E line yet in the MOP. This is best achieved by placing the injection conic's perigee at the vertical projection of the S-E line onto the MOP. This geometry is presented in Figure 2, with an example of the projection of the incoming S-E line at a declination of near +27°. Perigees are possible in both the upper and lower hemispheres by choosing the vertical projections of either the incoming, or its nadir, the outgoing S-E line. These perigees are comparable to the near 0° and 180° phasing of Figure 1.

Figure 2 assumes the inclination of the MOP to the equatorial plane to be 28.5°. This maximum inclination is the inclination of the MOP within .5° for the years 1967 through 1970. The inclination of the earth's equatorial plane to the ecliptic plane is a constant 23.5°, while the MOP is tilted a near constant 5.1° to the ecliptic. However, the line of nodes, which is the intersection of the MOP with the ecliptic, rotates in the ecliptic 360° every 18.6 years. This regression of the line of nodes results in a variable inclination of the MOP to the earth's equator of from 28.5° maximum to 18.5° minimum every 18.6 years. A minimum inclination of 18.5° occurs around 1976-1979.

A launch window for all projections of the S-E line onto the MOP, which in turn specifies the declination of the desired perigee throughout any year, is presented in Figure 3. Since the maximum inclination of the MOP to the equator is approximately 28.5°, all perigees constrained to lie in this plane would be limited to declinations of ± 28.5° during 1967 to 1970 and likewise to perigees between ± 18.5° during the years of minimum inclination.

Specification of launch time, launch azimuth and launch latitude results in the orientation of the geocentric parking orbit as well as the injection conic, since no powered plane changes are made. Thus, two daily launch opportunities occur when the plane specified by the launch site and launch azimuth passes through either possible perigee, itself specified by the vertical projection of the incoming S-E line or its nadir onto the MOP. Allowing all co-rotational launch azimuths of from 0° - 180° results in two 12-hour launch periods daily, or the entire 24 hours assuming no coast time in parking orbit restriction. Constraining launch azimuths to between 72° and 108° limits the window to a maximum of two 4.5-hour periods, or 9 hours daily.

Including the maximum coast in parking orbit constraint further limits the launch window. In computing the coast restriction, the total arc from launch to perigee was allowed to vary from a minimum of 33° to a maximum of 146° by the following breakdown:

	Min	Max
Burn arc from launch to parking orbit	24°	24°
Coast arc in parking orbit	0°	113°
Burn arc from parking orbit to perigee	9°	9°
TOTAL	33°	146°

The coast arc limit was derived assuming a 555.5 km (300 n. mi.) parking orbit with a resulting 5745 second period, or one 360° revolution in 95.75 minutes. Restricting coast time in orbit to 30 minutes allows a 113° arc and a direct ascent trajectory with 0° coast sets the lower limit. A schematic of the launch to injection goemetry is presented in Figure 4. Figure 5 shows the area in which perigees may be attained from KSC within the coast restriction. Figure 6 presents more specifically the range of perigee declinations between ± 28.5° that may be obtained from a Kennedy Space Center launch with a coast in parking orbit of 30 minutes or less for launch azimuths between 72 and 108 degrees.

Figures 3 and 6 show that the coast restriction within the 72° - 108° launch azimuth restriction is a limitation only at the more extreme declinations of the desired perigee. In the upper hemisphere restricted cases, the latitude of the desired perigee is so near the latitude of the launch site that perigee is passed while still burning to the parking orbit. Thus, some launch azimuths are impossible for the higher declinations of perigee, not achieving the minimum 33° arc the first pass through the perigee latitude, and after an almost complete revolution in the parking orbit, exceeding the 113° coast arc on the next pass. However, even the most restrictive case in the northern hemisphere where the desired perigee lies at +28.5° allows launch at azimuths of from 72° - 83°, resulting in a 3.3-hour window. A schematic of this case is shown in Figure 7a.

At the lower hemisphere perigees, the 33° minimum arc is always achieved, but the 146° total allowable arc begins to be exceeded for the more northerly launch azimuths after declinations of -13°. The most restrictive case at a perigee declination of -28.5° allows launch azimuths of 100° - 108° resulting in a 1.5-hour launch window. A schematic of the -28.5° case is shown in Figure 7b.

Since perigee may be chosen near either the incoming or outgoing S-E line, an almost constant 4.5-hour window is made available by choosing perigee to lie in the northern hemisphere where the coast time restriction has less effect. In Figure 3, only a small portion of the available launch window in the upper hemisphere is limited by the coast restriction. Since inclination of the MOP to the equatorial plane decreases from 28.5° to 18.5°, the coast restriction essentially disappears for years beyond 1969 because the allowable declination of perigee is more closely constrained.

No constraint has been placed on the relative inclination of the injection conic to the MOP. Should it be desirable to keep the orbits near in plane relative to the MOP, the flexibility of choosing perigee to lie in either the upper or lower hemisphere is limited. Changing perigee from the vertical projection of the incoming S-E line to its nadir changes the launch from one daily launch opportunity to the other, from one declination of perigee to its negative, and from a transit conic which is near in-plane to the MOP to more out of plane, or vice versa.

The injection-conic-MOP relative inclination reduces to a function of the KSC launch azimuth and whether perigee in the MOP is ascending or descending. Referencing Figure 2, the moon travels in the MOP from a maximum 28.5° declination south eastwardly down to a declination of -28.5°. As co-rotational easterly launches are specified within a launch-to-perigee arc of 146°, a more in-plane relative inclination of the transit conic plane to the MOP results when flying to perigees that are in the descending phase, the front half of the MOP shown in Figure 2.

Then, as the locus of projections onto the MOP ascends from declinations of -28.5° to +28.5°, the transit planes established from KSC to meet these perigees produce a more out-of-plane relationship, as they fly from the northerly KSC latitude easterly down to intersect an MOP that is inclined eastwardly up from south to north.

The incoming S-E line moves from a declination of 23.5° on June 21 each year, southeasterly down to a -23.5° declination on December 22, resulting in perigees on the MOP that move in the same direction and within $\pm$ 5° in declination. Thus, near in-plane launches occur each June 21 to December 22 for perigees near the incoming S-E line, and out-of-plane relationships are produced during this time if perigees are chosen at the nadir. From December 22 to June 21 the opposite relationship occurs. A time scale is included in Figure 3 for the years of approximately 1967-1970 when the MOP is near a maximum inclination to the equator of 28.5°. On June 22 the incoming S-E line pierces the earth at a declination of +23.5°. The vertical projection of this line intersects the MOP at a declination of +28.5°. On December 22 perigee reaches its minimum of -28.5° and begins its 6-month ascent. The inclination of the MOP to the equator during the year dictates the maximum perigee declination, or where the date of June 22 and December 22 would align with the declination scale. The maximum declination of perigee during the years 1976-79 represents a period when the MOP inclination is near its minimum. At this time on June 22, the vertical projection of the +23.5° incoming S-E line would result in perigee at +18.5° and the entire year would be scaled uniformly between the ± 18.5° declinations. The coast time constraint becomes less restrictive as the MOP inclination decreases.

Considering a time period of 1967-1970, the optimum launch window containing a maximum 4.5-hour window and near in-plane orbits would occur during the nearly 3¼ months when the declinations of the incoming S-E line projected onto the MOP descend from +18° to -13° or approximately August through early November. Thereafter, a trade-off would occur between shortening the in-plane launch window due to the coast time restriction or increasing the relative inclination of the orbits to the MOP by choosing perigee to be at the nadir, or upper hemisphere.

B. SUMMARY

The launch azimuth constraint of azimuths between 72° and 108° most severely limits the 1/8-class orbits. This constraint in itself limits the launch window to two periods daily of 4½ hours each. The coast time restriction of 30 minutes reduces the window further for orbits with perigees below -13° and above 18° in declination. If a near in-plane relative inclination of the conic to the MOP is maintained, only one launch window per day is available and perigee is constrained to be near the incoming S-E line from June 22 to December 22 and near the nadir from December to June.

Alternatives are available if needed to extend the launch window:

1. Plane changes could be made, since the 1/8-class orbit is relatively low and performance is high.

2. Sufficient orbital lifetime could be maintained with larger variations of perigee from the S-E line than that produced by the vertical projection of the S-E line onto the MOP. At the more extreme declinations, where coast is a window limitation, perigee could be placed further from the S-E line at a more median declination. An angular limit of perigee from the S-E line could be established such that sufficient orbital lifetime is preserved.

3. Parking orbit altitude could be raised, in effect, extending the angular limit that perigee could deviate from the S-E line.

III. ONE-HALF CLASS ARENSTORF ORBITS

This section of the study defines acceptable launch times and acceptable ascent trajectories to a parking orbit from which it is possible to inject into an Arenstorf-type orbit which is periodic with respect to the moon and the earth. The parking orbit is a 575 n. mi.

(1065 km) circular orbit which is reached by the method of direct ascent using the iterative guidance mode (Reference 1). The vehicle used for this study is the Saturn IB/Centaur. The time period considered is December 1967 to June 1968, and for this study the earth-moon plane is assumed to have an equatorial inclination of 28.3°, which is approximately 0.25° less than the latitude of the launch site. Therefore, a small plane change must be made even on the optimum launch time in order to get into the earth-moon plane. The Arenstorf orbit considered has a period of ½ month and encounters the moon once every month or at every other apogee passage. The Arenstorf orbit is defined by the C_3 which is -1.5427107 km^2/sec^2 and has an initial perigee of 1065 km.

A. THE ASCENT TRAJECTORY

Constructing the ascent trajectory consisted of solving a performance-optimization problem. The trajectory shaping philosophy used in this study is identical to that used for standard Saturn IB flights. The booster tilt program was shaped by an initial pitch-over maneuver which resulted in an in-plane zero angle-of-attack flight for the booster. The attitude programs for the second and third stage flights were generated by the Iterative Guidance Mode (IGM) which is being used on current flights of the Saturn vehicles. This program accomplished the necessary plane changes to put the vehicle into the required space-fixed circular parking orbit. The optimum propellant loading in the S-IB and the Centaur is the maximum loading, but the optimum propellant loading in the S-IVB stage is 190,000 lbs, an off-load of 40,000 lbs. Mixture ratio shift was used in the S-IVB stage, and the optimum shift point was found to be the point where 65 per cent of the S-IVB propellant had been consumed at high thrust (a mixture ratio of 5.4) and where the remaining 35 per cent of the S-IVB propellant was consumed at low thrust (a mixture ratio of 4.6). One final parameter was the launch azimuth. For the optimum launch time, the optimum launch azimuth is 90°. For early launches, that is, before the optimum launch time, the optimum launch azimuths were still 90°. For late launches, that is, launches after the optimum launch time, the optimum launch azimuths were greater than 90°. Launch azimuth as a function of launch time is shown in Figure 8.

B. THE LAUNCH WINDOW GEOMETRY

The earth-moon plane for a short period of time can be considered a space-fixed plane which can be defined by its equatorial inclination and its descending equatorial node. The equatorial inclination of this plane varies between 18.5° and 28.5° over a period of about 18.6 years. During the time period considered in this study, December 1967 - June 1968, the inclination varies between 28.0° and 28.5°. For this particular study, an equatorial inclination of 28.3° has been chosen for the trajectory calculations.

The launch window problem consists of injecting a vehicle into an orbit which lies in this plane and which will pass near the moon. An even more difficult problem is getting a periodic orbit, an orbit in which the vehicle will periodically pass near the earth and the moon. These periodic orbits are Arenstorf orbits and are the particular orbits for which this launch window is designed.

The launch window is done in two phases. The first phase is the ascent trajectory which takes the vehicle from the launch site to a parking orbit which, in this study, lies in the earth-moon plane. The second phase of the launch window is leaving the parking orbit and injecting into the Arenstorf orbit. With the first phase is associated the concept of a daily launch window, and with the second phase is associated the concept of a monthly launch window or the injection window.

The daily launch window will be discussed first. The latitude of the launch site (Cape Kennedy) is approximately 28.53° and a vehicle launched from this site on a 90° azimuth with no plane change will have an equatorial inclination of approximately 28.53°. (A launch on any other azimuth will result in a greater inclination.) The earth rotates while the motion of the earth-moon plane is negligible, so at one instant during each day there will be a minimum inclination between the orbital plane resulting from a 90° launch and the earth-moon plane. This instant is the optimum launch time. In this particular case the inclination of the earth-moon plane is 28.3°, so that the minimum inclination between the orbit plane and the earth-moon plane is about 0.25°. To get into the earth-moon plane, a 0.25° plane change must be made during the ascent at the optimum launch time. At any other time, the inclination between the two planes will be greater than at the optimum time. (The maximum inclination will occur 12 hours later and will be approximately 57°.) For times on either side of the optimum launch time, the required plane change will increase directly as the time from the optimum launch time increases. A launch window is then a period of time on either side of the optimum launch time during which launch can occur without requiring too large a plane change to get into the space-fixed plane. In this study a daily launch window of two hours width, one hour on either side of the optimum launch time, can be achieved with a spacecraft weight of 3800 lbs. This information is shown graphically in Figure 9. Figure 10 shows the earth, the earth-moon plane and the launch site. Point L_2 represents the optimum launch time, the time when the launch site is closest to the earth-moon plane. Point L_1 represents the launch site one hour before the optimum launch time, and point L_3 represents the launch site one hour after the optimum launch time. This figure shows the movement of the launch site relative to the earth-moon plane. Points 0_1, 0_2 and 0_3 represent the parking orbit injection points resulting from launching at L_1, L_2 and L_3, respectively. Since launch can occur any time when the launch site is between L_1 and L_3, the orbital injection point can lie anywhere between 0_1 and 0_3.

The monthly launch window (also referred to as the injection window) arises from the lifetime restriction on the Centaur. Reference to Figure 11 will facilitate the explanation of the monthly launch window. This figure is a schematic diagram showing the earth, the parking orbit, and the lunar orbit, all of which lie in the earth-moon plane so that all maneuvers can be made without any plane change.

