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PERIODIC LANDING ZONE ANALYSIS FOR EARTH-ORBITAL MISSIONS

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MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
September 23, 1968

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PERIODIC LANDING ZONE ANALYSIS FOR EARTH-ORBITAL MISSIONS

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By Richard I. Green and Richard C. Jacobs

1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this paper is to present an analysis of the interrelation of planning factors used to develop periodic landing zone support of manned low-earth-orbital missions. Optimizing recovery zone size, location, distribution, and number is of primary interest. It is hoped that this information will simplify planning techniques for persons knowledgeable in only general recovery procedures. Department of Defense (DOD) space flight operations personnel as well as Landing and Recovery Division personnel of the NASA Manned Spacecraft Center will find that the information contained herein has a direct application to their recovery planning activities.

1.2 SCOPE AND LIMITATIONS

In the future, manned space flight missions will be of long duration (up to 1 year in earth orbit), requiring a change in scope of recovery force participation. To keep the number of recovery vehicles to a minimum and maintain the desired recovery capability, the landing zones must be optimized. In general, the various planning factors which determine the number, size, and relative location of the landing zones are discussed. The launch site and launch abort recovery postures are not discussed because of their relatively short-duration support requirements and because it is anticipated that future needs will remain about constant. End-of-mission landings will occur in one of the planned landing zones. Contingency landing area support should continue to be an after-the-fact operation, employing aircraft at either deployed or home bases. Only space flight missions having orbital inclinations from 28.5° to 90° and altitudes of 100 to 300 nautical miles, either elliptical or circular, are considered in this paper. The landing zone information is applicable to water or land-landing recovery zones.

2.0 PLANNING FACTORS

The major planning factors which determine the number, size, and location of recovery zones have been divided into mission factors, recovery factors, and associated factors.

2.1 MISSION FACTORS

2.1.1 In-Orbit Wait Time

The elapsed time between opportunities to support a landing in the recovery zone is defined as the in-orbit wait time. The maximum allowable interval depends to a great extent on the probabilities and nature of possible spacecraft system failures. During the later Gemini Program flights, a three-revolution (approximately 4-1/2 hours) gap between recovery opportunities, occurring once each day, was accepted. It is logical to assume that allowable in-orbit wait times will tend to increase as confidence is gained in spacecraft systems.

2.1.2 Frequency of Landing Opportunities

The frequency of landing opportunities determines the in-orbit wait periods during any mission. The ideal long-duration recovery posture provides landing opportunities at equally spaced time intervals throughout the flight, which causes all in-orbit wait times to be equal. Normally, this optimum condition can be attained only under ideal circumstances because of limiting factors, such as logistics and weather.

2.1.3 Mission Parameters

Each space flight is designed to accomplish specific objectives, and recovery support must be planned to fit the basic mission profile. The most restraining mission parameters for recovery planning are orbital inclination and, to a lesser extent, orbital altitude or period. These mission parameters are discussed in further detail in section 3.0.

2.2 RECOVERY FACTORS

2.2.1 Access and Retrieval Time

Access time includes the time frame within which recovery personnel are required to locate the spacecraft, install the flotation collar, and open the spacecraft hatch. Although this is an important consideration, another controlling quantity in recovery planning is retrieval time. This term includes the time frame from the predicted time of landing to the time when the crew and/or spacecraft is aboard ship and postretrieval examinations and operations can be initiated. For preliminary ship recovery operations planning, spacecraft and crew retrieval times are treated as the same quantity.

2.2.2 Recovery Vehicle Performance

The basic recovery vehicle for water recovery sites is a ship of acceptable capability and having a sustained cruise capability of at least 15 knots. This speed governs minimum theoretical retrieval time and is a factor in determining recovery zone size.

For initial on-scene assistance, an aircraft such as the HC-130H can provide the necessary recovery support. This aircraft cruises at 285 knots and has an operating radius of 2150 nautical miles. These performance figures are considerations in determining access times.

2.2.3 Zone Location Restrictions

2.2.3.1 Latitude.- Except for contingencies, recovery operations are restricted to a region between latitudes 40° north and 40° south. All planned recovery zones are thus constrained to this band of latitudes because of the greater certainty of an equable environment.

2.2.3.2 Landmass.- Sites are to be located far enough from any landmass so as to accommodate the service module impact point and the command module footprint.

2.2.3.3 Logistics.- The section of any recovery site is governed by the desired orbital coverage and influenced by recovery force logistics. Currently, a preference is given to sites located in the Northern Hemisphere, and only under exceptional circumstances are Southern Hemisphere sites considered in developing recovery concepts.

2.2.3.4 Weather.- Because the seasonal variations in weather are relatively large, it is not possible to develop generalized recovery concepts based on weather. Normally, recovery sites are selected far enough apart so that they will not be affected by the same weather system at the same time.

2.3 ASSOCIATED FACTORS

The number of landing opportunities can be affected by other variable factors. Possible landing dispersions about a nominal target point can increase access and retrieval times; hence, they must be taken into account when determining orbital coverage for a recovery zone. On the other hand, spacecraft reentry maneuverability (side range) could allow for selection of target points nearer recovery forces.

Additional target point movement may be obtained by orbital plane and period adjustments. Since the total movement caused by these maneuvers depends on the time remaining prior to the deorbit maneuver and the propellant available, no general statements can be made without restricting the discussion to a specific mission.

3.0 ZONE SIZE DETERMINATION

The minimum size of any recovery zone is determined by a combination of factors such as the latitude of the desired zone, the orbital inclination, and ground track spacing. Variables dependent upon spacecraft performance such as landing dispersions and in-orbit maneuvering capability also dictate to some extent the zone size. For example, in figure 1, a required 400-nautical-mile zone radius is shown to be a combination of a 300-nautical-mile ship capability and a 100-nautical-mile spacecraft lateral capability.

For simplicity, any recovery zone will be considered a fixed area that provides a landing opportunity when an orbital ground track passes through the area. The movements of recovery elements within recovery zones are highly mission dependent and are changed only in real time during a flight. Therefore, the position of any recovery element is assumed to be at the zone center, and its movements will be optimized in real time.

Land-landing recovery zones are fixed geographical areas which possess terrain features suitable for successful landings. A land-landing opportunity is available when the ground track passes over the zone or is within the side-range capability of the spacecraft. The total effectiveness of a land-landing zone is thus highly dependent on the spacecraft design and characteristics.

3.1 PERIODIC VERSUS RANDOM COVERAGE

Periodic coverage is defined as that coverage which insures recovery support on a specified recurring basis. Any other coverage is considered random. To generalize for the types of missions under consideration (orbital inclinations of 28.5° to 90° and altitudes ranging from 100 to 300 nautical miles), a zone must cover the distance between sequential ground tracks. If a zone covers this distance, a ground track will pass through the zone at least once each 24 hours for any random mission. When one zone is not large enough to be periodic, two or more zones can be so located that the required distance is covered. Figure 2 shows how two zones can provide the required coverage between successive ground tracks. With these zone arrangements, at least one passage every 24 hours is assured for the example mission. When one circular zone is large enough to be periodic, then two passes per 24 hours, one ascending track and one descending track, are covered. Figure 3 demonstrates how smaller zones could be grouped to provide the same coverage as one periodic circular zone. Two-zone and three-zone groupings are shown, but any number of zones can be used. The important conditions to remember are that the sum of the zone diameters equals the distance between successive ground tracks, and the zones must be oriented properly to cover ascending and descending ground tracks.

3.1.1 Repeating Ground Tracks

Various orbits within the selected mission ranges result in repeating ground tracks and are exceptions to the minimum zone size covering the distance between successive ground tracks. Mission altitude and inclination determine how often ground tracks repeat. Figure 4 shows the dependence of ground track repetition on mission altitude and inclination.

For ground tracks which repeat approximately every day, a zone needs to be only a point on the ground track to provide at least one-revolution-per-day coverage. The first-day ground tracks are the same on succeeding days. For ground tracks which repeat approximately every other day, the zone must cover one-half the distance between sequential revolutions to maintain periodic once-per-day coverage. If the zone remains a point on the ground track, coverage would be periodic, but it would be provided only once every 2 days. For a ground track which repeats every 72 hours, a zone must be two-thirds the distance between sequential revolutions to provide the once-per-day landing opportunity. The size relationships of periodic recovery zones for 1-, 2-, and 3-day repeating ground tracks are shown in figure 5.

From the foregoing, it becomes evident that as the time required to repeat ground tracks increases, the larger the zone must be to provide a set periodic recovery opportunity. Therefore, for any random mission within the inclination and altitude ranges under consideration, the minimum zone area must be large enough to cover the distance between the successive or sequential ground tracks.

3.1.2 Nonrepeating Ground Tracks

Since repeating ground tracks are only special cases, this analysis will deal with the general conditions of nonrepeating ground tracks. It has been assumed that a zone must provide coverage at least once per day to be periodic. The exact zone size will depend on the site latitude, the orbital inclination, and the orbital altitude.

3.2 ZONE SIZE

Remembering that zone size should be kept at a minimum value while still remaining periodic, the effects of site latitude, orbital inclination, and altitude are discussed in the following paragraphs.

3.2.1 Site Latitude

Although a zone extends over a range of latitudes, it can be assumed that the site latitude is the latitude of the center of the circular area. In figure 6, the effect of latitude change on zone size is shown. When the zone is moved away from the equator the minimum periodic zone size decreases. Hence, for any given mission, to maintain the same coverage as site latitude increases, the zone area or radius decreases. Whereas, if movement is toward the equator, the zone radius must increase. These statements are valid only when the site latitudes are less than the inclination of the mission. Zones at latitudes beyond the mission inclination must be large enough to encompass some latitude area in which ground tracks lie before any coverage is provided.

3.2.2 Inclination

Figure 7 illustrates the zone size required for a given site latitude for two different orbital inclinations. It can be seen that as inclination increases, the zone size or radius increases.

3.2.3 Altitude or Period

The third factor affecting zone size is the orbital altitude, or the period of the orbit, and the resulting ground track. For a given site latitude and mission inclination, an altitude increase results in an orbit period increase. Therefore, the successive ground tracks are further apart since the separation between ground tracks is the amount of earth rotation during one revolution. The zone must expand to remain periodic. Figure 8 depicts this altitude adjustment effect. Within the 100- to 300-nautical-mile altitude range, however, the altitude changes can be considered negligible when compared with the impact of site latitude and inclination changes.

3.3 LANDING OPPORTUNITY INTERVAL

With the many variables involved in zone selection, a common means of describing the relative value of any one site compared to another must be used. The landing opportunity interval is one method of measurement. This concept is a modification of a basic method of recovery operations planning given in reference 1.

3.3.1 Definition

A landing opportunity interval is a segment of the equator associated with a given recovery zone. Any ascending ground track passing through this segment will also pass through the associated recovery zone. For any one circular recovery zone there are two landing opportunity intervals. Each interval for a Northern Hemisphere zone is formed by projecting two ground tracks, one on either side of the zone, back to their ascending intercepts with the equator. One interval is associated with ascending ground tracks through the zone, and the other with descending tracks through the zone. For a circular periodic zone, the two intervals are of equal length and individually cover at least the longitudinal separation between two successive ground tracks. This minimum separation for the mission ranges under consideration is 22° to 24°, depending on inclination and altitude. Figure 9 shows how the landing opportunity interval is formed.

3.3.2 Relative Interval Location for Various Site Latitudes

The relative locations of the landing opportunity intervals for one zone is a function of the zone latitude and the orbital inclination. In turn, the relative interval location dictates the maximum in-orbit wait and the frequency of coverage provided by the zone. For discussion purposes, it will be assumed that the separation between successive ground tracks is 24° of longitude. Site latitude can generally be divided into equator, off-equator, optimum-latitude, and above-optimum-latitude locations.

3.3.2.1 Equator sites.- A zone on the equator will have landing opportunity intervals as shown in figure 10. The interval spacing is independent of mission inclination. However, the zone radius must increase as inclination or altitude increases to maintain the minimum interval length (periodic coverage). The maximum in-orbit wait can be calculated by noting the number of successive revolutions that can be placed through the longest longitude band between landing opportunity intervals (no-coverage interval). For the equator site, the maximum will occur once each day. An approximate maximum in-orbit wait time, in revolutions, can be calculated in the following manner:

$$\frac{I_M}{S} + 1 = W$$

where I_M = maximum no-coverage interval, degrees of longitude

S = separation between successive revolutions, degrees of longitude

W = maximum in-orbit wait, revolutions

$\frac{I_M}{S}$ must be rounded off to the next higher integer when not a whole number.

Example: When $S = 24°$, $I_M = 168°$

$$W = \frac{168°}{24°} + 1$$

$$W = 8 \text{ revolutions}$$

Example: When $S = 22°$, $I_M = 169°$

$$W = \frac{169°}{22°} + 1$$

$$W = 9 \text{ revolutions}$$

Example: When $S = 23°$, $I_M = 168.5°$

$$W = \frac{168.5°}{23°} + 1$$

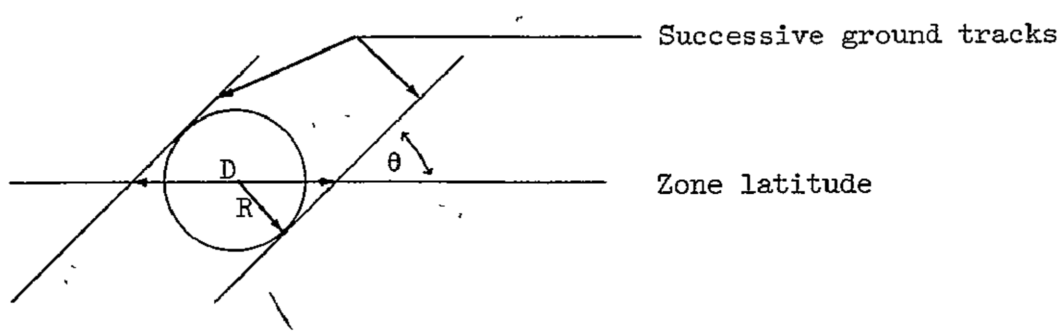
$$W = 9 \text{ revolutions}$$

3.3.2.2 Off-equator sites.- From the point of view of landing-opportunity-interval spacing, an equator zone provides the best possible arrangement. As the zone is moved off the equator, the required zone radius decreases, but the intervals begin to converge. The convergence rate depends on the mission inclination. As inclination increases, the intervals converge less for a given change of latitude. Therefore, when the zone is moved away from the equator, the no-coverage intervals become more unbalanced, and the maximum in-orbit wait time increases. Figure 11 demonstrates the interval movement. The maximum in-orbit wait can again be calculated by the method discussed in paragraph 3.3.2.1 if the no-coverage interval is known.

3.3.2.3 Optimum-latitude sites.- When the zone is moved far enough off the equator to cause the landing opportunity intervals to form one interval, the zone is at the optimum latitude or most-pass location. This optimum latitude is the one where the circular zone is tangent to a latitude parallel equaling the mission inclination and provides the most number of consecutive landing opportunities. Obviously, for zones of constant radius, as the inclination increases, the optimum latitude increases. A zone at the optimum latitude will provide the maximum total landing-opportunity-interval length for any given zone radius. All coverage is concentrated on consecutive revolutions, and the maximum in-orbit wait can be large. Since there is only one landing opportunity interval, the minimum periodic zone radius can be reduced to a value giving a total landing-opportunity-interval length equaling 24° or the longitude separation between successive revolutions. Although the zone would be periodic, only one passage per day would be assured. Figure 12 shows optimum-latitude sites where the intervals are 48° and 24° in length.

3.3.3 Approximating Minimum Periodic Radius

The minimum radius required for a periodic recovery zone can be approximated by the following method.



where θ = acute angle between ground track and zone latitude parallel, degrees

D = distance between successive ground tracks measured on the site center parallel, nautical miles

R = zone radius, nautical miles

$$R = \frac{D \tan \theta}{2(\sin \theta \tan \theta + \cos \theta)} \quad \text{when} \quad \theta < 90^\circ$$

$$R = \frac{D}{2} \quad \text{when} \quad \theta = 90^\circ$$

The ground tracks are assumed to be parallel at a constant true heading. Using this method, example radii were calculated for different site latitudes and orbital inclinations. These radii are listed in table I and are based on 23° of longitude separation between successive ground tracks. A 24° separation would increase the radius values a maximum of 30 nautical miles (zone at equator for 90° inclination mission). Therefore, the radius values can be used for general planning purposes in the range of missions under discussion.

4.0 COMBINING TWO OR MORE ZONES

The landing-opportunity-interval method can be used for recovery zone planning when two or more zones are required. The site locations can be optimized to evenly distribute the intervals on the equator and thereby reduce the maximum in-orbit wait.

4.1 ZONES ON SAME LATITUDE PARALLEL

Zones positioned on the same latitude parallel have been divided into equatorial, optimum-latitude, and off-equator locations. No more than four zones are considered, although the same principles apply regardless of the number of sites used. The minimum periodic zone size is assumed for all locations.

4.1.1 Equatorial Locations

The interval spacings for two, three, and four equatorial recovery zones are shown in figure 13. Each zone is positioned to divide the maximum no-coverage interval into two equal no-coverage intervals. Note that the number of intervals is twice the number of zones. It is possible to make all the no-coverage intervals equal except one interval which is always smaller. Therefore, the maximum in-orbit wait is a minimum when the equatorial sites are spaced approximately as follows:

Number of equatorial zones	Longitudinal separation, deg
2	96
3	64 or 128
4	48

To convert the no-coverage intervals into an in-orbit wait time, the method described in paragraph 3.3.2.1 can be used. For direct conversion, table II lists the no-coverage interval length for ground tracks which have 22°, 23°, and 24° of longitude between successive ground tracks. The in-orbit wait associated with the interval lengths is expressed in revolutions. Conversion to hours and minutes is obtained by multiplying the wait in revolutions by the revolution period. For the equatorial zones shown in figure 13, the in-orbit wait is as follows:

Number of equatorial zones	In-orbit wait, revs.
1	8
2	4
3	3
4	2

4.1.2 Optimum-Latitude Locations

Two, three, and four zones at the optimum latitude will require spacing to form landing opportunity intervals as shown in figure 14. Again, the maximum in-orbit wait can be taken from table II by noting the no-coverage interval length. It should be remembered that the required periodic zone radius is less than the periodic equatorial zone radius. The number of intervals is equal to the number of recovery zones. Optimum latitude locations are ideal for orbital inclinations less than 40°. Inclinations greater than 40° require that this type of zone be located in latitudes unfavorable for recovery operations. The relative longitudinal spacing for optimum-latitude zones is as follows:

Number of optimum-latitude zones	Longitudinal separation, deg
2	180
3	120
4	90

When the minimum periodic zone (longitudinal separation between ground tracks) is used for optimum latitude zones, only one pass per day is guaranteed for each zone. However, the minimum periodic zone radius is only 30 to 50 nautical miles. The following in-orbit waits are possible with the optimized locations shown in figure 14.

Number of optimum-latitude zones	In-orbit wait, revs.
1	15
2	8
3	5
4	4

4.1.3 Off-Equator Locations

As previously discussed, the relative interval locations for zones off the equator depend on the orbital inclination. When zones are combined, the optimization problem is magnified. There is no simple solution for determining the maximum in-orbit wait time, since each zone's intervals depend on site latitude and orbital inclination. It can be shown that the maximum in-orbit wait will be in the range of wait times between the minimum-periodic-zone equatorial sites and optimum-latitude sites. The best relative spacing will also lie in the range of longitudinal separations for the equatorial and optimum-latitude sites. These values are given in the following table.

Number of off-equator zones	Range of maximum in-orbit waits, revs.	Range of longitudinal separation, deg
1	8 to 15	--
2	4 to 8	96 to 180
3	3 to 5	64 to 128
4	2 to 4	48 to 90

When the number of zones is specified, an off-equator optimum latitude can be found; however, the latitude is again dependent on orbital inclination. For example, if two zones are considered, the four resulting landing opportunity intervals must be placed 90° apart to balance the no-coverage intervals. In figure 11 it was shown that as the zone is moved off the equator the intervals begin to converge, and it will be recalled that the amount of convergence for a given latitude movement depends on the orbital inclination. Therefore, it is possible to find a latitude where the intervals for one site are separated by 90° of longitude (center to center). With two zones located on the proper latitude and separated by 180° of longitude, the no-coverage intervals (66°) are in balance. Figure 15 shows this interval spacing on the equator. From table II the maximum in-orbit wait is found to be four revolutions. For two optimized equatorial zones, the maximum no-coverage interval is 72° or four revolutions. Hence, the maximum in-orbit wait will occur more often for the equatorial sites. Additionally, the minimum periodic-zone radii needed would be less for the off-equator sites.

Figures 16 and 17 show the optimum landing-opportunity-interval spacing for three and four zones at their best off-equator latitude parallel. This approach can be used for sites at any latitude if two factors are known for each site. First, the longitudinal separation between the interval centers (Y in fig. 16(b)) must be available. Secondly, the longitudinal separation between the site center longitude and its nearest interval center longitude (X in fig. 16(b)) will have to be known. Table III lists these values for example missions and site latitudes. The X and Y values will be used in the graphical solution (section 5.0) when plotting intervals relative to a selected zone center.

4.2 ZONES ON SAME LONGITUDE

Generally, zones located on the same longitude provide very good coverage for low-inclination orbits (below 40°). High-inclination orbits would require zones to be located at latitudes exceeding 40° to maintain optimum spacing. The prevailing weather conditions for these zones are unfavorable for recovery operations.

It will be recalled that the landing opportunity intervals associated with a Northern Hemisphere zone are formed by projecting the ground tracks on either side of the zone back to their ascending intercepts with the equator. The intervals for a Southern Hemisphere zone are formed by projecting the ground tracks forward from the zone to the points where they ascend through the equator. These intervals should be thought of as preceding the zone as in the Northern Hemisphere, however.

Zones located on the same longitude line should be placed symmetrically with respect to the equator. For an even number of zones, half the zones are located above the equator and half below. For an odd number of zones, one zone is positioned at the equator and the remaining zones divided between the Northern and Southern Hemispheres along a constant longitude. The following discussion is limited to two-, three-, and four-zone concepts; but the basic approach is applicable to any number of zones.

4.2.1 Two Zones

Two zones on the same longitude provide four landing opportunity intervals. To distribute the intervals evenly, it might be assumed that the interval centers for each zone must be spaced 90° apart. When this is done, however, the resulting no-coverage interval spacing is unbalanced, as shown in figure 18(a). Note in this example that a 24° difference between no-coverage intervals "a" and "b" exists. This would indicate that no-coverage interval "b" is equivalent to an in-orbit wait of 5 hours (from table II). In actuality, this interval is decreased by 24° because the ground track regresses by this amount every spacecraft revolution as a result of the earth's rotation. In the final analysis, two of the four landing-opportunity-interval centers are 90° apart and two are 78° apart (with two 66° and two 54° no-coverage intervals). The maximum wait time is, therefore, four revolutions for all no-coverage intervals with the frequency of occurrence of maximum wait higher for two of the total four intervals.

Figure 18(b) shows the optimum spacing of landing opportunity intervals for two zones on the same longitude. The spacing of the intervals is such that the no-coverage intervals are effectively equal. The recovery zone sites are located at a latitude where the longitudinal difference between ascending and descending ground tracks passing through a zone center is 84°. Assuming that the landing opportunity intervals are 24°, as in the preceding example, the four no-coverage intervals would be 60° after compensating for the earth's rotation. The wait time would again be four revolutions with all intervals having the same frequency of maximum wait.

4.2.2 Three Zones

For three zones on the same longitude, the objective is to distribute the six intervals as evenly as possible. As in the two-zone same-longitude concept, only the longitudinal separation between passages at the landing-opportunity-interval centers should be considered. It is possible to locate two sites at a latitude (one in the Northern Hemisphere and one in the Southern Hemisphere) where the longitudinal separation is 56°. The third site would be at the equator. Figure 19 shows the three sites and resulting intervals. If the minimum periodic zone radius were used for each zone location, the six no-coverage intervals would be 32°, or a three-revolution wait. The required zone radius is larger for the equatorial zone than for the other two zones.