The arc between 0_1 and 0_3 represents possible orbital injection points, 0_1 representing the injection point for the earliest possible daily launch and 0_3 representing the injection point for the latest possible daily launch. These two points will remain fixed regardless of other variations, such as the moon's position about the earth. Point B is a typical projection of the earth-moon line, a line between the center of the moon and the center of the earth, onto the parking orbit. B is defined to always lie on the opposite side of the earth from the moon. The arc from 0_1 to C is the coasting arc. The orbital coast time cannot exceed 30 minutes; therefore, for the 575 n. mi. circular orbit, the arc 0_1 C cannot exceed 101.5°. Point C is the second ignition point for the Centaur and CE is the burn arc which, for this parking orbit and given energy level of the Arenstorf orbit, is about 10°. Point E is the lunar injection point. The perigee of the Arenstorf orbit, Point D, is roughly midway between C and E.

At launch, conditions are as shown in Figure 11. The earth-moon line is at B and the moon is at M_2. Since the perigee of the Arenstorf orbit is at point D, the apogee will be at point M_3. The Arenstorf orbit considered has a period of ½ lunar month. Thus, ¼ lunar month after launch the spacecraft will be at M_3. During that interval of time, the moon will also have moved from M_2 to M_3. One-half lunar month later, the spacecraft will be back at M_3 and the moon will be at M_1; thus, the spacecraft will approach the moon closely only at every other apogee passage, or once each month. The trajectories which pass near the moon in the first apogee passage are referred to as closed loop trajectories (Reference 2).

It should be noted that in order to synchronize the period of the Arenstorf orbit with the period of the moon it was necessary to require that at lunar injection the angle between the earth-moon line, point B, and the perigee of the Arenstorf orbit, point D, be roughly 90° measured counterclockwise from B to D. (The exact value varies from day to day.) This particular case illustrated here also included the maximum orbital coast, the arc 0_1 C. If the case of no orbital coast is considered, that is, if ignition occurs at the orbital injection point, then the perigee point D moves back on the orbit 101.5°. To maintain the same relative angle between B and D, point B must move backward on the orbit by 101.5°; this has the effect of moving the moon from M_2 back roughly to the point M_1. Since the coast can vary any desired amount from 0 to 30 minutes, then the moon may be anywhere on the arc between M_1 and M_2. In fact, this arc may be 101.5° which is approximately 28 per cent of a lunar month or approximately 7.6 days.

Another possibility for increasing the monthly launch window which has not yet been considered is to sychronize the period of the Arenstorf orbit with the moon's orbit such that at the spacecraft's first apogee passage the moon will be 180° away and at the spacecraft's second apogee passage there will be a close approach to the moon. This type trajectory is referred to as an open loop trajectory. For this possibility there would be a close approach to the moon on each even apogee passage, whereas on the cases discussed previously there would be a close approach to the moon on each odd apogee passage.

The geometry of this particular possibility is shown in Figure 12 for the 30-minute orbital coast. The moon is at M_4 at launch and will be at M_1 when the spacecraft is at M_3. The second time the spacecraft gets to M_3 the moon will be there. In this case, the required angle between B' and D measured counterclockwise from B' to D is approximately 270°. For the zero orbital coast possibility, the perigee point D would be moved backward on the parking orbit by 101.5°, and the moon would correspondingly be moved backward in its orbit by 101.5°. Consequently, for this particular type of orbit synchronization, launch can occur at any time when the moon is roughly between M_3 and M_4 or approximately 7.6 days each lunar month. By including the possibility of using both open loop and closed loop trajectories, the monthly launch window can be doubled to give about 15 days out of the month during which launch can occur. In summary, launch can occur when the moon is between M_1 and M_2 or between M_3 and M_4.

A most useful and directly applicable representation of the information shown schematically in Figures 11 and 12 is a plot of the latitude of the perigee points resulting from igniting immediately after injection into the parking orbit (Figure 13) or after 30 minutes of parking orbit coast time from points 0_1 and 0_3 (Figure 14).

The launch windows can be obtained by imposing the information shown in Figures 13 and 14 on a plot of the declination of the required value of the perigee point D as a function of time. (The phase of the declination of the required value of D is approximately 90° behind the declination of the moon for lunar encounter at first apogee passage and approximately 90° ahead of the declination of the moon for lunar encounter at the second apogee passage.) Figure 15 shows the declination of the required value of D as a function of time for December 1967 and May 1968 for lunar encounter at the first apogee passage with the information in Figures 13 and 14 imposed. Points D and D' represent the perigee points resulting from ignition at the earliest and latest orbital injection points, respectively, and D'' and D''' represent the perigee points resulting from ignition after 30 minutes of orbital coast time from the earliest and latest injection points, respectively. Figure 16, analogous to Figure 15 but drawn 180° out of phase to it, gives information relating to which launch can occur in order to have a close approach to the moon on the second apogee passage and succeeding even apogee passages.

On Figure 15 the projection of points D and D''' onto the horizontal scale gives the interval when launch can occur for a close approach to the moon on the first apogee passage and each odd apogee passage thereafter. Likewise, in Figure 16, the projection of points D and D''' onto the horizontal scale gives similar information relating to even apogee passages. However, as it shall now be seen, some of the restrictions which must be satisfied will narrow this launch window.

When the required perigee lies between the points D and D' on Figure 15, the requirement of a daily launch window of 2 hours cannot be satisfied. For instance, the day of the month which requires that the perigee be at D (on Figure 15) would have only one instant at which launch could occur. That instant would be the earliest possible moment in the 2-hour launch window. As the required perigee point moves from D to D', the daily launch window gradually widens from one instant to 2 hours. Thus, only on the days after the required perigee point gets to or past D' will the daily launch window be widened to 2 hours.

Similarly, the orbit coast time restriction of 30 minutes will eliminate the region between D'' and D'''. If the spacecraft is injected into the parking at the earliest possible launch time, immediate ignition results in placing the perigee at D. If, instead of immediate ignition, a coast time of 30 minutes is used, the perigee will be at D''. The days which require a perigee past D'' will require more than 30 minutes of orbital coast for the earliest launch time.

To summarize, the requirement of a 2-hour daily launch window excludes the region from D to D', and the restriction of 30 minutes orbital coast time excludes the region from D'' to D'''. Thus, the launch window is narrowed from the region between D and D''' to the region between D' and D'' by these two requirements.

One other constraint which has not been mentioned to this point, but which must be satisfied, is one relating to the stability of the orbit. This constraint is that the initial perigee of the Arenstorf orbit must lie on or within a few degrees of the earth-sun line (this means that the perigee must occur near local noon or local midnight). This restriction cannot widen the launch windows shown thus far, but will narrow them. Figures 17 and 18 give the dates in December 1967 and May 1968 when stable orbits may be achieved as well as the expected lifetime of the orbits [2].

Figure 19 shows plots of the declination of the required perigee points for closed loop and open loop trajectories for December 1967. The points D' and D'', shown previously in Figures 15 and 16, are shown on this plot. These represent the range of perigee points which may be realized with the defined launch vehicle. Also shown and denoted by X and X' are the required perigee points of the trajectories shown in

Figure 17 which represent stable orbits. The projection of D' and D" onto the horizontal axis represents the launch days which are possible after satisfying all launch vehicle constraints. The projection of points X and X' onto the horizontal axis represents days on which stable orbits can be achieved with a lifetime greater than 90 days. Only where these two areas overlap are all requirements and restrictions satisfied. Figure 19 shows that there are only about 2 days (December 4 and 5) on which launch can occur for the closed loop trajectories and there are no days on which launch can occur for the open loop trajectories. Figure 20 gives the same information as described in Figure 19, but is for May 1968. Launch dates for open loop trajectories occur on May 1 and May 2 and again on May 30. Launch dates for closed loop trajectories are May 15 and May 16.

December 4 and 5, on which a closed loop trajectory is possible after satisfying all constraints, are days which give a lifetime of only 90 days (see Figure 17). The injection windows on May 1, 2, and 30 give a whole year lifetime. Those on May 15 and 16 again give only a 90-day lifetime. Thus, in this period considered (December 1967 - May 1968), we find only 3 days on which all constraints are satisfied and which yield a year's expected lifetime. The injection window for the Arenstorf orbits is seen to be very narrow for the existing Centaur vehicle. If the Centaur's lifetime could be extended only about 15 minutes, that would have the effect of moving D" in Figures 19 and 20 further along the curve such that the whole area of orbit stability could be encompassed and the launch window would be opened up considerably.

Another possibility for increasing the injection window is by not requiring a two-hour daily launch window. If, for instance, only a one-hour daily launch window were required and that time could be taken from the optimum launch time to one hour after the optimum launch time, D" could be moved from its present position to a position approximately half way between its present position and the position of D'". This would add about one day to the injection windows shown in Figures 19 and 20.

Another possibility is to lower the perigee altitude of the Arenstorf orbit; this in turn implies lowering the parking orbit. With a lower parking orbit, the defined vehicle should have sufficient performance capability to enable the placement of the daily launch window in a nonoptimum place, namely, one to three hours after the optimum launch time such that the injection points occur closer to the area of stability. From those injection points, 30 minutes of orbital coast time will encompass the area of stability, thus increasing the injection window. Intuitively, one would suspect that lowering the perigee altitude of the Arenstorf orbits would narrow the region of stability; this is indeed the case, but fortunately the region of stability is not narrowed nearly so much as one might suspect. Figure 21 gives the region of stability for May 1968 for an Arenstorf orbit which has a perigee of only 200 km.

Comparing this figure to Figure 18, which has a perigee altitude of 1065 km, shows that each injection window loses only about two days, one day on each end of the window. Figure 22 shows a plot of the required perigee latitudes of the trajectories referred to in Figure 21 with the region of stability indicated between X and X' as before. The area accessible to the vehicle is that between D' and D". The overlapping area is the injection window. There are two time periods in May-June 1968 during which stable open loop trajectories are possible. The vehicle can now reach all of the days during the first time period and all but about 1/2 day of the last time period.

Similarly for the closed loop trajectories, all but about 1/2 day of the injection window period is accessible to the launch vehicle. Thus, lowering the parking orbit altitude has increased the injection window. Figures 21 and 22 reveal about 10 days which give a year's expected lifetime. This compares with 3 days on which orbit can be achieved with a year's expected lifetime for the higher altitude parking orbit.

C. SUMMARY

A spacecraft in an Arenstorf orbit periodically passes near the earth and the moon and consequently receives large perturbations from the moon. As a result of these perturbations, the perigee oscillates. To have a long lifetime (to prevent the perigee from dipping into the atmosphere too soon), it is desirable to have the initial perigee as high as possible. The upper limit on the altitude of the initial perigee is determined by the performance characteristics of the launch vehicle. The upper limit was determined to be 575 n. mi. (1065 km) for a payload of the order of 4,000 lbs. The Arenstorf orbit is required to lie in the plane of the moon's orbit about the earth; this is reached by going through a circular parking orbit which itself lies in the MOP and which has an altitude equal to the altitude of the perigee of the Arenstorf orbit. In the time period considered (December 1967 - June 1968), the MOP has an inclination approximately equal to the latitude of the launch site such that it is possible to get into the MOP from the launch site with only a small plane change for a 2-hour daily launch window. The required values of the declination of the perigees of the Arenstorf orbits for this time period are extremely negative, and as a result large coast times in the parking orbit are required to reach them, coast times very near the maximum coast time capability of the Centaur which is 30 minutes. These considerations result in severely limited launch windows. There are no days in December and only three days in May which give a year's expected lifetime. A tradeoff study revealed that it is possible to lower the perigee of the Arenstorf orbit to 200 km, thus increasing vehicle performance capability, and increasing the launch windows. This was done for May only and in that month the launch window was increased to 10 days which give a year's expected lifetime.

TABLE I

CONTROL WEIGHTS FOR S-IB/S-IVB/CENTAUR

S-IB Stage	111,656 lbs.
S-IVB Prop.	880,514 lbs.
S-IVB Stage	30,740 lbs.
Shroud	5,600 lbs.
S-IVB Prop.	190,000 lbs.
CENTAUR	5,950 lbs.
Centaur Prop.	30,000 lbs.
Payload	Varied
TOTAL	1,254,460 + Payload