4.2.3 Four Zones

Figure 20 illustrates the four-zone arrangement with optimum spacing for a constant longitude. Two of the zone centers are located at a latitude where the longitudinal spacing between ascending and descending ground tracks through each center is 42°. The other two zone centers are located at a latitude where this spacing is 126°. The eight resulting intervals are 42° apart; and, with zones of minimum periodic size, the no-coverage intervals become 18°, or two revolutions of wait. Of course, the required radius for sites nearer the equator is larger than those at the higher latitudes.

4.3 DISCUSSION

The zone locations discussed in the preceding sections, 4.1 and 4.2, are optimum theoretical locations when the maximum in-orbit wait is considered to be of primary importance. Practically speaking, optimum spacing is not possible when three or more periodic recovery zones are needed. The major restriction is intervening landmasses. One exception is zones on the same longitude supporting low-inclination missions. Although possible, the concept is questionable because equatorial and Southern Hemisphere zones must be used.

When it is not possible to optimize locations, some general suggestions should be remembered. First, if possible, always locate the zones at the optimum or highest allowable latitude to obtain the greatest number of supported revolutions for any given zone radius. Second, certain latitude or longitude adjustments to optimum locations are always possible without increasing the maximum in-orbit wait time. Finally, all solutions should be plotted graphically and verified by computer.

5.0 GRAPHICAL SOLUTION

With many variable recovery and mission parameters, it is exceedingly difficult to establish a combination of sites that are optimum for the entire range of missions. Solutions employing graphical techniques are proposed to obtain the desired zone arrangement and location for any specific mission.

In any graphical solution, the optimum case is stated initially and modified accordingly in developing the desired recovery concept. Each individual concept is then cross checked using a computer programed to determine the number of ground track intercepts for a specified zone size.

The following procedural steps are recommended in developing a suitable recovery concept (see flow diagram, fig. 21).

a. Obtain or determine the allowable retrieval time based on desired crew and/or spacecraft retrieval time and ship speed.

b. Establish the maximum acceptable recovery zone size. For water landings, the maximum acceptable radius is governed by a combination of retrieval time and ship speed. The maximum radius of operation for land landings is determined by spacecraft side-range capability and terminal landing area size.

c. Compare the maximum acceptable radius for congruity to the minimum radius (24-hour periodic) derived from table I.

d. If the periodic (24-hour) zone is larger than the maximum acceptable radius of operation, the retrieval time must be increased for water landings or the zone size must be increased for land landings. It should be noted that the spacecraft side range and ship speed are treated as unalterable quantities.

e. Using mission inclination and zone latitude restriction, determine the acceptable band of latitudes.

f. Referring to sections 4.1.1 through 4.1.3 in the text, determine and plot the optimum location, spacing, and zones. For off-equator locations, table III must be used to determine interval center locations for various latitudes (see section 4.1.3).

g. From figures 22, 23, 24, 25, and 26, select the appropriate landing opportunity interval considering the spacecraft side-range capability for the candidate site.

h. See table II to convert the no-coverage interval to in-orbit wait time. If unacceptable, proceed to step i for possible remedial suggestions.

i. Possible modifications:

(1) Increase the number of zones.

(2) Adjust zone longitude and/or latitude.

(3) Increase zone size.

j. Compare the selected zone location and recovery constraints for compatibility. If unacceptable, repeat all necessary steps from step f.

k. Finalize the recovery zone concept with a computer program.

l. Record necessary output data.

6.0 REFERENCE

The Boeing Company: Mission Requirements of Lifting Systems - Operational Aspects. Contract NAS 9-3522, June 29, 1965.

TABLE I.- MINIMUM RADII[a] FOR PERIODIC ZONES AT VARIOUS SITE LATITUDES AND ORBITAL INCLINATIONS

[23° separation between successive ground tracks]

Site latitude, deg	Inclination									
	28.5°	33°	38°	43°	48°	51.6°	60°	70°	80°	90°
0	323	375	425	472	512	544	597	650	680	690
5	323	373	421	467	508	532	593	645	675	685
10	304	360	407	454	497	528	581	640	669	679
15	271	333	382	437	483	511	571	624	658	667
20	222	295	354	408	459	494	551	607	638	650
25	151	235	302	369	420	459	526	581	615	627
30		155	253	317	378	417	490	552	587	598
35			156	253	324	370	444	511	553	564

[a]All radii in nautical miles.

TABLE II.- CONVERSION OF NO-COVERAGE INTERVAL LENGTH[a] TO IN-ORBIT WAIT FOR VARIOUS SEPARATIONS BETWEEN GROUND TRACKS

In-orbit wait, revs.	Longitudinal separation between successive ground tracks		
	22°	23°	24°
1	0	0	0
2	1 to 22	1 to 23	1 to 24
3	23 to 24	24 to 46	25 to 48
4	25 to 66	47 to 69	49 to 72
5	67 to 88	70 to 92	73 to 96
6	89 to 110	93 to 115	97 to 120
7	111 to 132	116 to 138	121 to 144
8	133 to 154	139 to 161	145 to 168
9	155 to 176	162 to 184	169 to 192
10	177 to 198	185 to 207	193 to 216
11	199 to 220	208 to 230	217 to 240
12	221 to 242	231 to 253	241 to 264
13	243 to 264	254 to 276	265 to 288
14	265 to 286	277 to 299	289 to 312
15	287 to 308	300 to 322	313 to 336
16	309 to 330	323 to 345	
17	331 to 352		

[a]All intervals given in degrees.

TABLE III.- RELATIVE INTERVAL CENTERS FOR VARIOUS MISSION INCLINATIONS AND SITE LATITUDES

Inclination, deg	Site latitude, deg	X, deg	Y, deg
29.000	1.000	1.675	165.369
	5.000	8.432	151.855
	10.000	17.233	134.254
	15.000	26.885	114.949
	20.000	38.231	92.258
	25.000	53.470	61.779
33.000	1.000	1.425	165.869
	5.000	7.165	154.388
	10.000	14.590	139.540
	15.000	22.590	123.538
	20.000	31.650	105.419
	25.000	42.704	83.311
	30.000	58.577	51.566
38.000	1.000	1.178	166.362
	5.000	5.919	156.880
	10.000	12.017	144.686
	15.000	18.499	131.721
	20.000	25.651	117.417
	25.000	33.928	100.864
	30.000	44.241	80.238
	35.000	59.361	49.997
43.000	1.000	.981	166.758
	5.000	4.923	158.873
	10.000	9.975	148.769
	15.000	15.301	138.117
	20.000	21.087	126.544
	25.000	27.604	113.512
	30.000	35.298	98.124
	35.000	45.079	78.561
48.000	1.000	.816	167.087
	5.000	4.096	160.527
	10.000	8.288	152.142
	15.000	12.684	143.352
	20.000	17.413	133.893
	25.000	22.654	123.411
	30.000	28.672	111.375
	35.000	35.919	96.882

TABLE III.- RELATIVE INTERVAL CENTERS FOR VARIOUS MISSION INCLINATIONS AND SITE LATITUDES - Continued

Inclination, deg	Site latitude, deg	X, deg	Y, deg
53.000	1.000	0.675	167.369
	5.000	3.387	161.944
	10.000	6.849	155.022
	15.000	10.464	147.792
	20.000	14.329	140.060
	25.000	18.570	131.579
	30.000	23.360	121.999
	35.000	28.969	110.780
58.000	1.000	.551	167.617
	5.000	2.764	163.191
	10.000	5.585	157.549
	15.000	8.525	151.669
	20.000	11.655	145.408
	25.000	15.067	138.584
	30.000	18.883	130.953
	35.000	23.280	122.160
63.000	1.000	.439	167.841
	5.000	2.203	164.313
	10.000	4.450	159.819
	15.000	6.789	155.142
	20.000	9.273	150.174
	25.000	11.970	144.779
	30.000	14.969	138.782
	35.000	18.391	131.937
68.000	1.000	.336	168.046
	5.000	1.688	165.344
	10.000	3.409	161.902
	15.000	5.199	158.321
	20.000	7.100	154.520
	25.000	9.160	150.399
	30.000	11.444	145.831
	35.000	14.038	140.642
73.000	1.000	.240	168.239
	5.000	1.205	166.309
	10.000	2.435	163.850
	15.000	3.715	161.289
	20.000	5.076	158.568
	25.000	6.553	155.614
	30.000	8.191	152.337
	35.000	10.052	148.616

TABLE III.- RELATIVE INTERVAL CENTERS FOR VARIOUS MISSION INCLINATIONS AND SITE LATITUDES - Concluded

Inclination, deg	Site latitude, deg	X, deg	Y, deg
78.000	1.000	0.149	168.422
	5.000	.745	167.229
	10.000	1.507	165.705
	15.000	2.303	164.112
	20.000	3.154	162.410
	25.000	4.084	160.551
	30.000	5.122	158.474
	35.000	6.309	156.100
83.000	1.000	.060	168.600
	5.000	.300	168.120
	10.000	.609	167.501
	15.000	.938	166.843
	20.000	1.298	166.123
	25.000	1.703	165.313
	30.000	2.169	164.380
	35.000	2.720	163.280

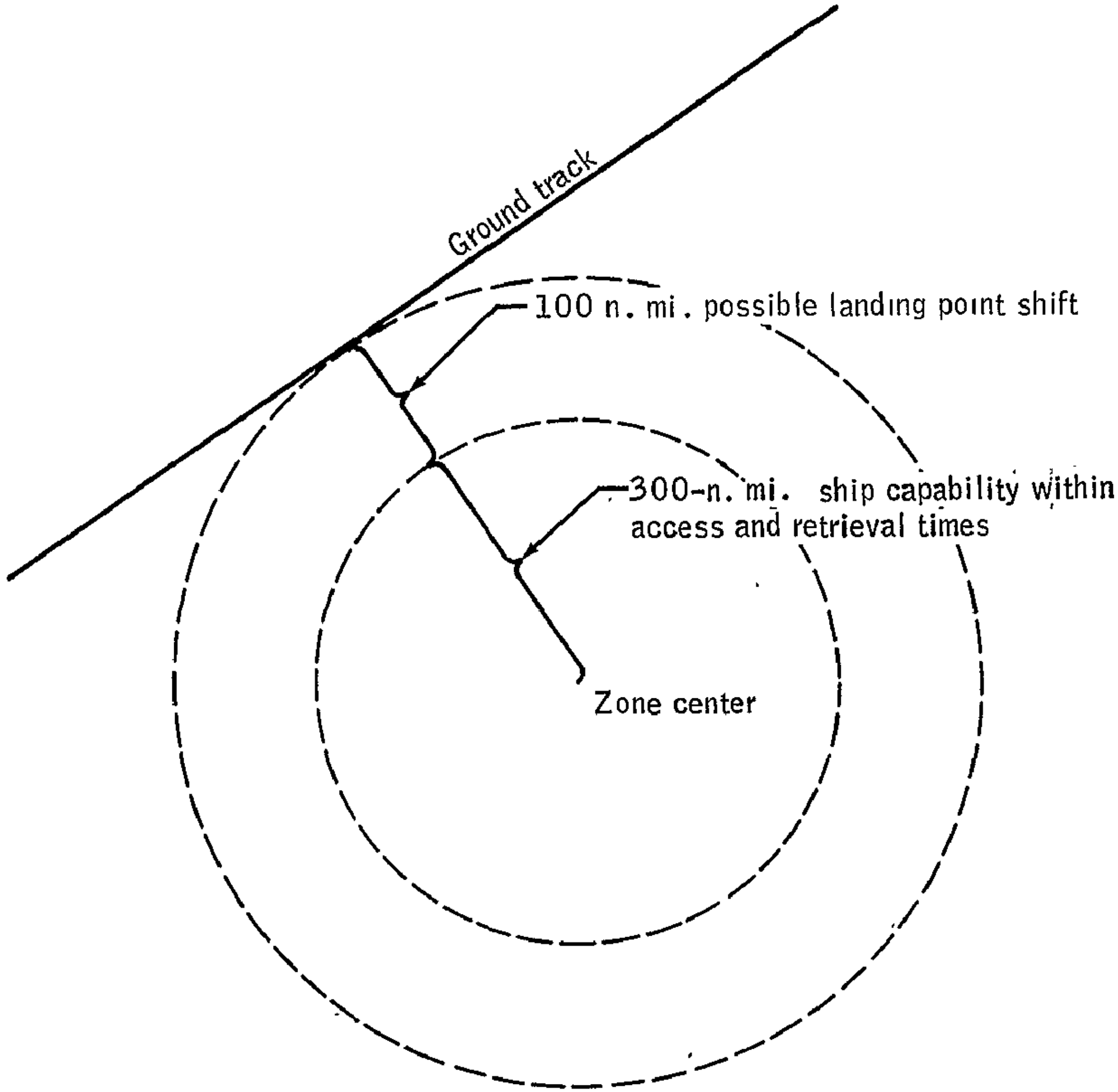
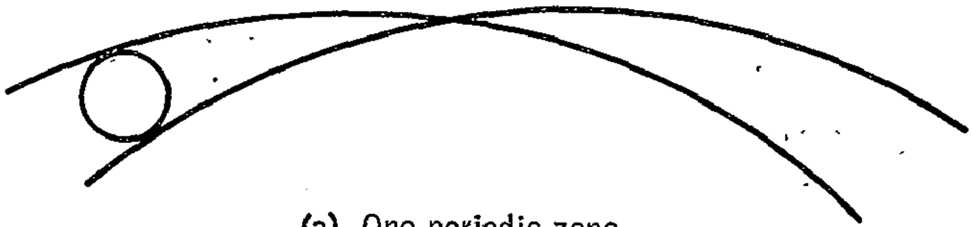
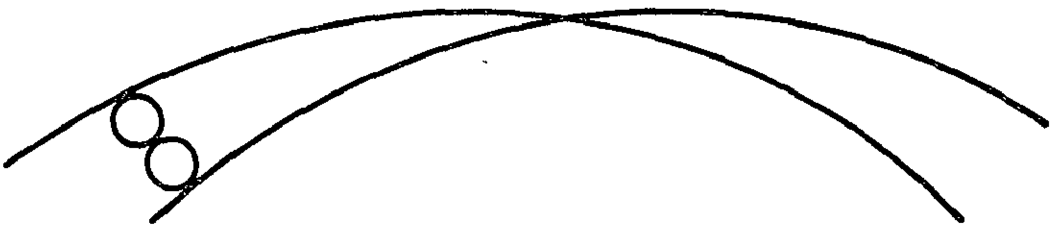


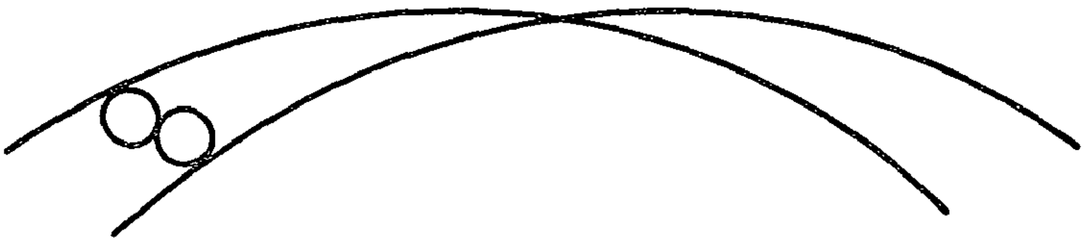
Figure 1.- Example of periodic recovery zone — 400-nautical-mile radius.



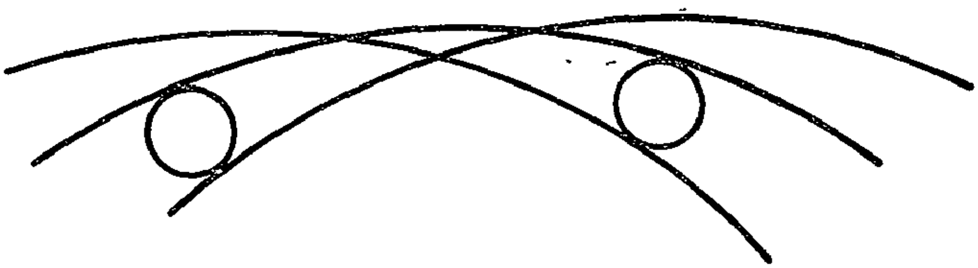
(a) One periodic zone.



(b) Two adjacent zones centered on a line perpendicular to ground tracks.

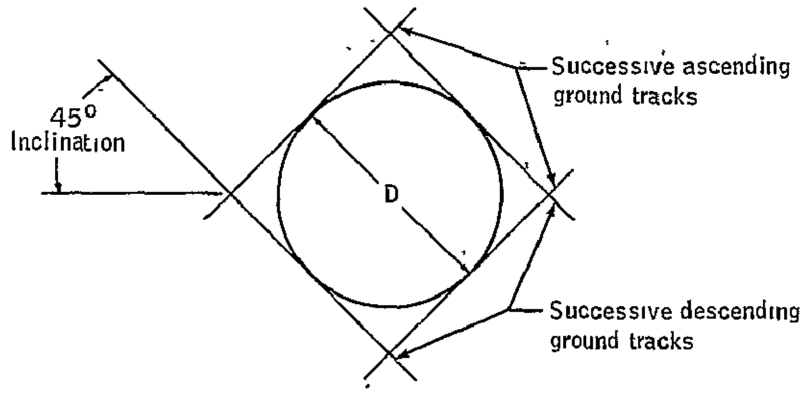


(c) Two adjacent zones centered on a line not perpendicular to ground tracks.

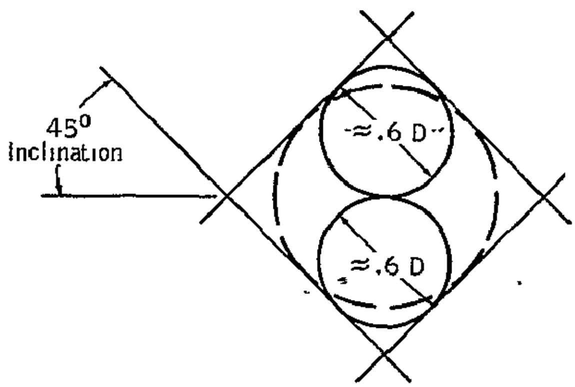


(d) Two zones not adjacent to each other.

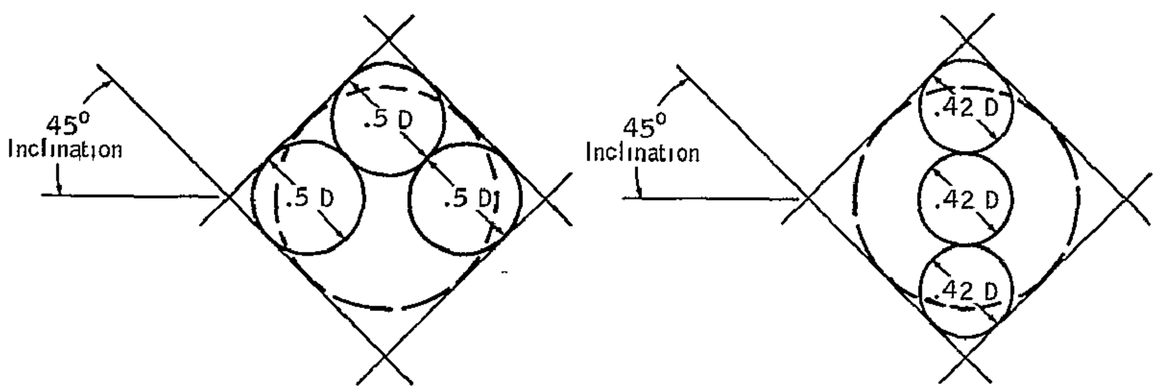
Figure 2.- Two zones used to cover distance between ground tracks on successive revolutions.



(a) One periodic zone



(b) Two zones to duplicate coverage of one periodic zone



(c) Three zones to duplicate coverage of one periodic zone.

Figure 3 – Zone combinations needed to cover one ascending and one descending ground track per day

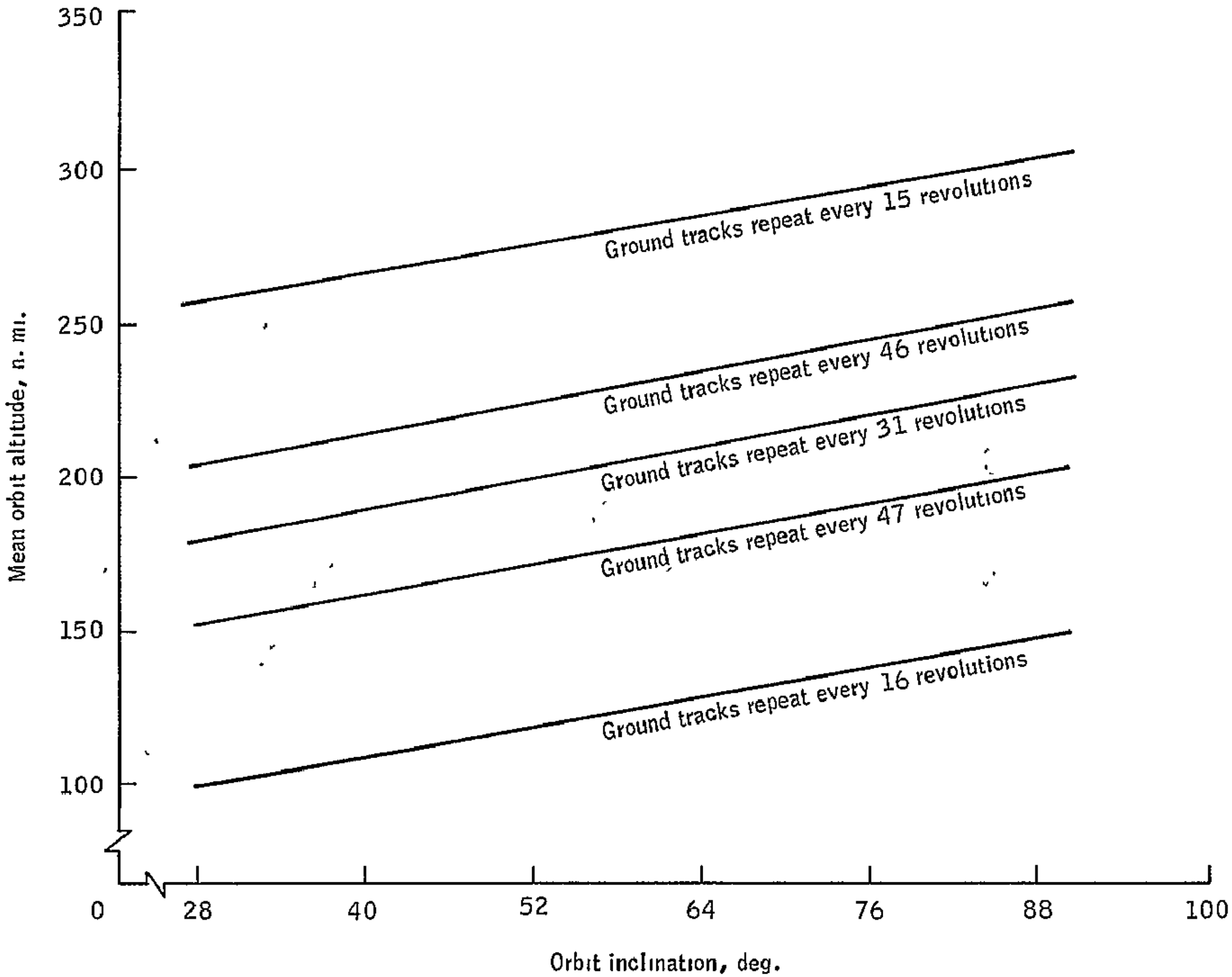
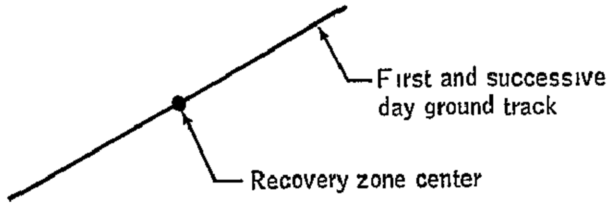
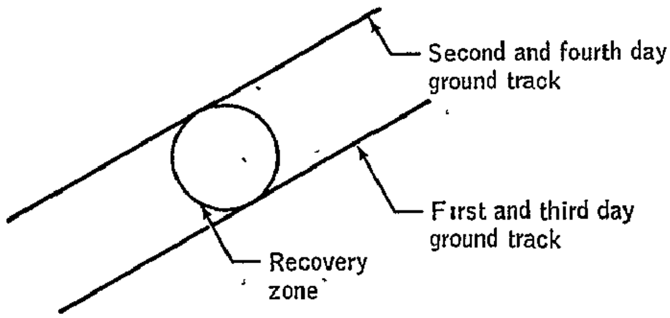


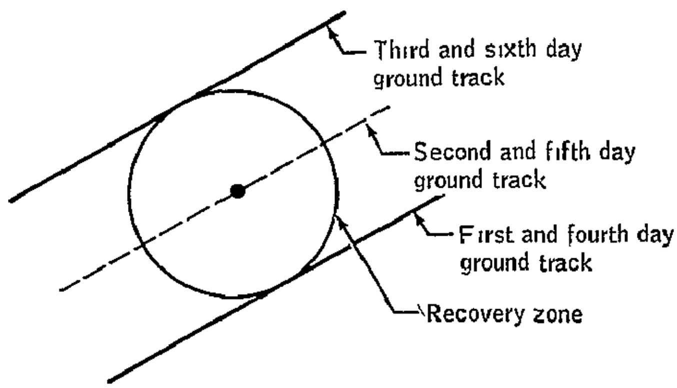
Figure 4 - Orbital conditions for repetitive ground tracks.