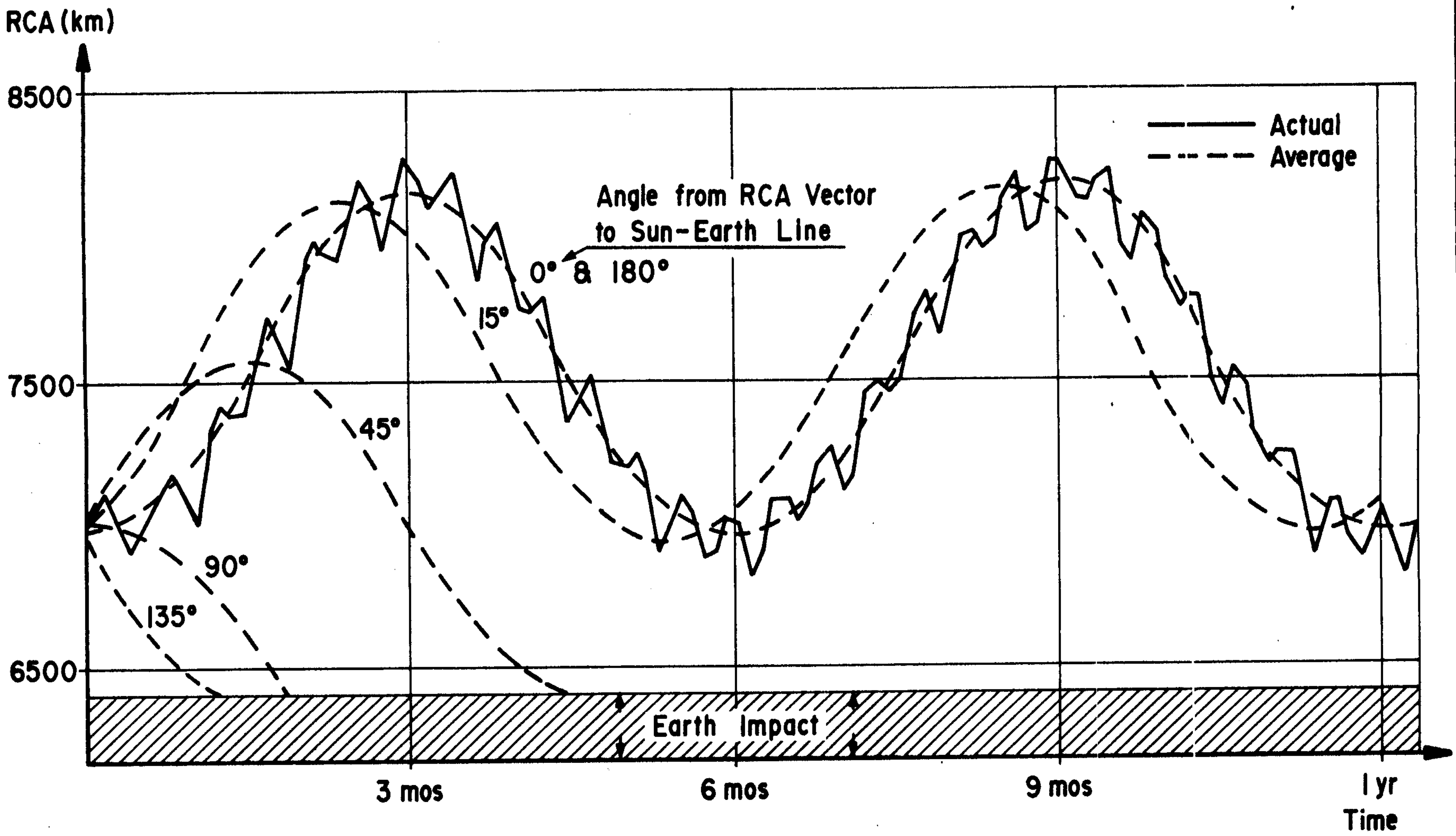


FIG. 1. RCA AS A FUNCTION OF ANGULAR DISTANCE OF INJECTION CONIC LINE OF APSIDES TO SUN-EARTH LINE

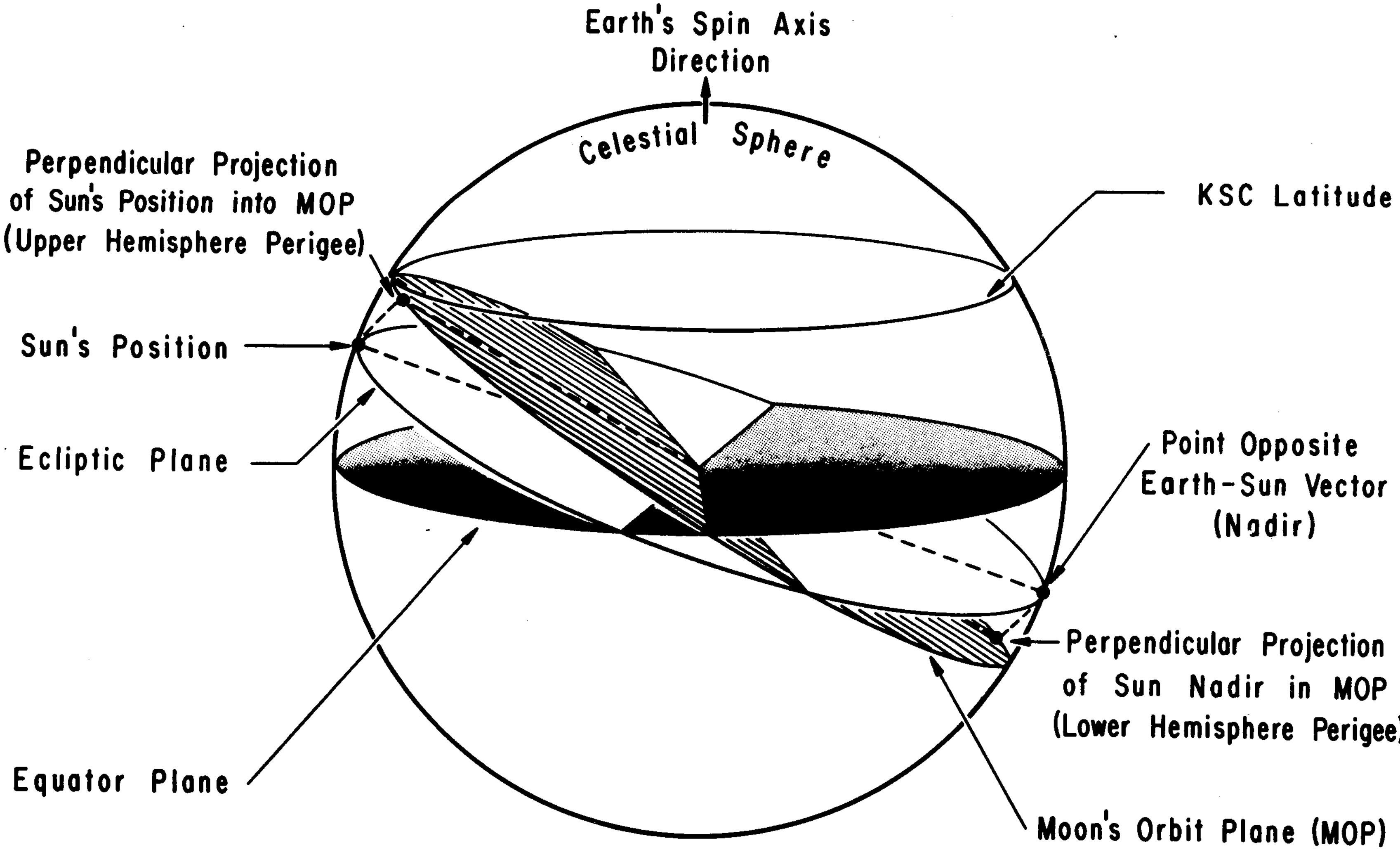
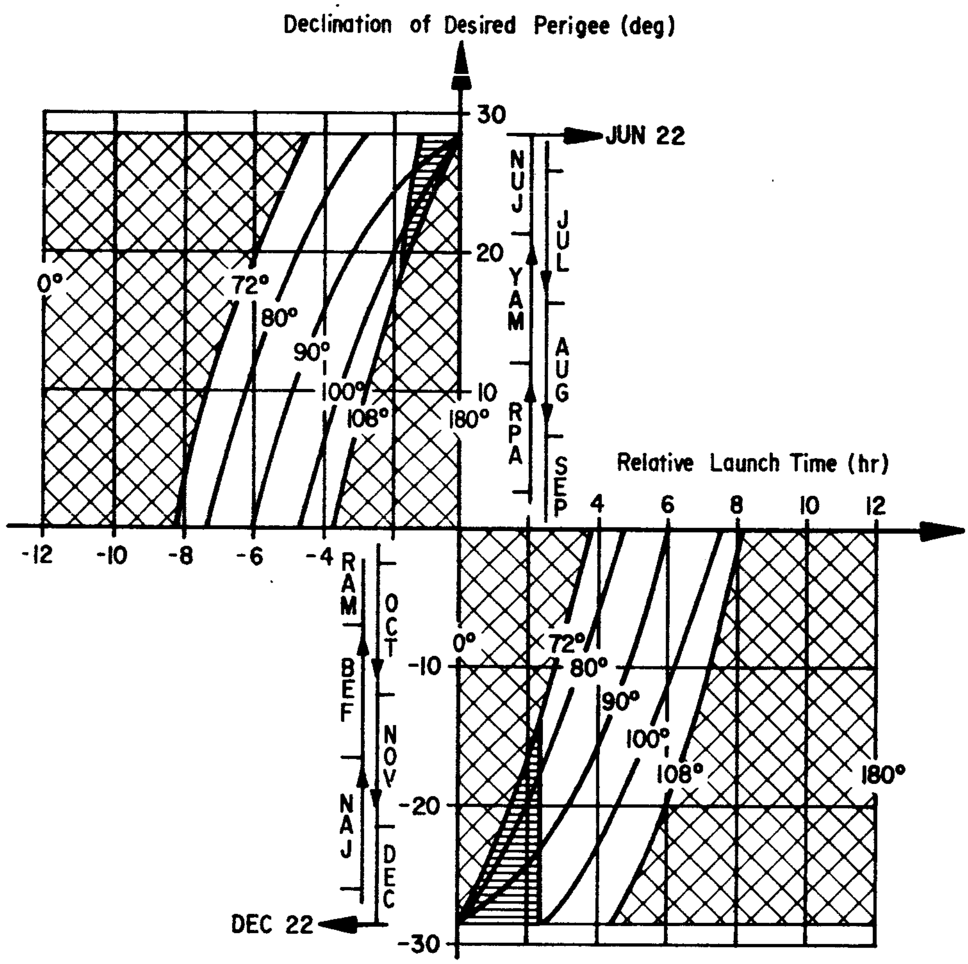


FIG. 2 SCHEMATIC OF PERPENDICULAR PROJECTIONS OF THE SUN'S POSITION (AND ITS NADIR) INTO THE MOON'S ORBIT PLANE AS ACCEPTABLE PERIGEE LOCATIONS

Perigee Placed at the Vertical Projection of the Sun-Earth Line Onto the Moon's Orbit Plane



Reference Time Chosen Midway Between Due East Launch Opportunities

Azimuth Restriction 72°–108°

Coast Restriction ≤30 min

Descending Perigee Represents Near In-Plane Launch
Ascending Perigee Represents Out-Plane Launch

Date Scale for Period of Near Maximum Inclination of MOP to EQ (1967–1970)