(a) Repetitive each day.



(b) Repetitive at two-day intervals.



(c) Repetitive at three-day intervals

Figure 5.- Periodic recovery zones for repetitive ground tracks

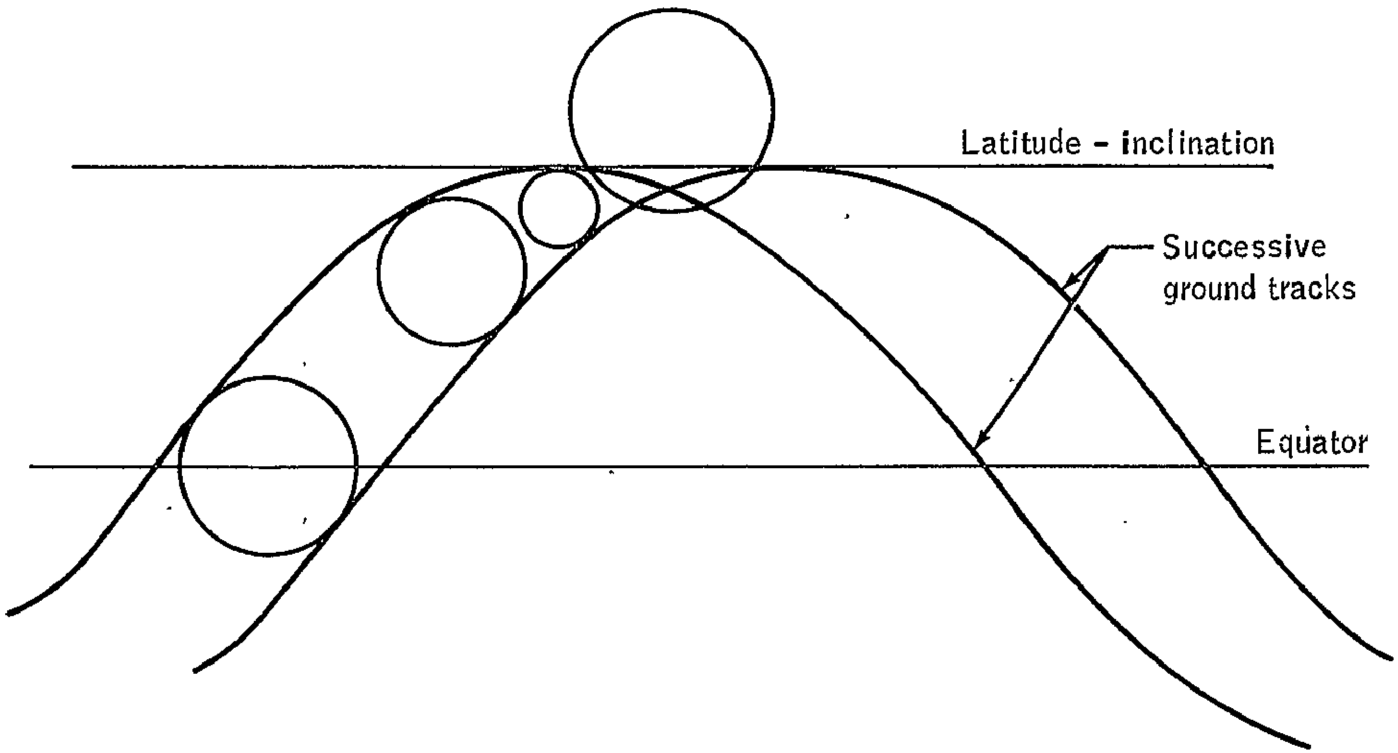


Figure 6.- Site latitude effect on minimum periodic zone size.

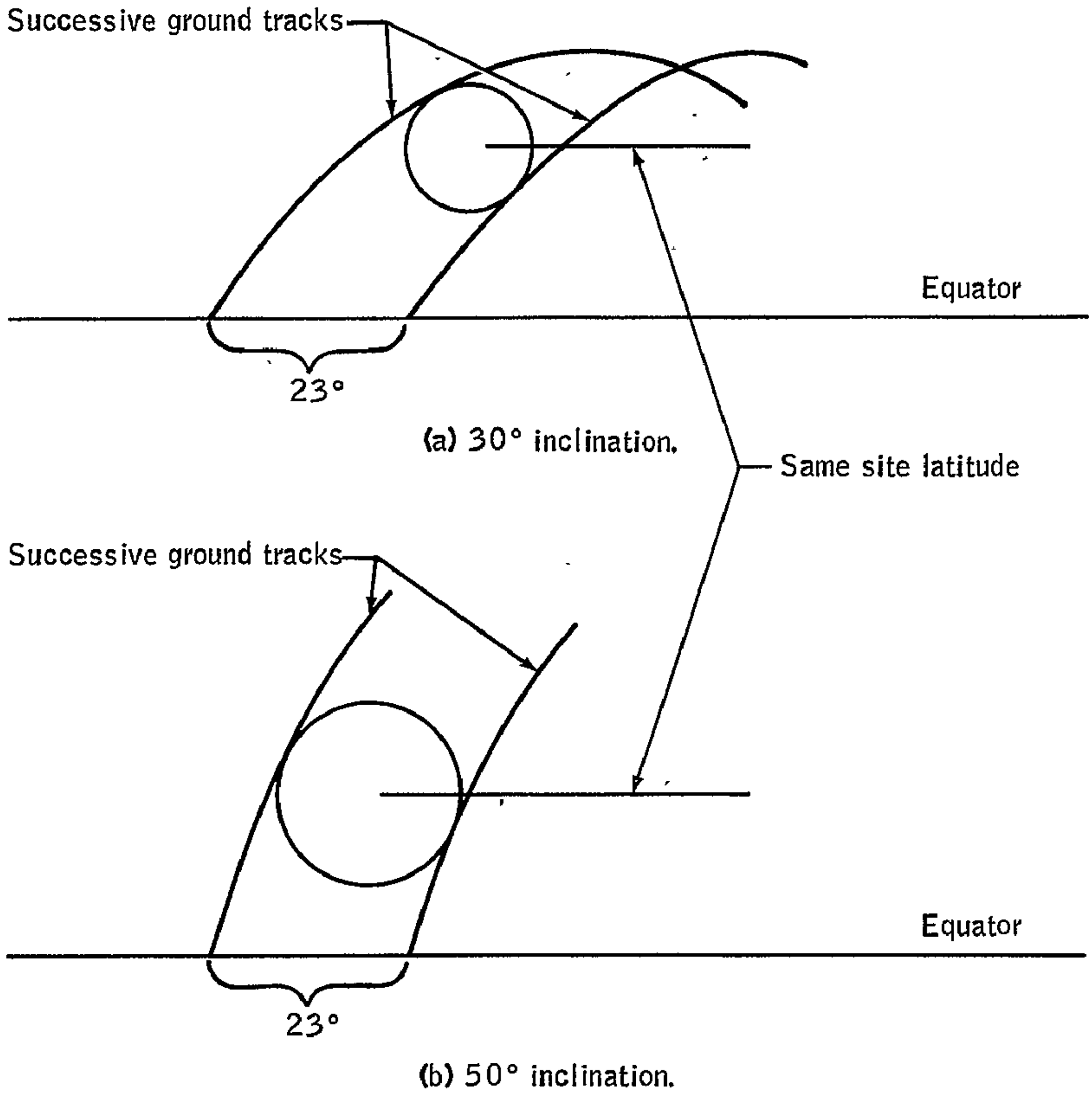


Figure 7.- Inclination effect on minimum periodic zone size at a given site latitude.

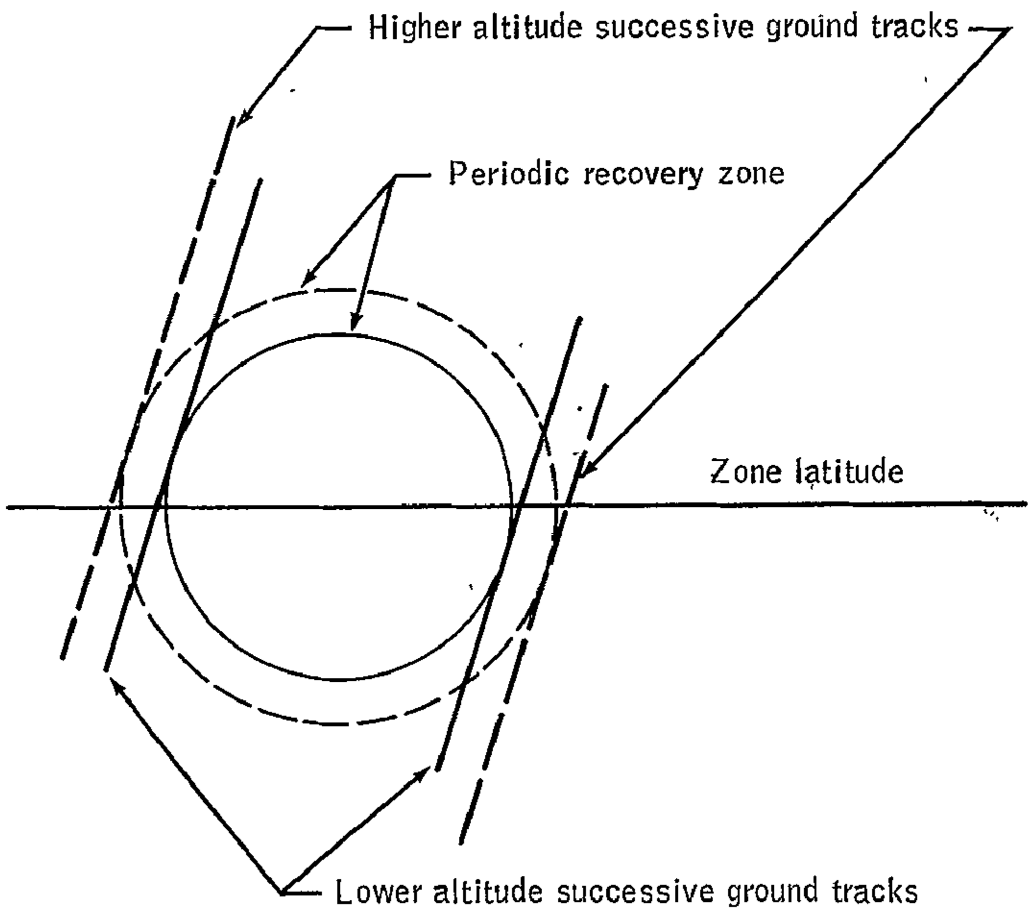
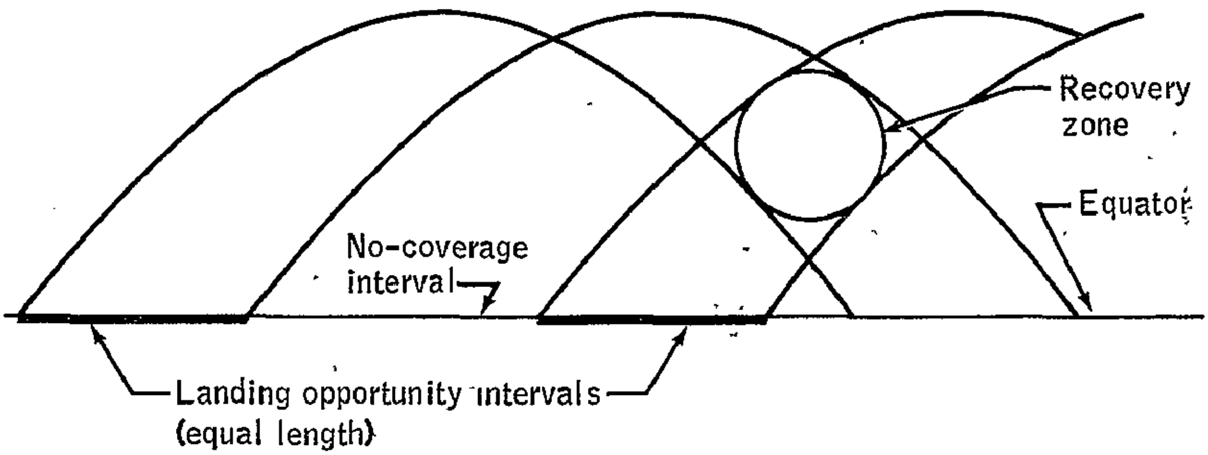
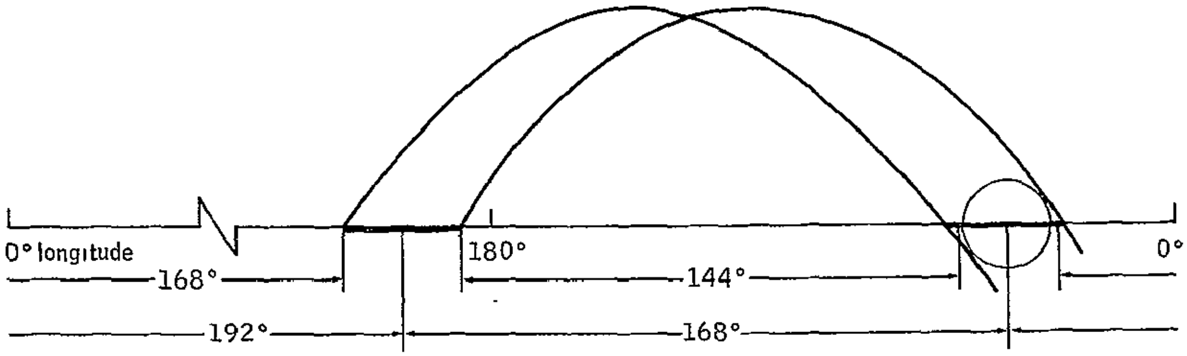