FIG. 3 LAUNCH WINDOW FOR 1/8 CLASS ORBIT

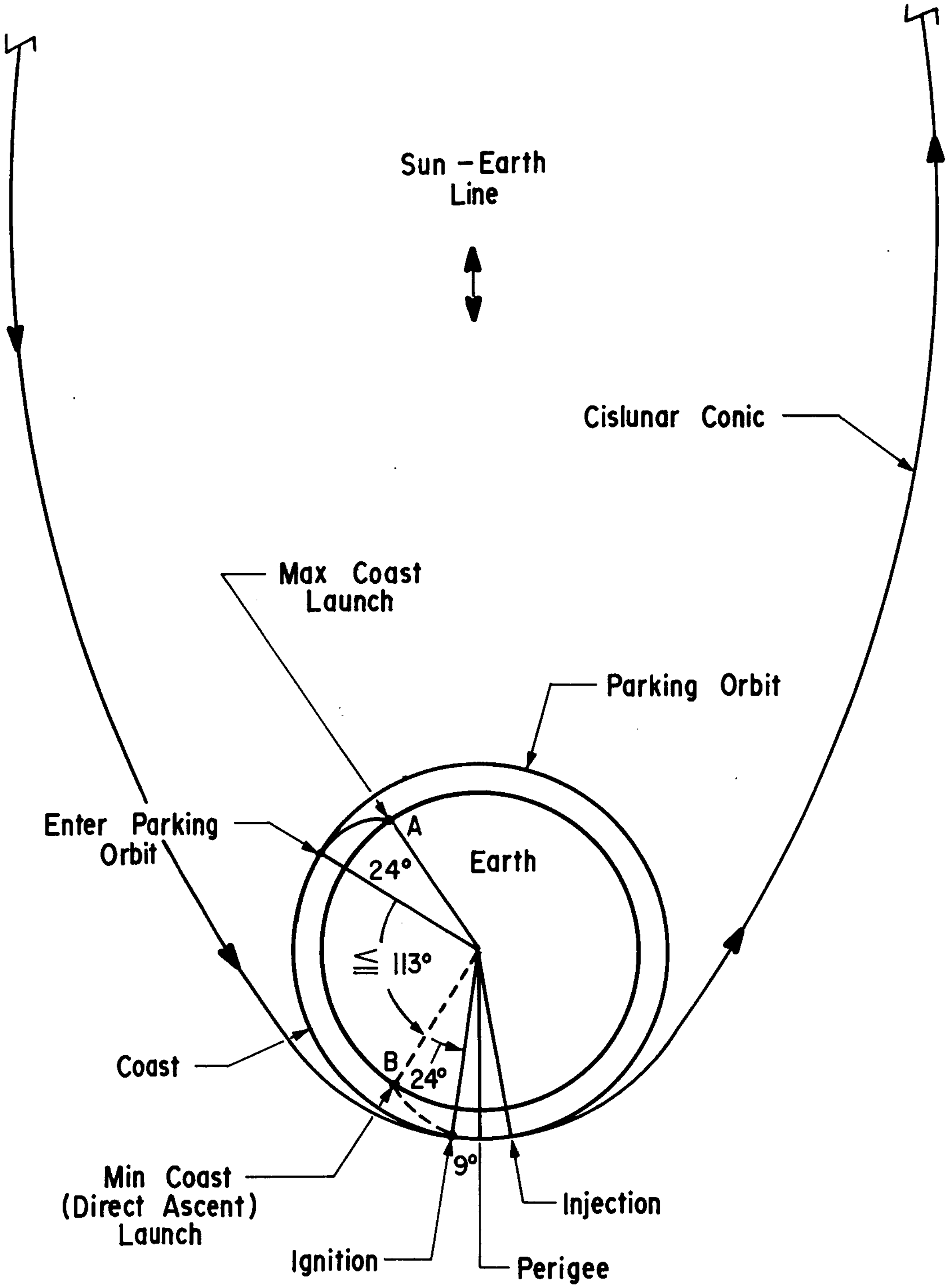


FIG. 4 LAUNCH TO INJECTION SCHEMATIC 1/8 CLASS ORBIT

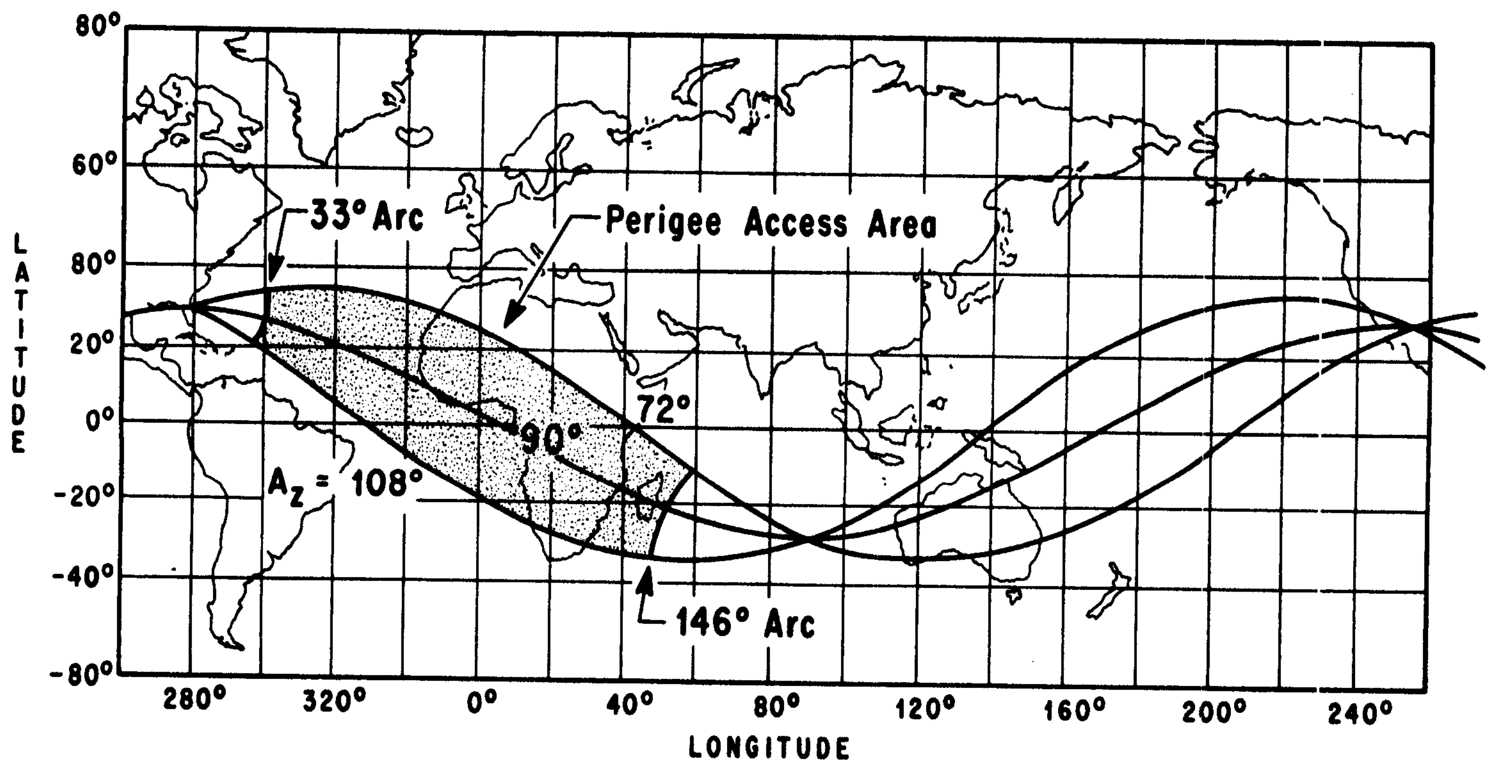


FIG. 5 PERIGEE ACCESS AREA

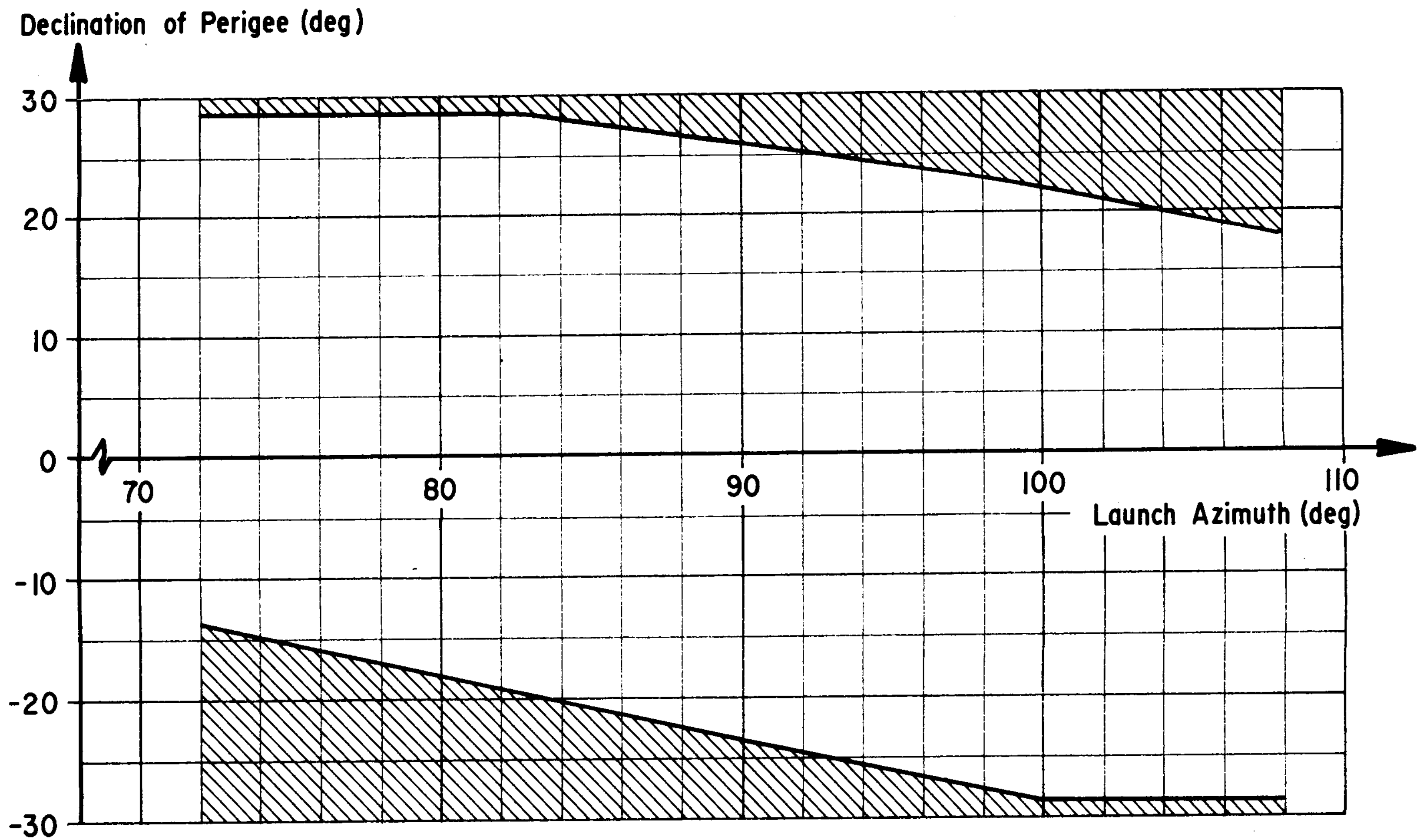


FIG. 6 RANGE OF PERIGEE DECLINATION THAT MAY BE ATTAINED FROM KSC ASSUMING A SATURN IB/CENTAUR COAST TIME RESTRICTION OF 30 MINUTES OR LESS