Figure 8.- Effect of orbital altitude on minimum periodic zone size at a given site latitude and orbital inclination.



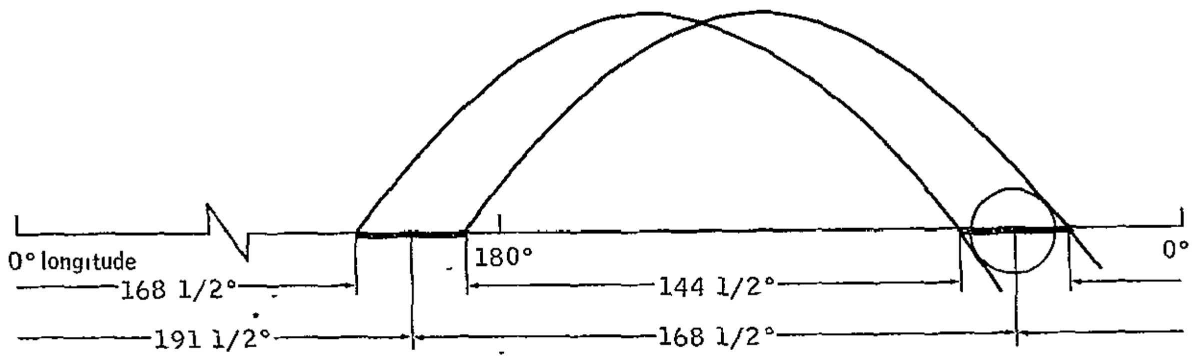
For a zone to be periodic, each interval must be equal to or greater than the longitudinal separation between successive ground tracks.

Figure 9.- Landing opportunity intervals for a given recovery zone.



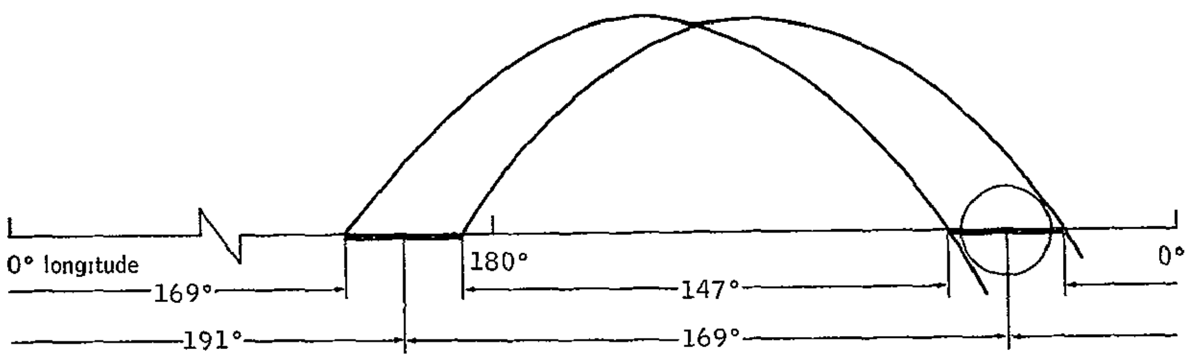
Maximum no-coverage interval is 168°, or eight-revolution wait.

(a) 24° separation between successive ground tracks



Maximum no-coverage interval is 168 1/2°, or nine-revolution wait.

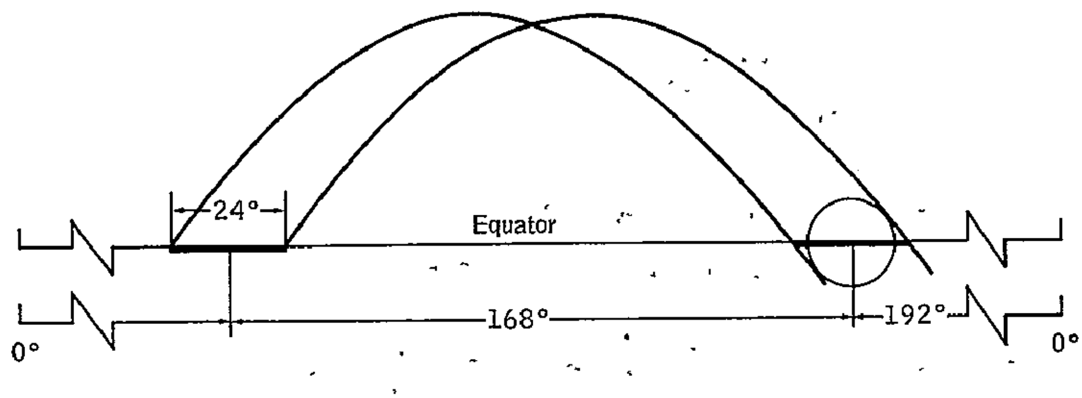
(b) 23° separation between successive ground tracks.



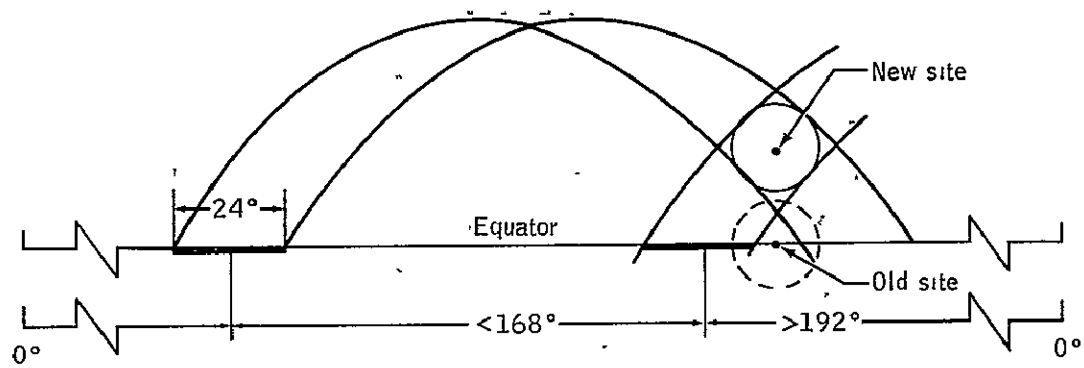
Maximum no-coverage interval is 169°, or nine-revolution wait.

(c) 22° separation between successive ground tracks

Figure 10 - Landing opportunity intervals for periodic equatorial zones.

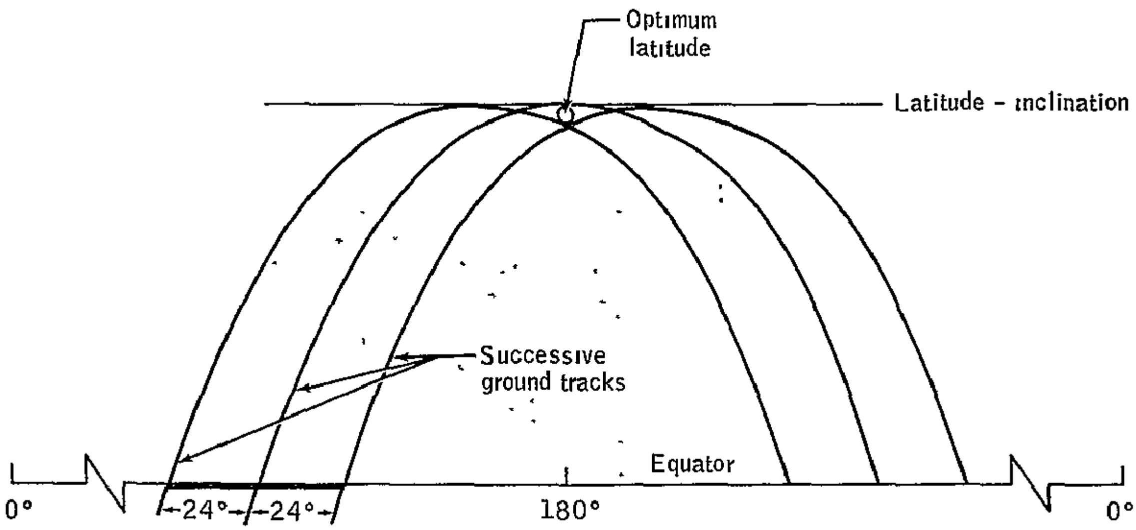


Equator zone no-coverage interval is 192°, or eight-revolution wait

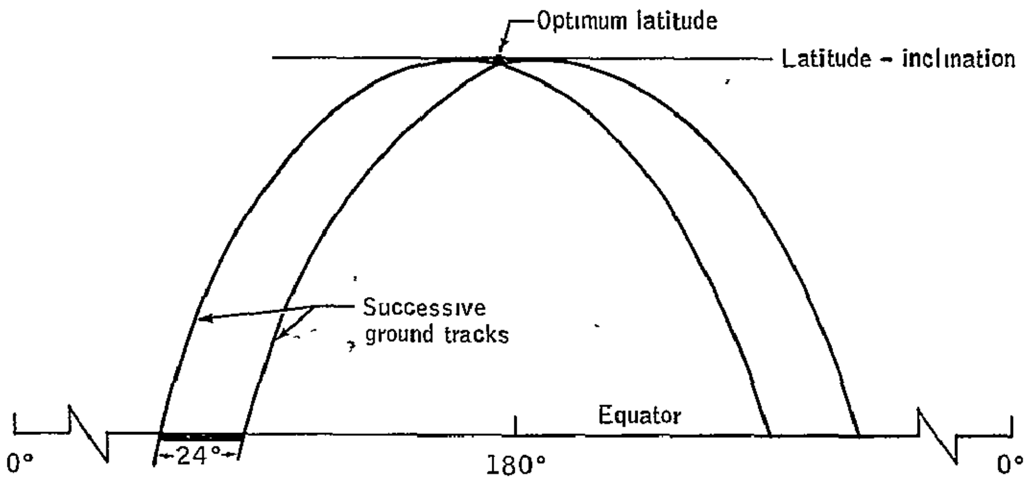


Off-equator zone no-coverage interval is >192°, or >eight-revolution wait

Figure 11 - Landing opportunity interval movement when recovery zone is moved away from equator