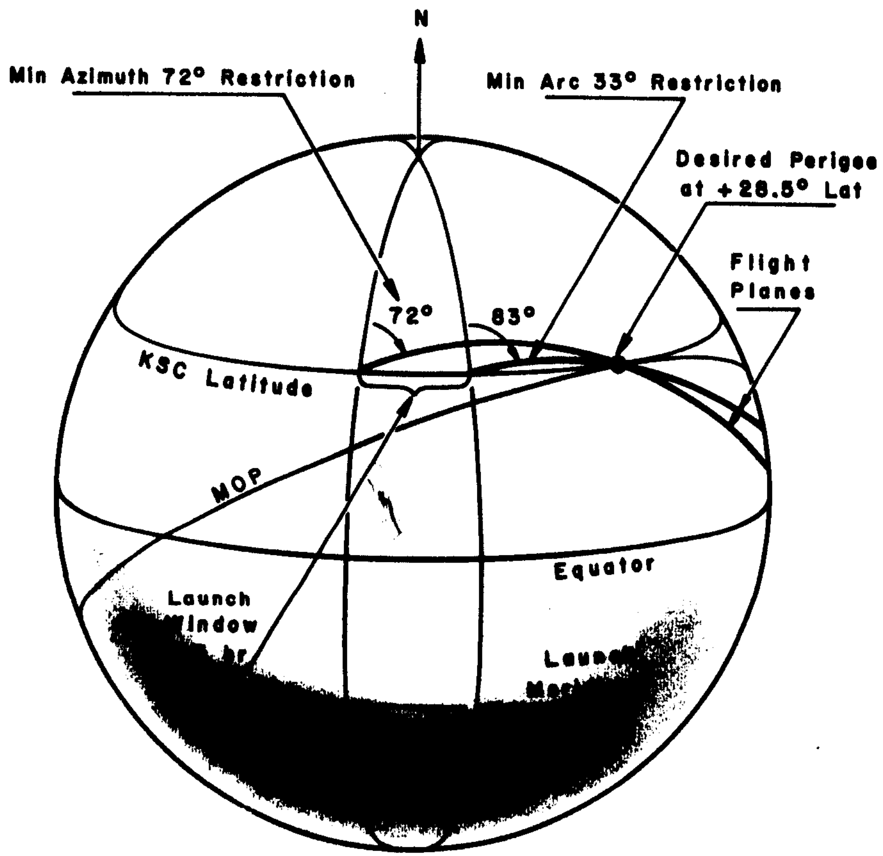


FIG. 7a LAUNCH WINDOW FOR PERIGEE AT +28.5°

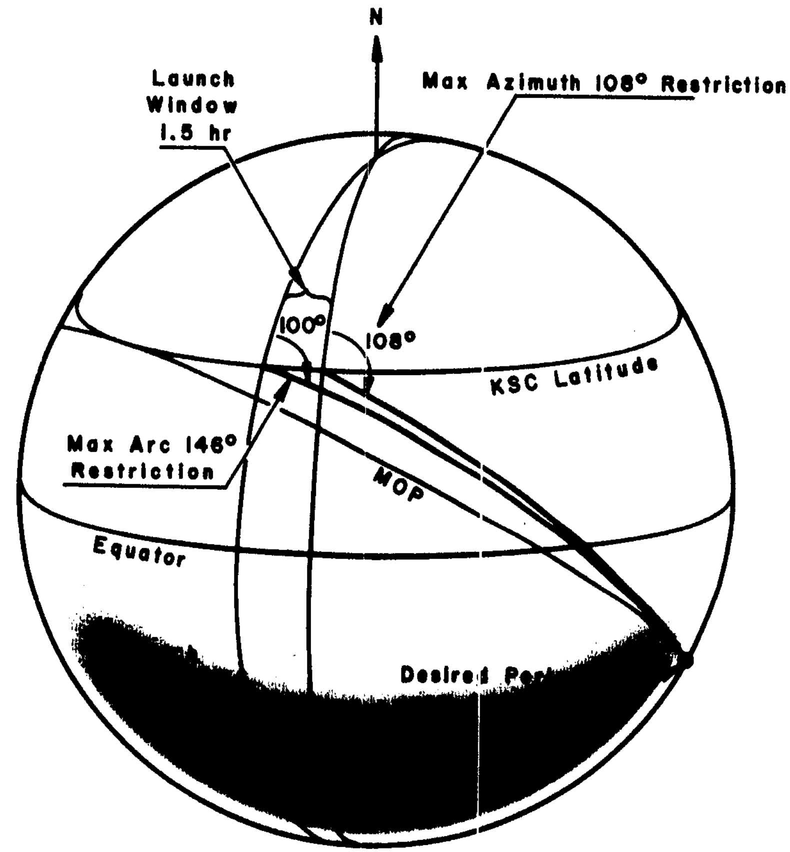


FIG. 7b LAUNCH WINDOW FOR PERIGEE AT -28.5°

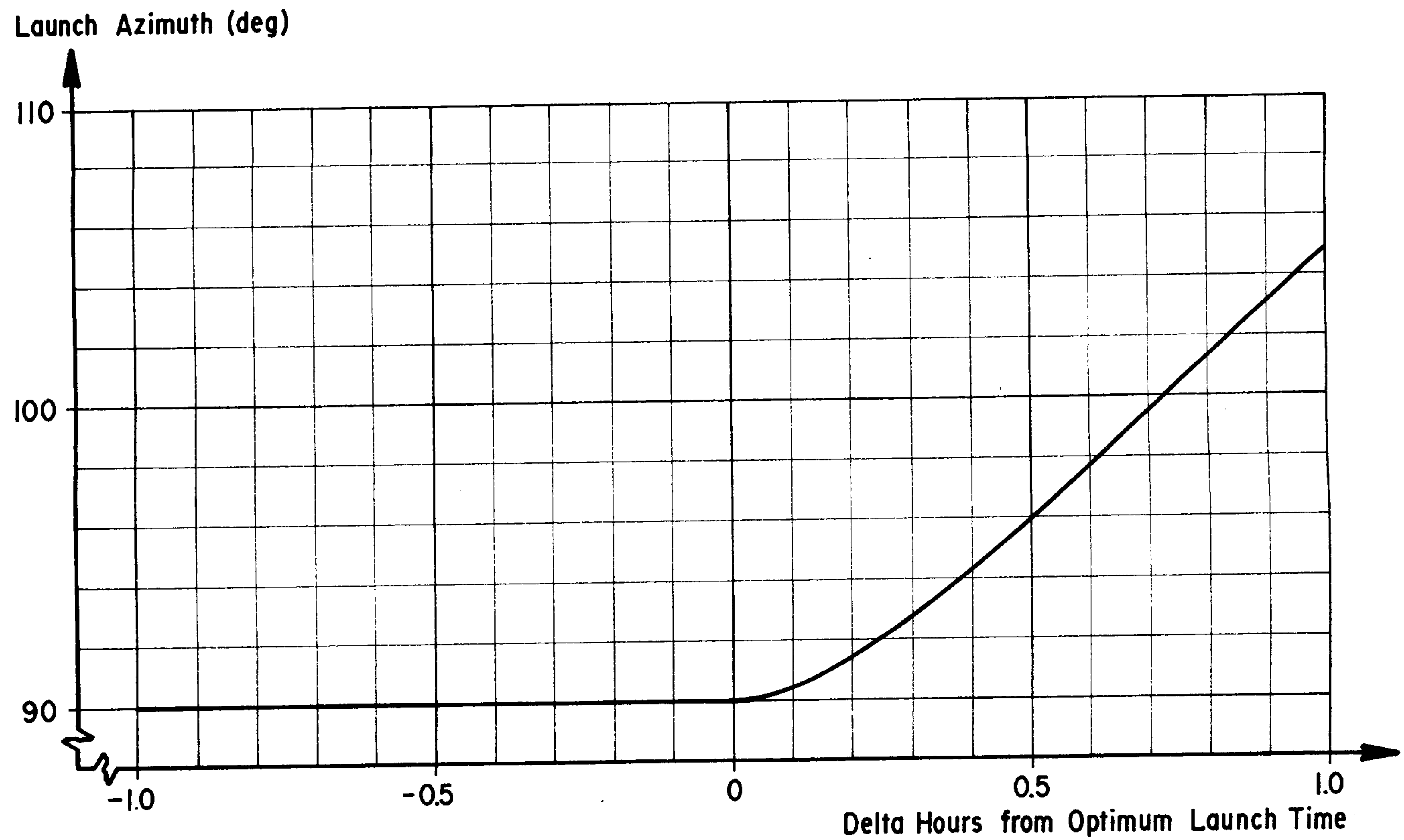


FIG. 8 OPTIMUM LAUNCH AZIMUTH AS A FUNCTION OF LAUNCH TIME FOR A TWO HOUR LAUNCH WINDOW FOR THE 1/2 CLASS ORBIT

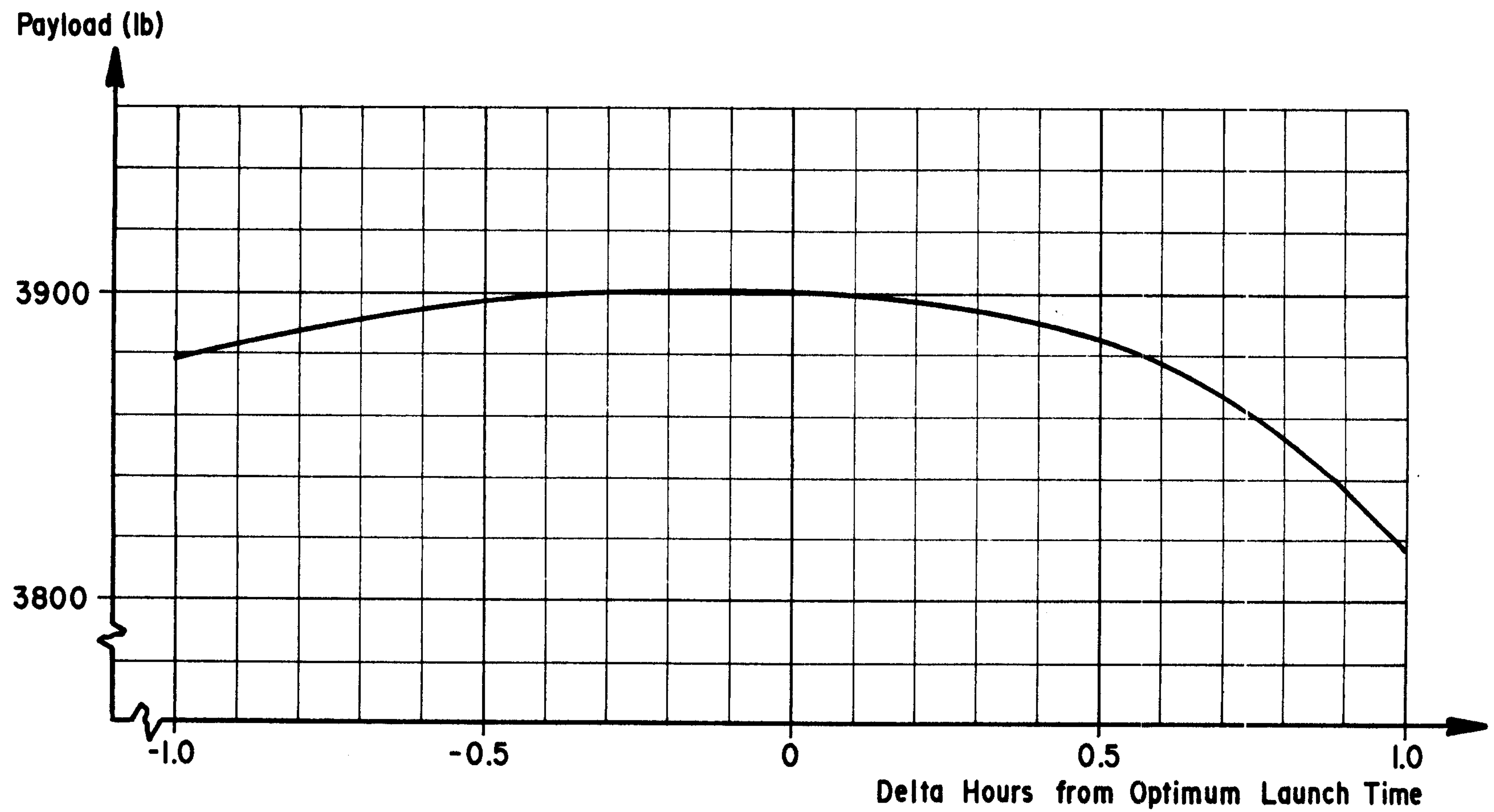
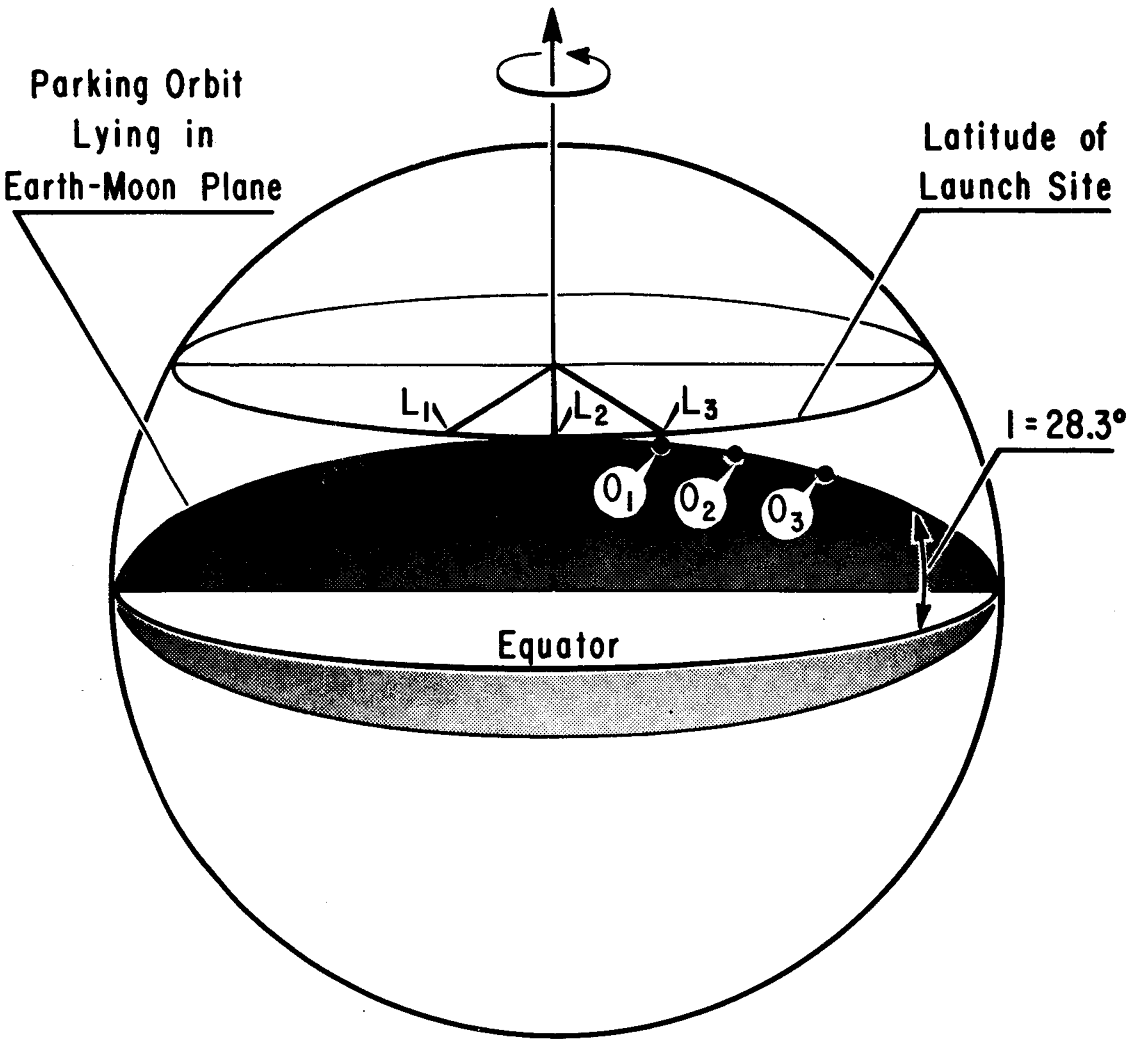


FIG. 9 PAYLOAD AS A FUNCTION OF DELTA LAUNCH TIME FOR A TWO HOUR LAUNCH WINDOW FOR THE 1/2 CLASS ORBIT FROM A 575 N M CIRCULAR PARKING ORBIT



L_1: Launch Site 1hr Prior to Optimum Launch Time
L_2: Launch Site at Optimum Launch Time
L_3: Launch Site 1hr After Optimum Launch Time

O_1: Orbital Injection Point Resulting from Launching at L_1
O_2: Orbital Injection Point Resulting from Launching at L_2
O_3: Orbital Injection Point Resulting from Launching at L_3

FIG. 10 THE LAUNCH SITE
RELATIVE TO THE EARTH-MOON PLANE
AT VARIOUS LAUNCH TIMES

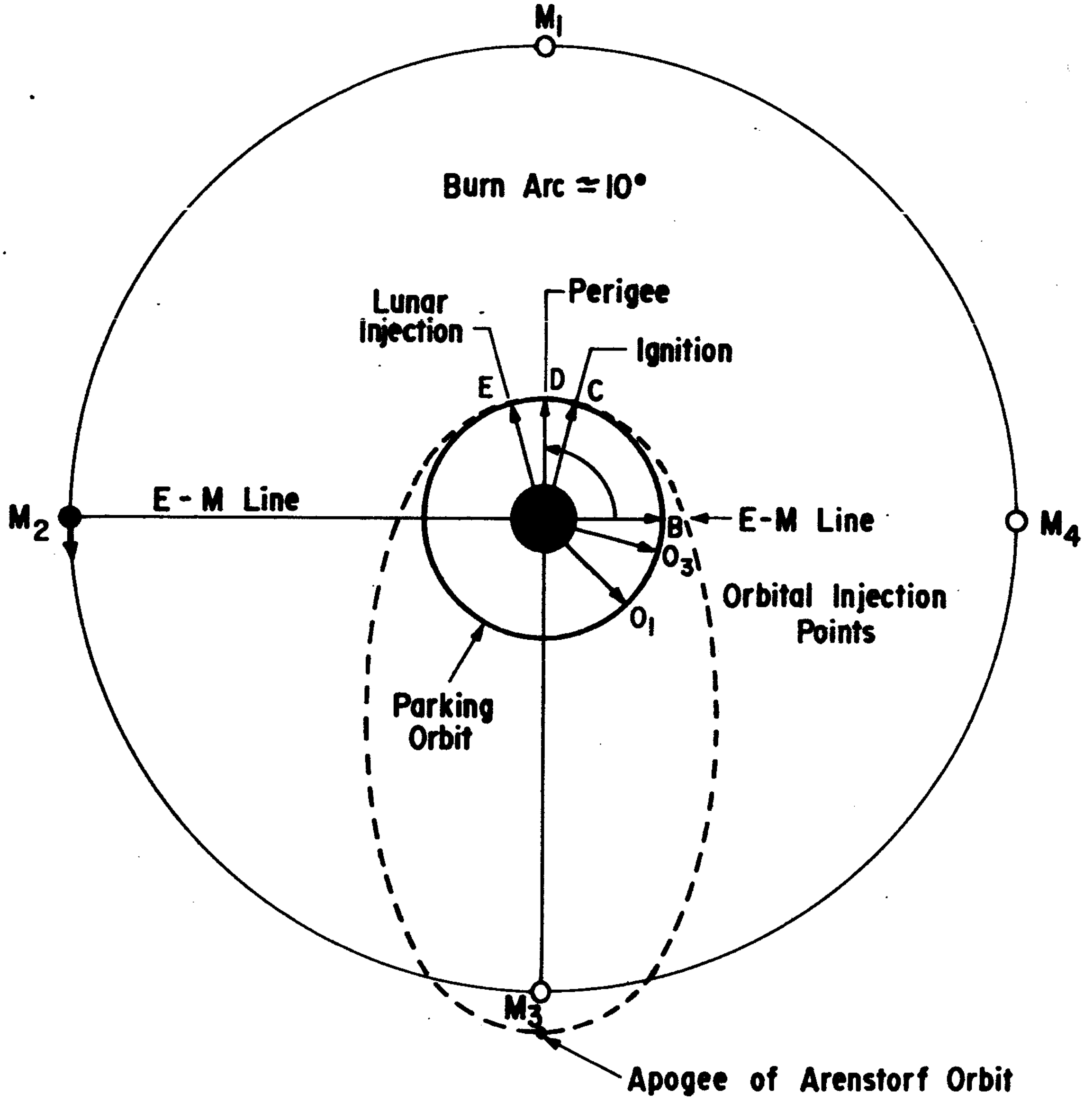


FIG. 11 POSITION OF THE MOON RELATIVE TO THE EARTH AT LAUNCH FOR CLOSED LOOP TRAJECTORIES

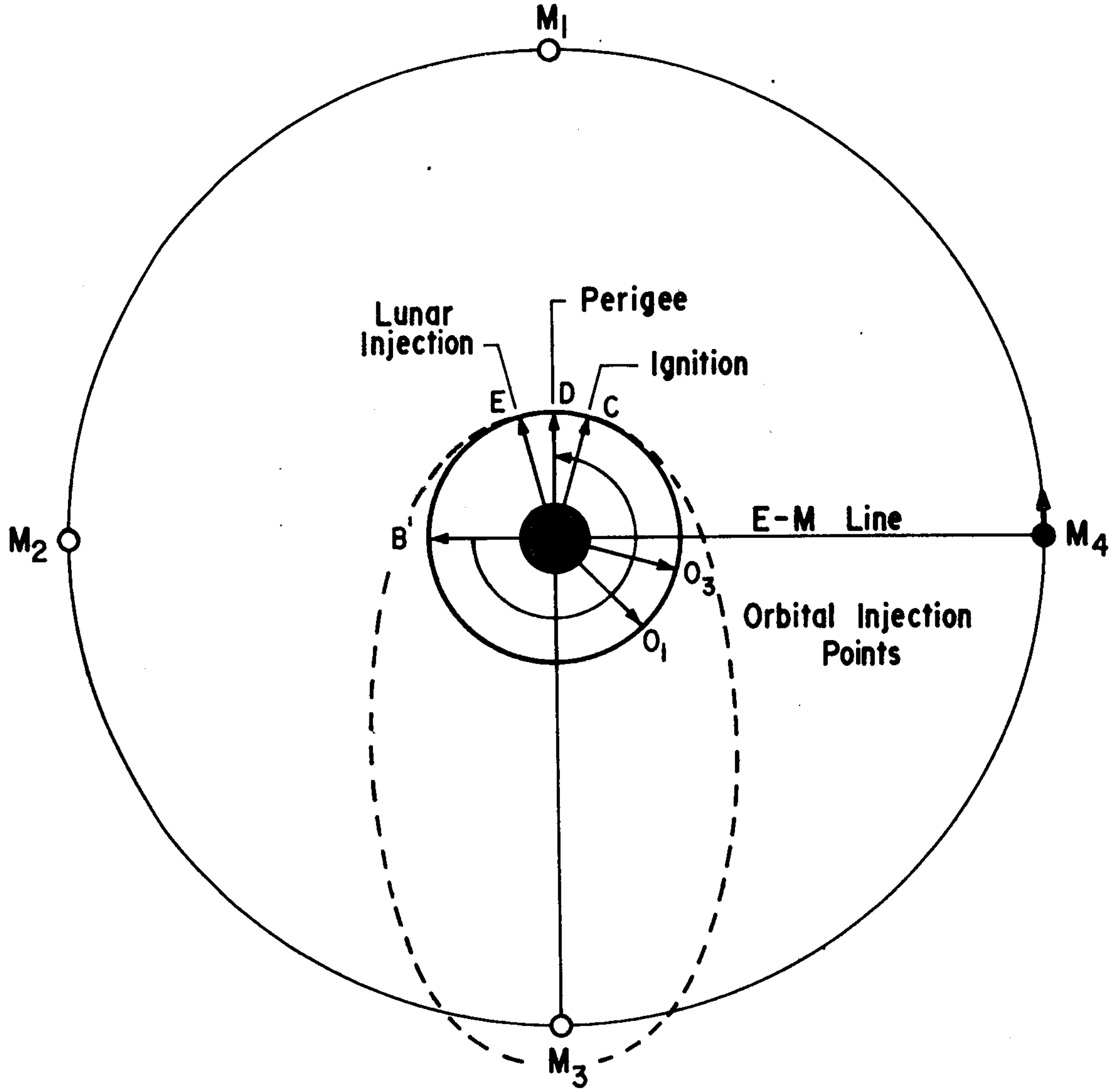


FIG. 12 POSITION OF THE MOON RELATIVE TO THE EARTH AT LAUNCH FOR OPEN LOOP TRAJECTORIES

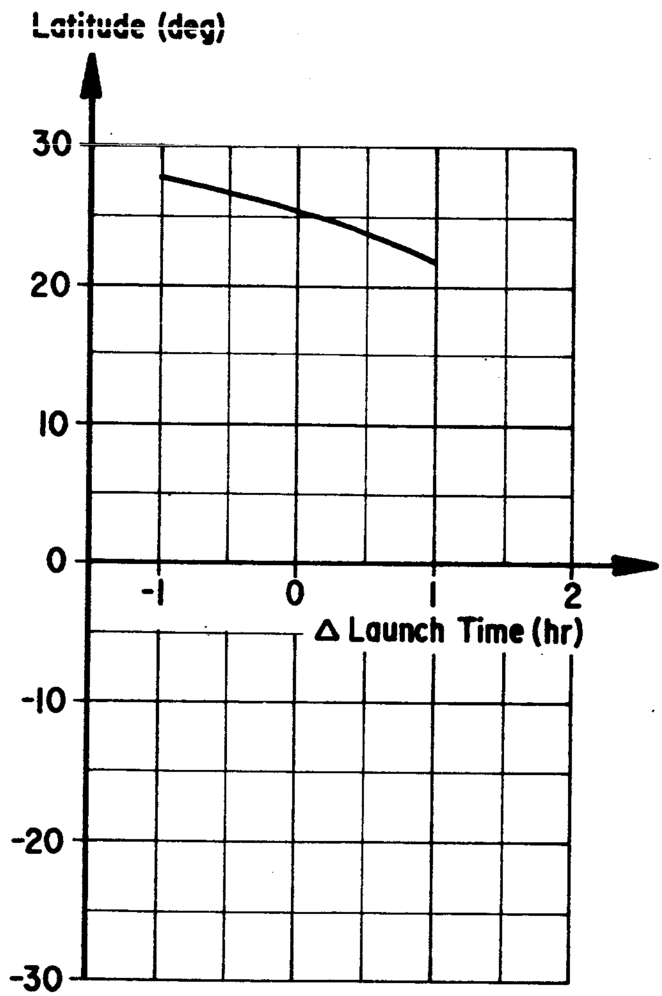


FIG. 13 LATITUDE OF PERIGEE POINTS AS A FUNCTION OF LAUNCH TIME FOR NO ORBITAL COAST

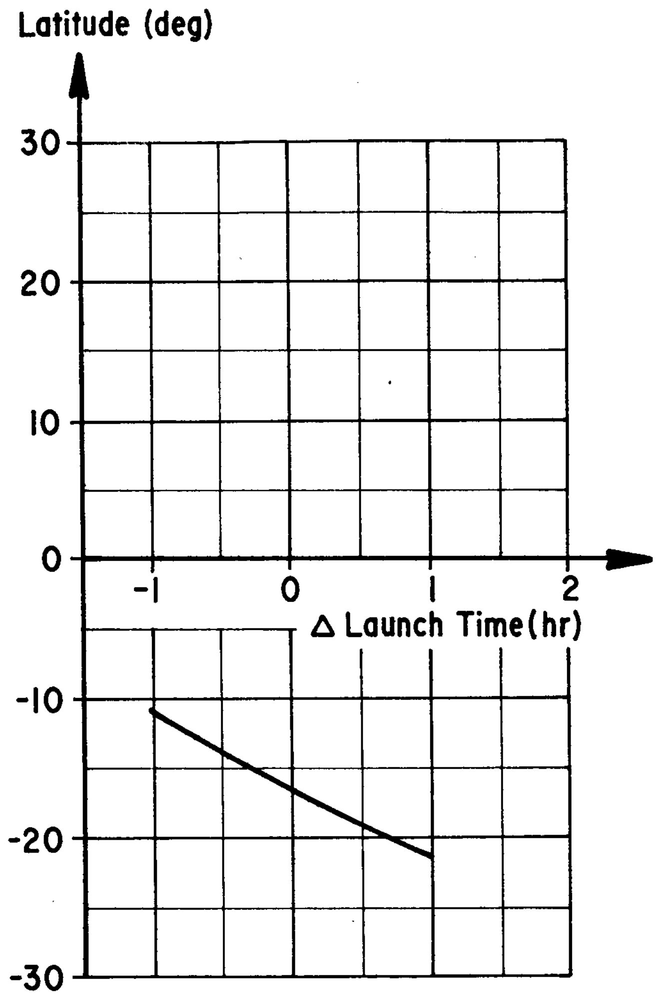


FIG. 14 LATITUDE OF PERIGEE POINTS
AS A FUNCTION OF
LAUNCH TIME FOR 30 MINUTES ORBITAL COAST TIME

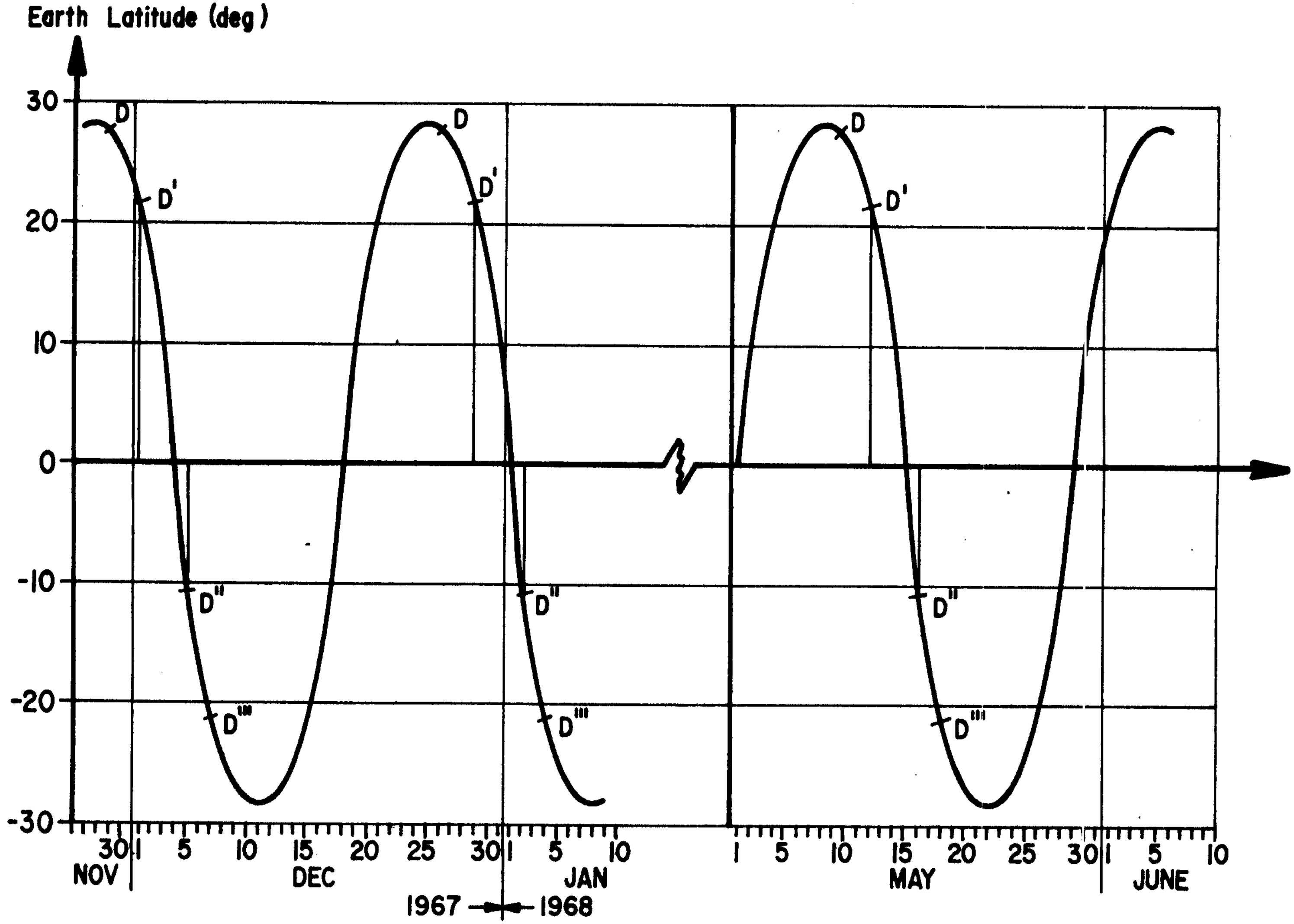


FIG. 15 DECLINATION OF THE REQUIRED VALUE OF PERIGEE AS A FUNCTION OF TIME FOR DEC 1967 AND MAY 1968 FOR CLOSED LOOP TRAJECTORIES