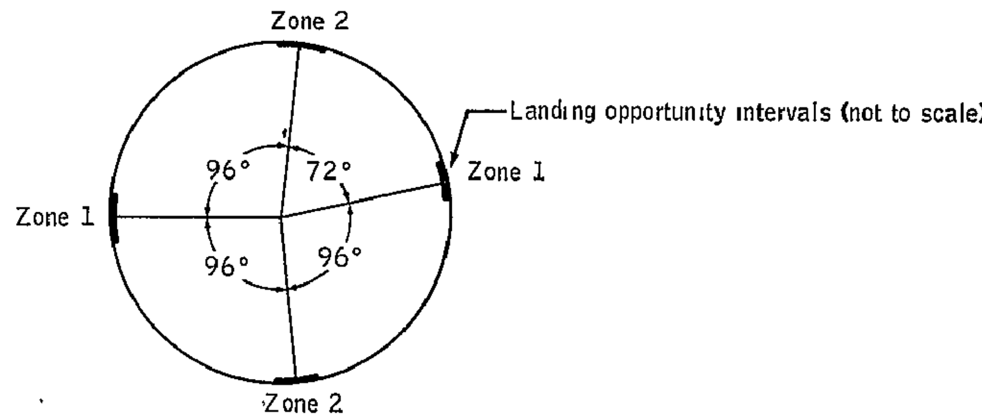


(a) Two consecutive revolutions per day assured.

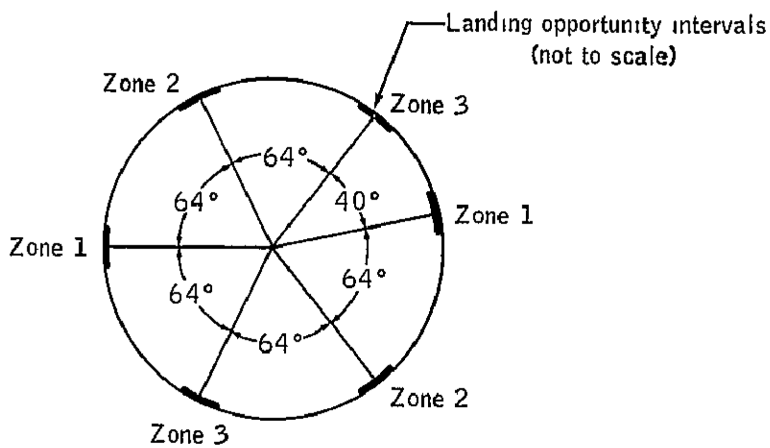


(b) One revolution per day assured.

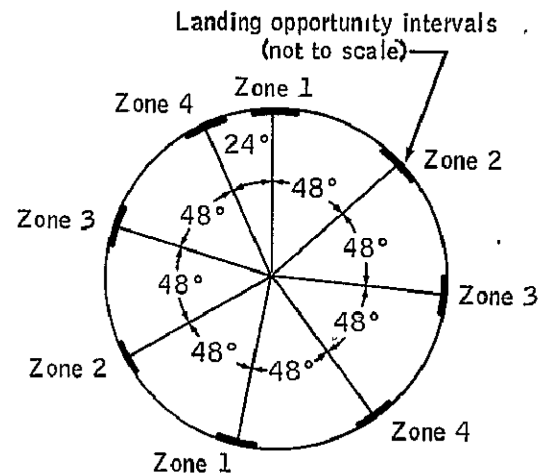
Figure 12.- Optimum-latitude sites for periodic recovery zones.



(a) Two zones showing four landing opportunity intervals with a maximum longitudinal separation of 96° and a four-revolution maximum wait.

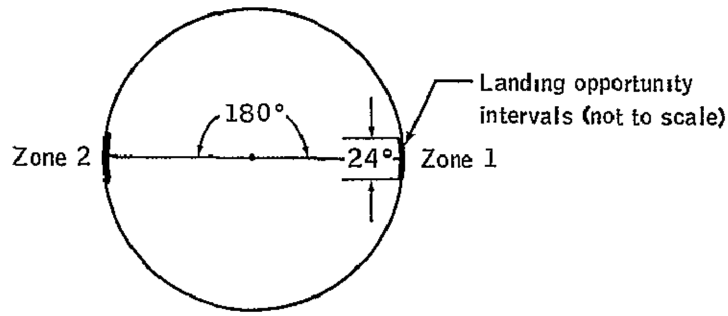


(b) Three zones showing six landing opportunity intervals with a maximum longitudinal separation of 64° and a three-revolution maximum wait.

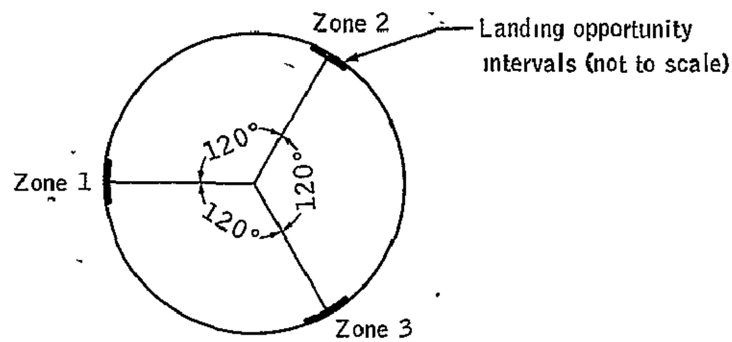


(c) Four zones showing eight landing opportunity intervals with a maximum longitudinal separation of 48° and a two-revolution maximum wait.

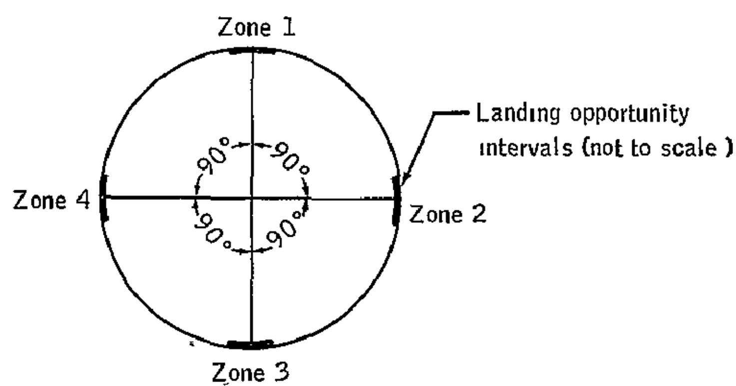
Figure 13.- Landing-opportunity-interval spacing for equatorial recovery zones.



(a) Two zones with a longitudinal separation of 180° and an eight-revolution maximum wait.

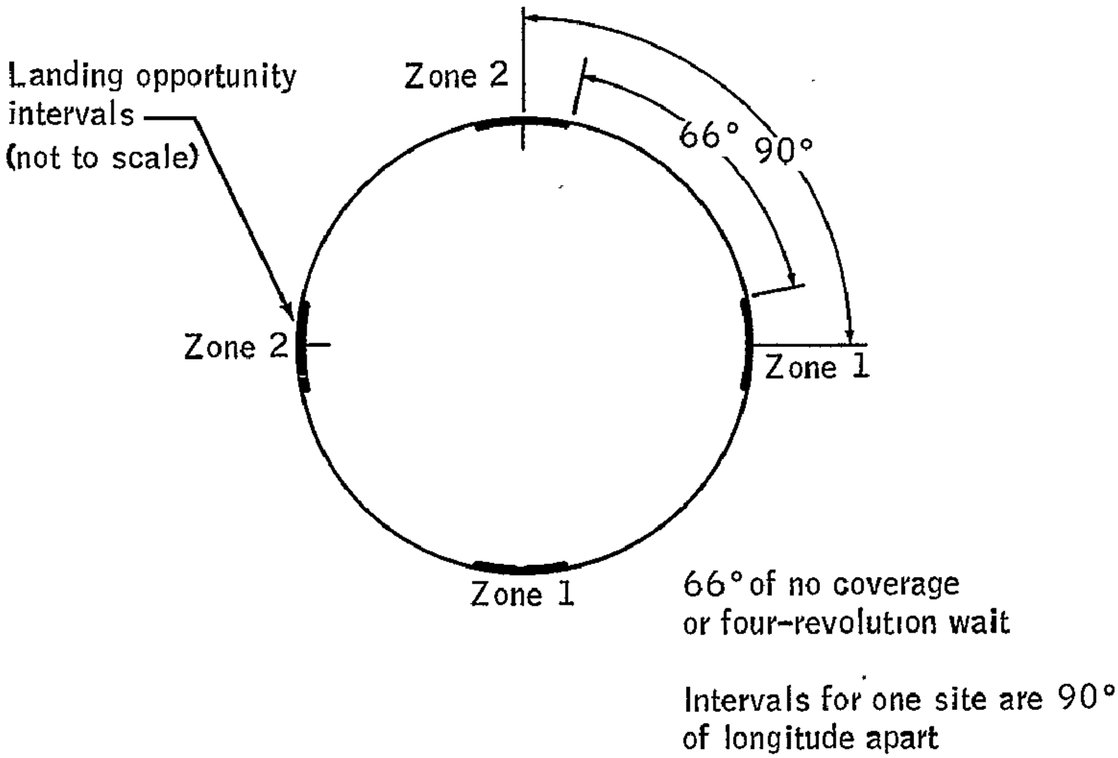


(b) Three zones with a longitudinal separation of 120° and a five-revolution maximum wait.



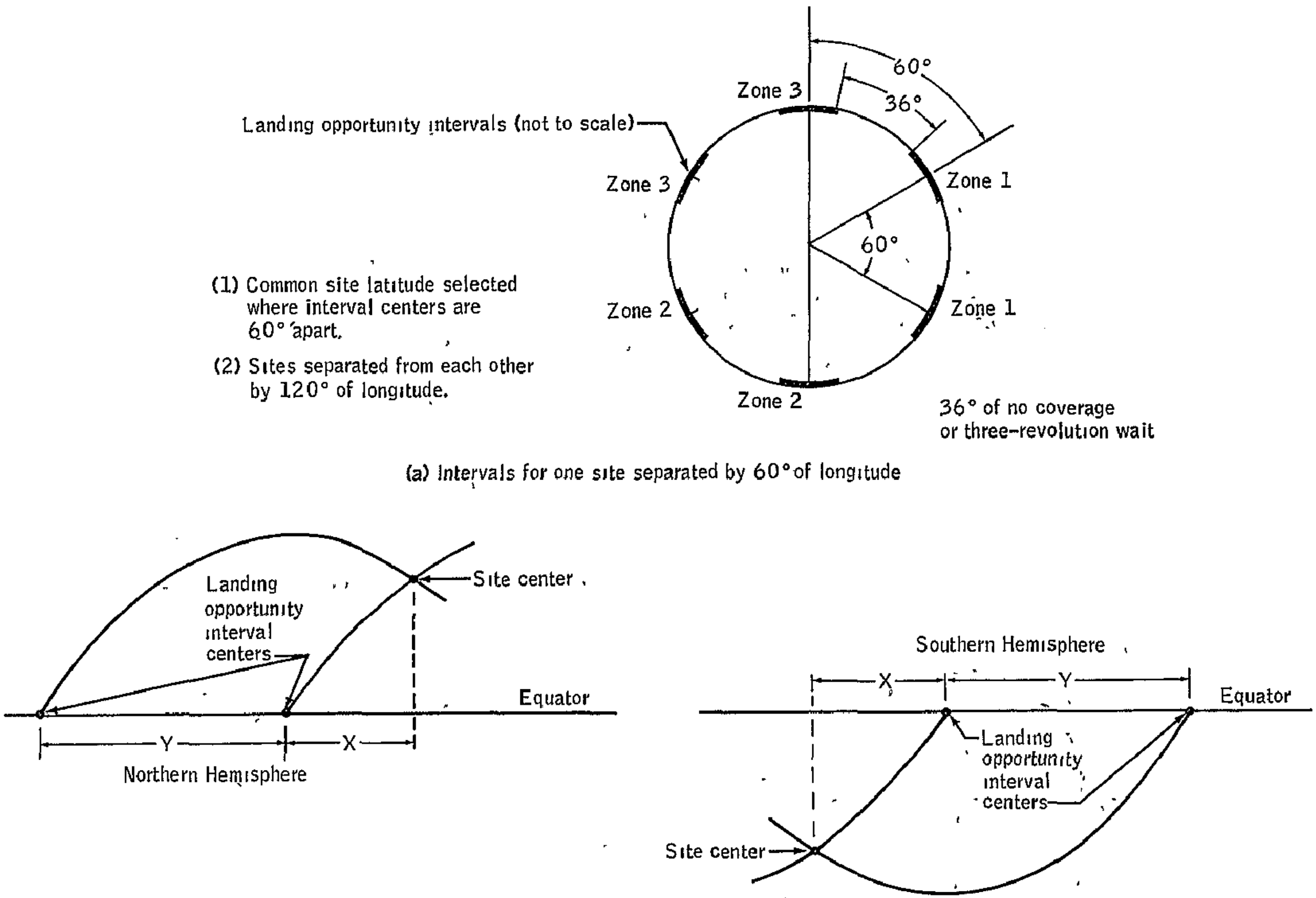
(c) Four zones with a longitudinal separation of 90° and a four-revolution maximum wait.