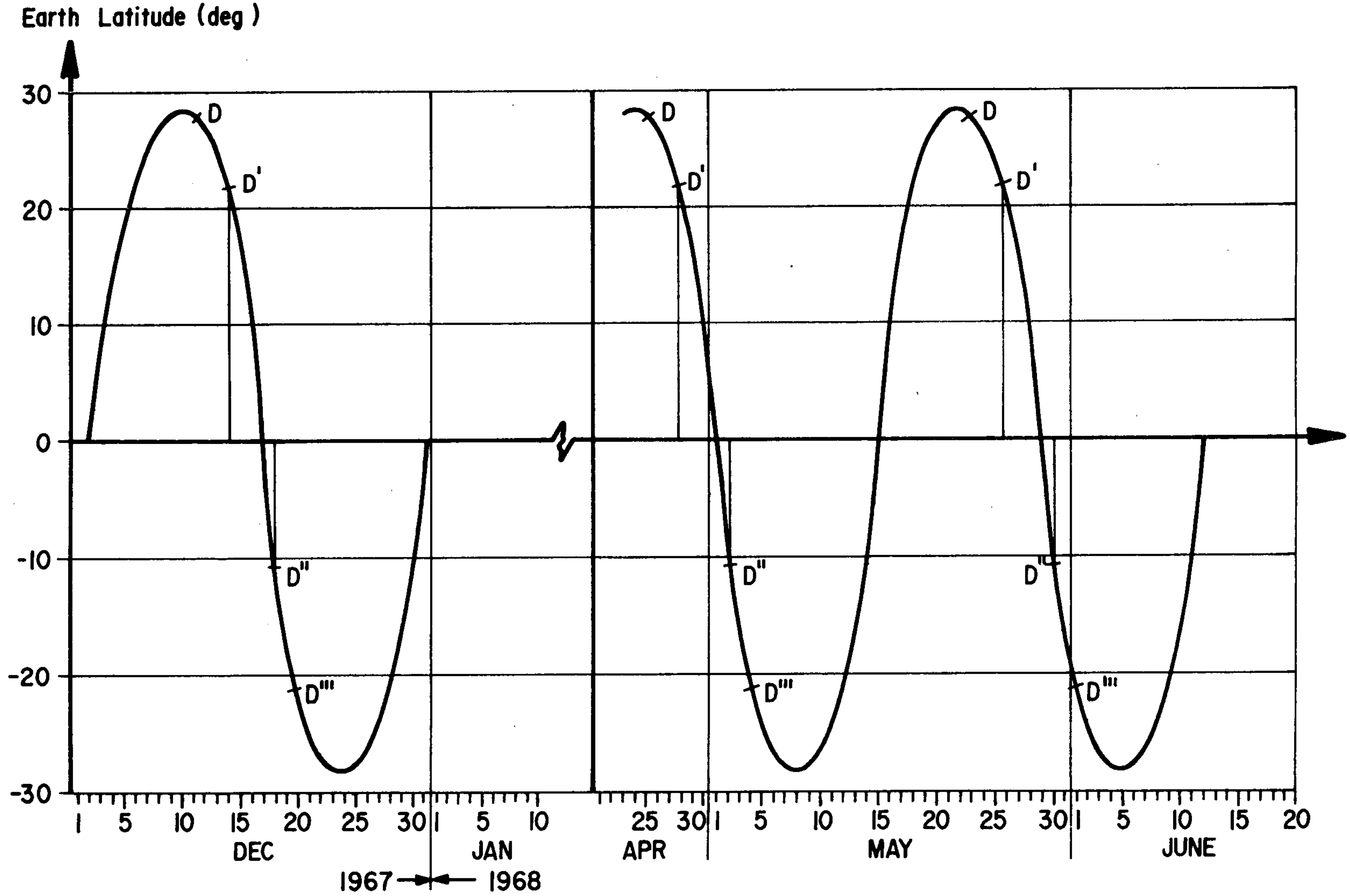


FIG. 16 DECLINATION OF THE REQUIRED VALUE OF PERIGEE AS A FUNCTION OF TIME FOR DEC 1967 AND MAY 1968 FOR OPEN LOOP TRAJECTORIES

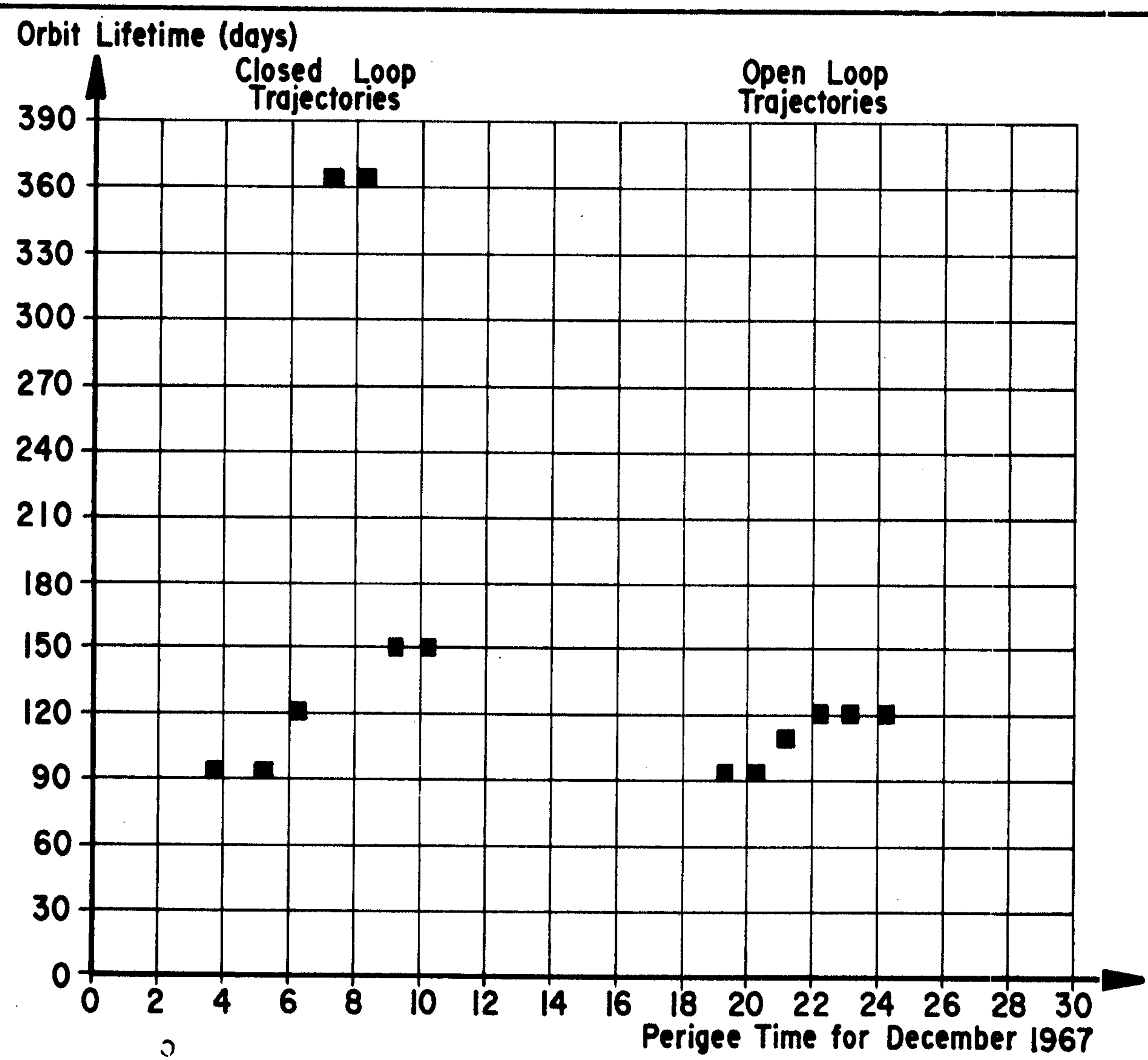


FIG. 17 LIFETIME AS A FUNCTION OF LAUNCH DATE
Ratio 1/2
Perigee Altitude = 575 N M

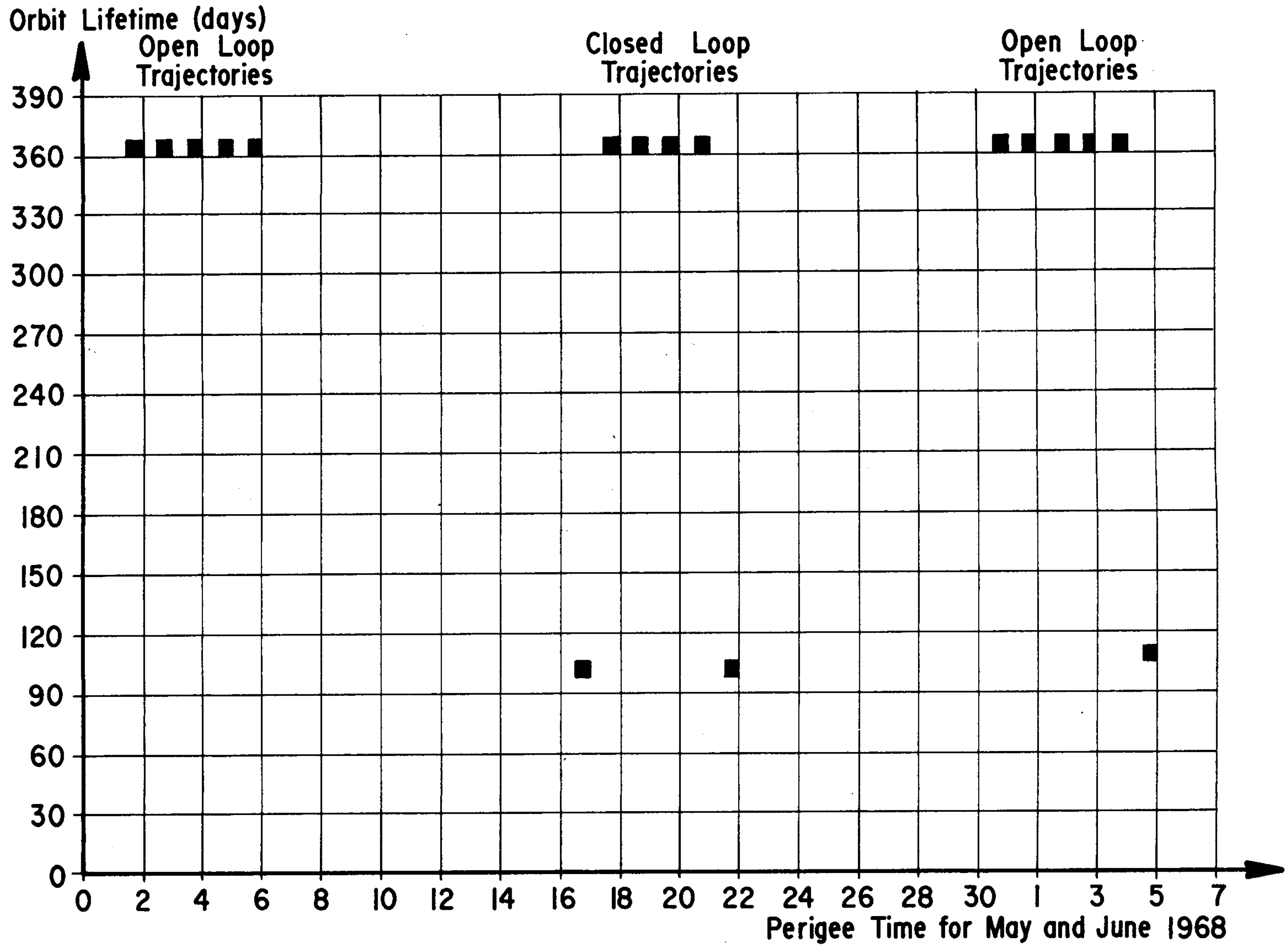


FIG. 18 LIFETIME AS A FUNCTION OF LAUNCH DATE
Ratio 1/2
Perigee Altitude =575 N M

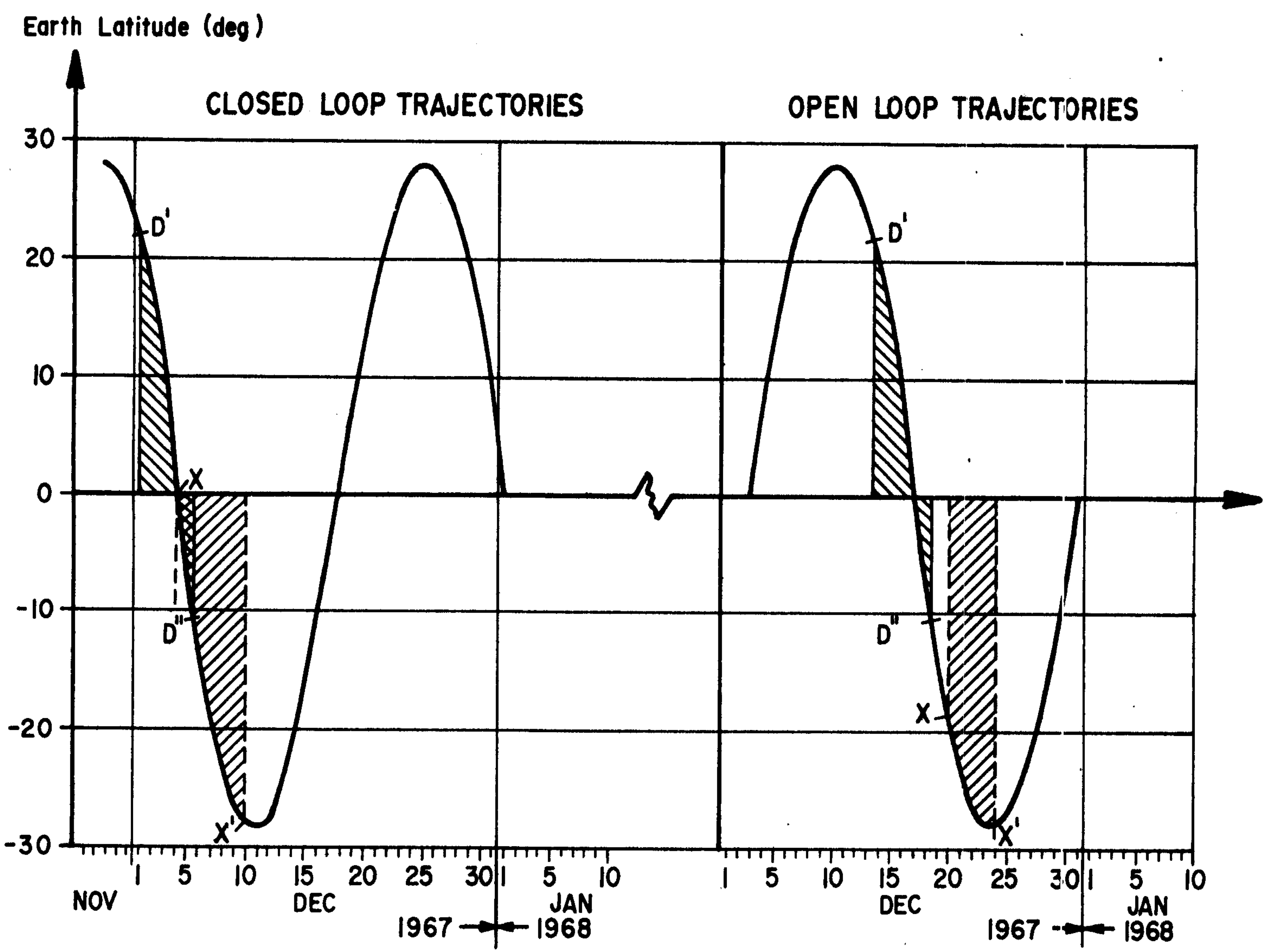


FIG. 19 INJECTION WINDOW FOR DECEMBER 1967

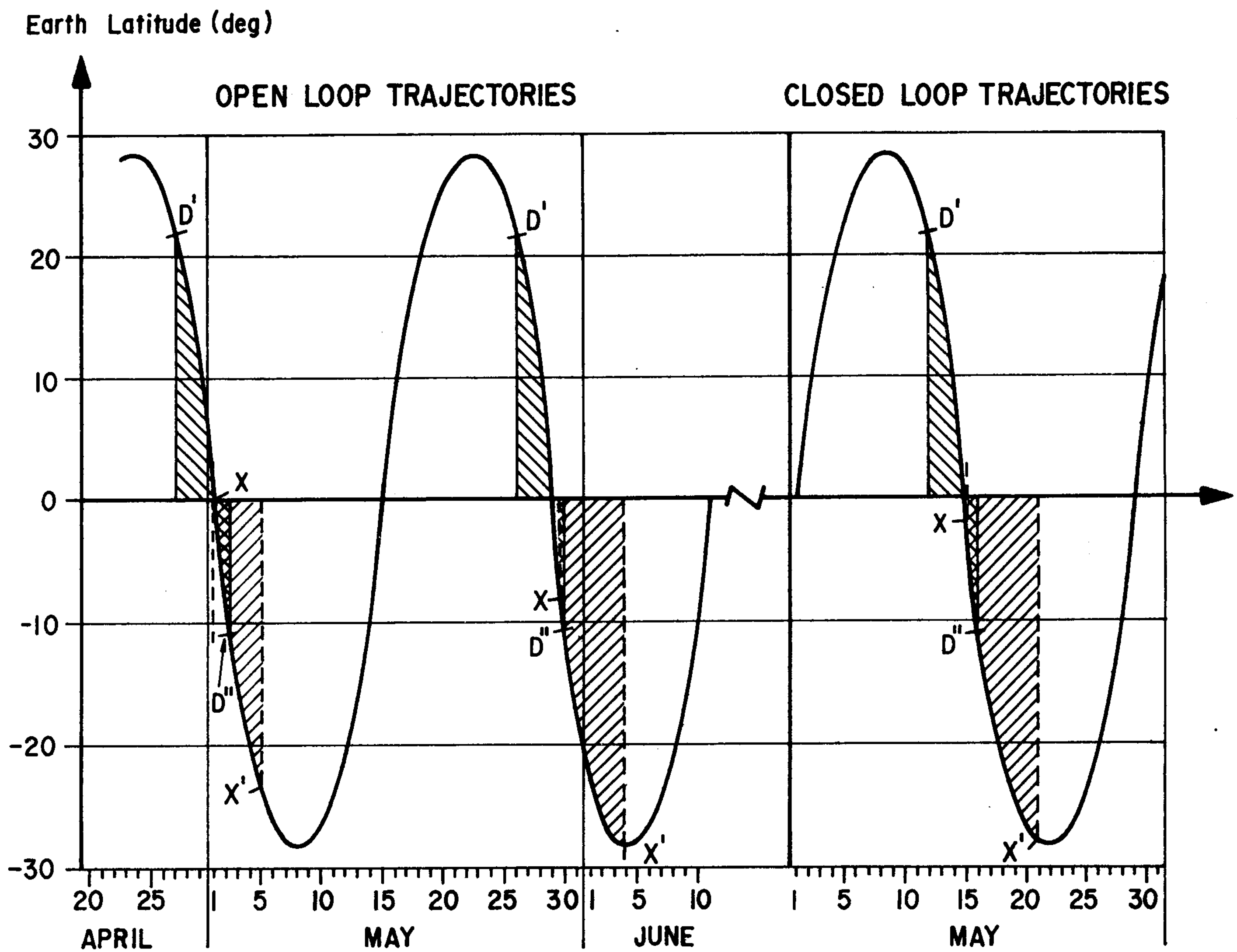


FIG. 20 INJECTION WINDOW FOR MAY 1968

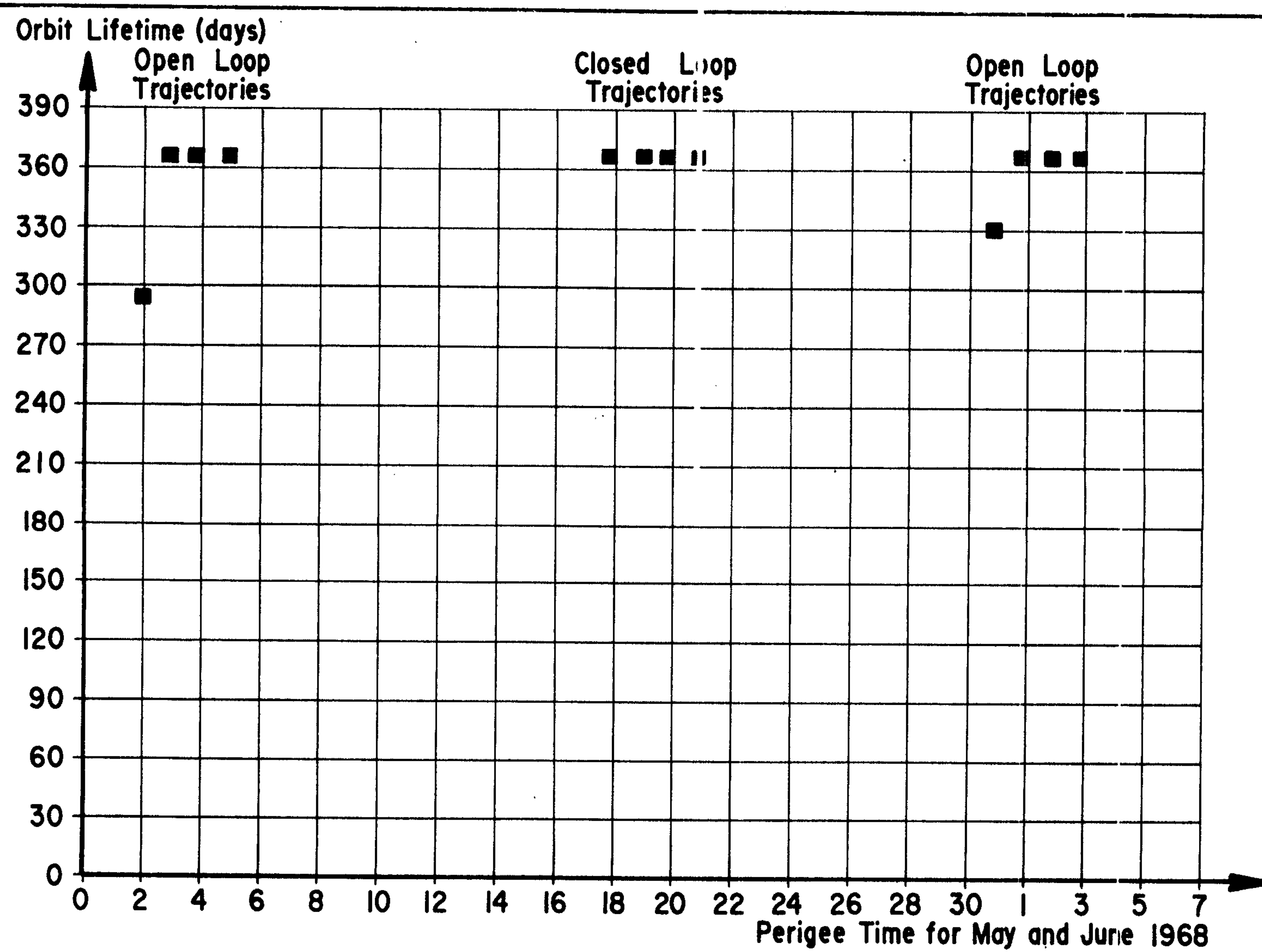


FIG. 21 LIFETIME AS A FUNCTION OF LAUNCH DATE
Ratio 1/2
Perigee Altitude = 200 km

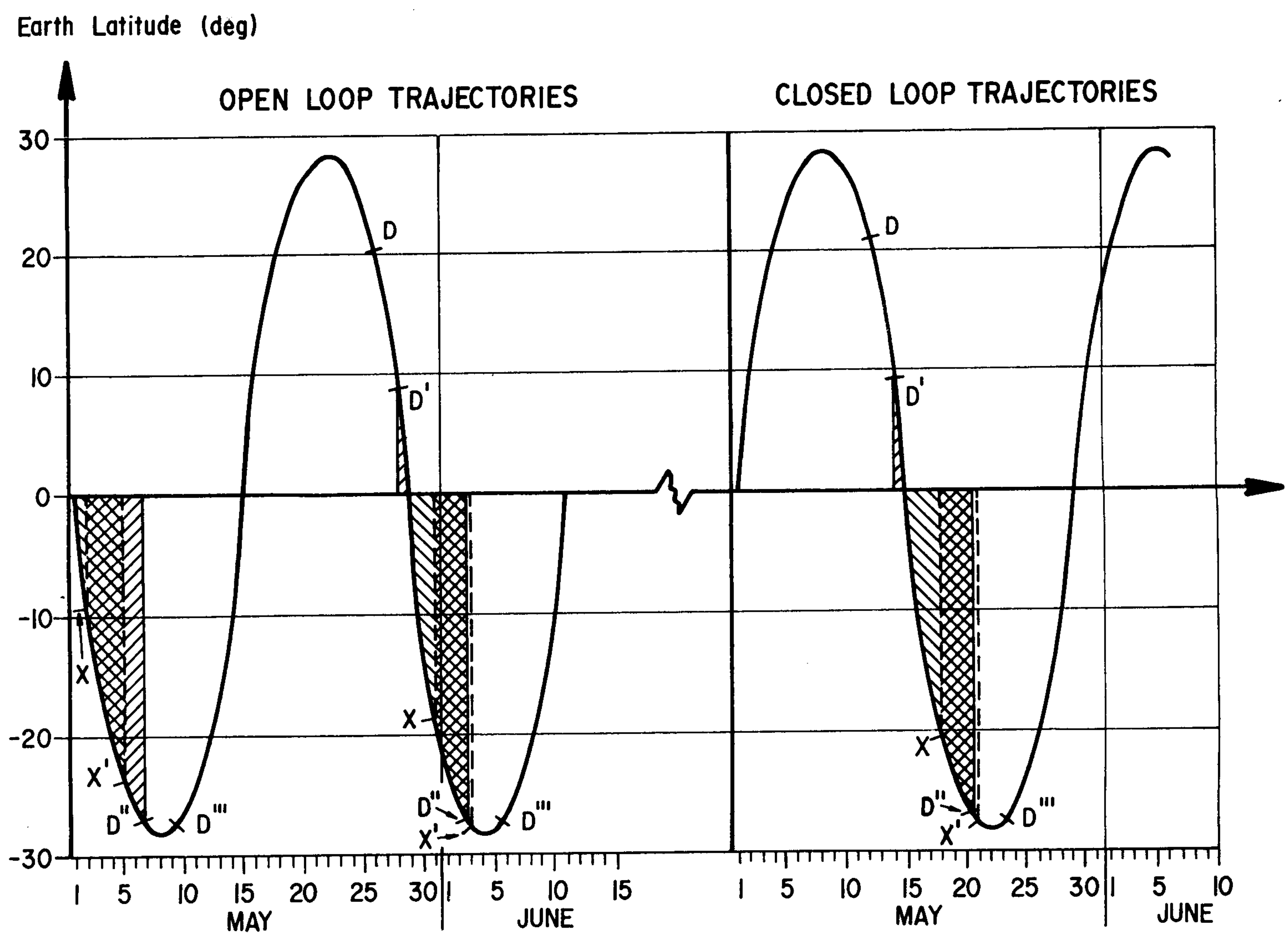


FIG. 22 INJECTION WINDOW FOR MAY 1968 FOR AN ARENSTORF ORBIT WITH A PERIGEE ALTITUDE OF 200 km

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1. Smith, Isaac E., "A Three-Dimensional Ascending Iterative Guidance Mode," TM X-53358, May 1965, Unclassified.

2. Causey, Wilton E., "Injection Opportunities for Cislunar Pegasus Trajectories with Ratio 1/2 (December 1967 - May 1968)" August 1965, Unclassified.

TM X-53354

APPROVAL

LAUNCH WINDOWS FOR TWO TYPES OF ORBITS SYNCHRONOUS WITH THE LUNAR PERIOD

By E. H. Bauer and L. D. Mullins

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.

This document has also been reviewed and approved for technical accuracy.

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