Figure 14 - Landing-opportunity-interval spacing for
optimum-latitude recovery zones.



(1) Common site latitude selected where interval centers are 90° apart.
(2) Sites separated from each other by 180° of longitude.

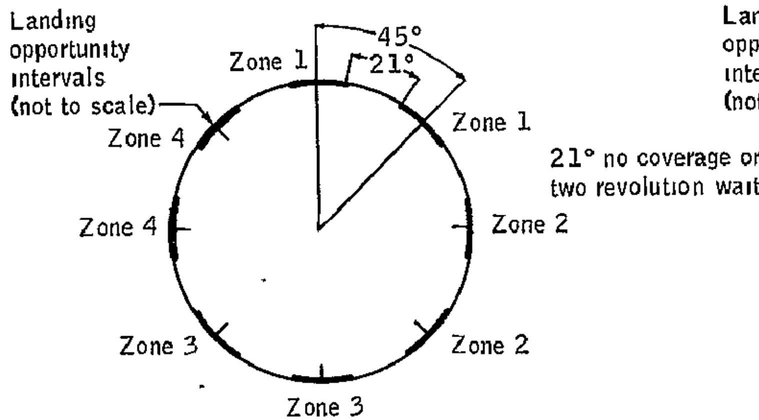
Figure 15.- Optimum landing-opportunity-interval spacing for two off-equator zones.



(a) Intervals for one site separated by 60° of longitude

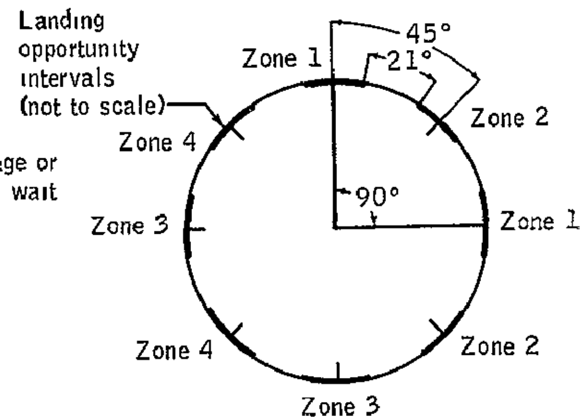
(b) Relative interval centers.

Figure 16 - Optimum landing-opportunity-interval spacing for three off-equator zones.



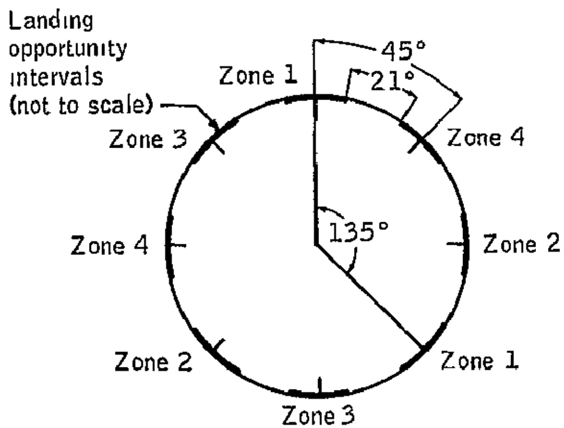
(1) Common site latitude selected where interval centers are 45° apart.
(2) Sites separated from each other by 90° of longitude.

(a) Intervals for one site separated by 45° of longitude.



(1) Common site latitude selected where interval centers are 45° apart.
(2) Sites separated from each other by 45° and 135° of longitude.

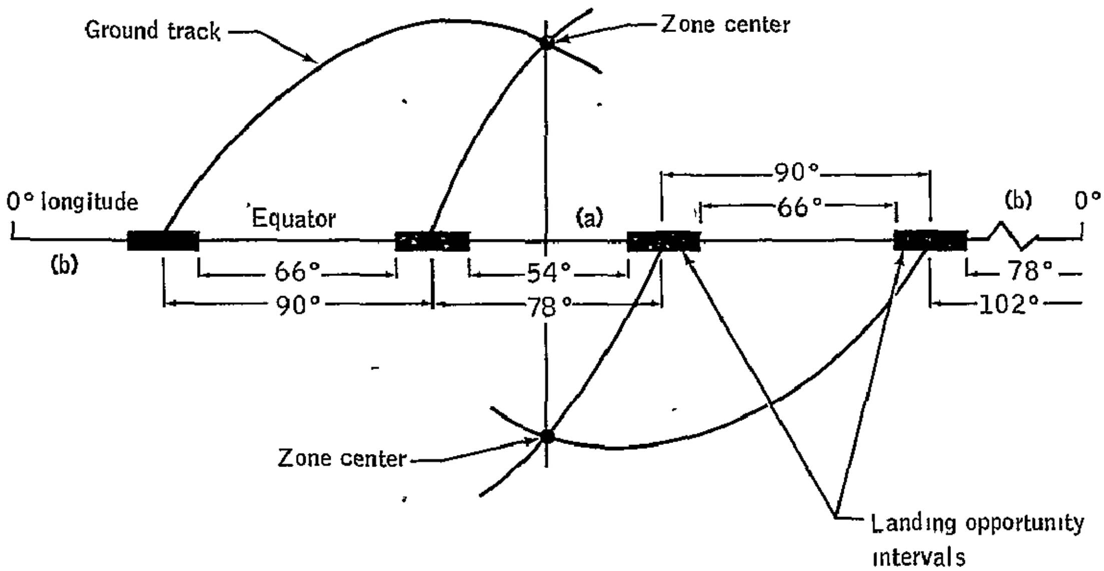
(b) Intervals for one site separated by 90° of longitude.



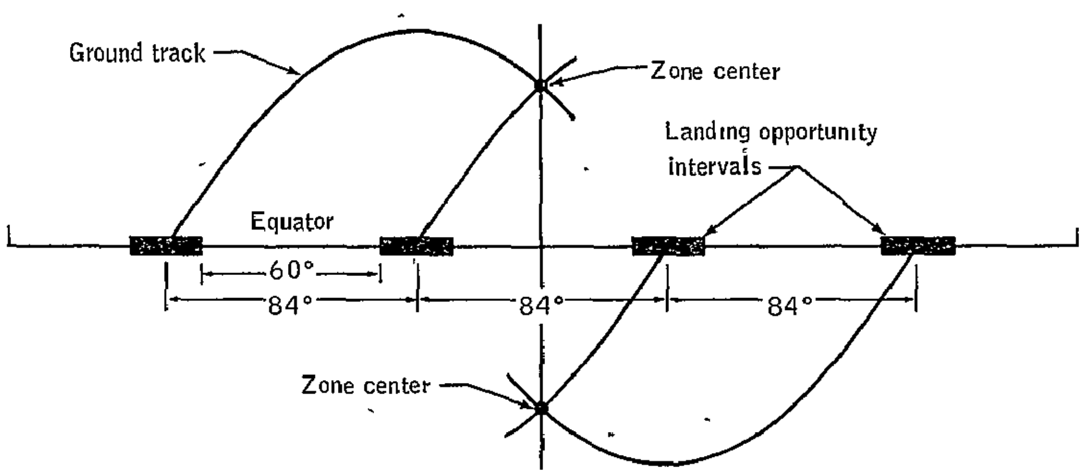
(1) Common site latitude selected where interval centers are 45° apart.
(2) Sites separated from each other by 90° of longitude-same as (a) but at a lower latitude-thus, a larger zone is needed to remain periodic.

(c) Intervals for one site separated by 135° of longitude.

Figure 17 - Optimum landing-opportunity-interval spacing for four off-equator zones.



(a) Zones at latitude where distance between interval centers for one site is 90°.



(b) Zones at latitude where distance between interval centers for one site is 84°.

Figure 18 - Two zones on same longitude — optimum landing-opportunity-interval spacing.

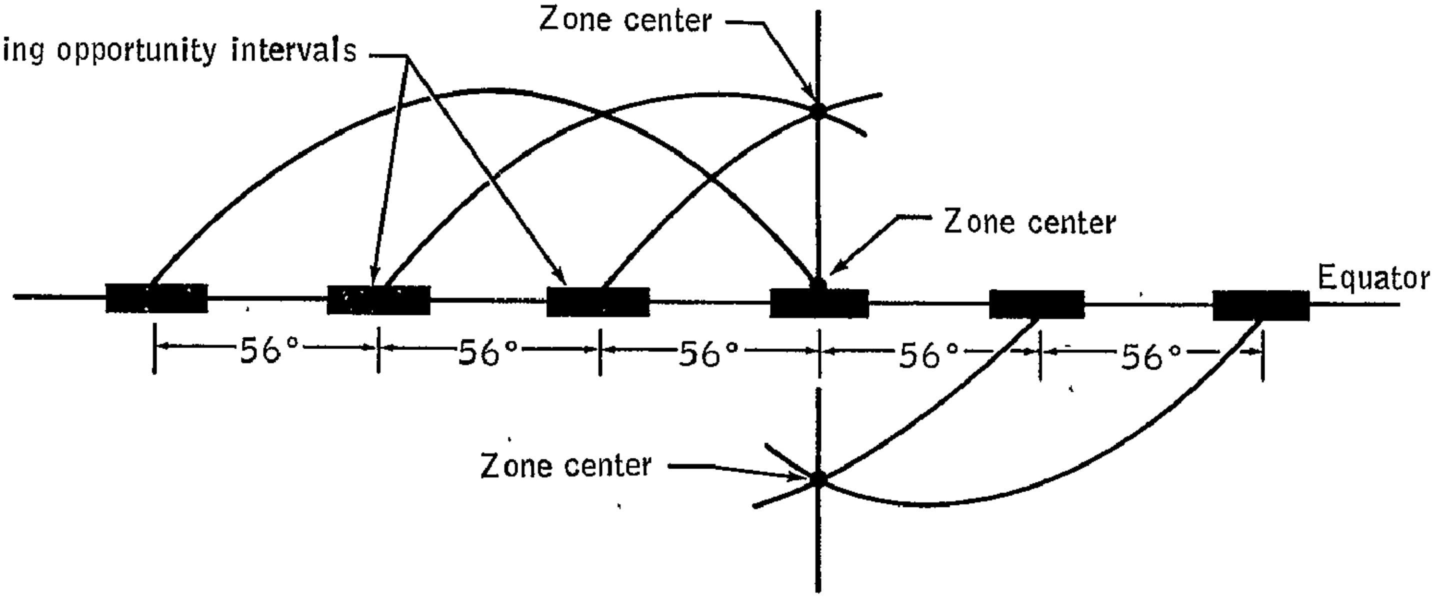


Figure 19.- Three zones on same longitude — optimum landing-opportunity-interval spacing.

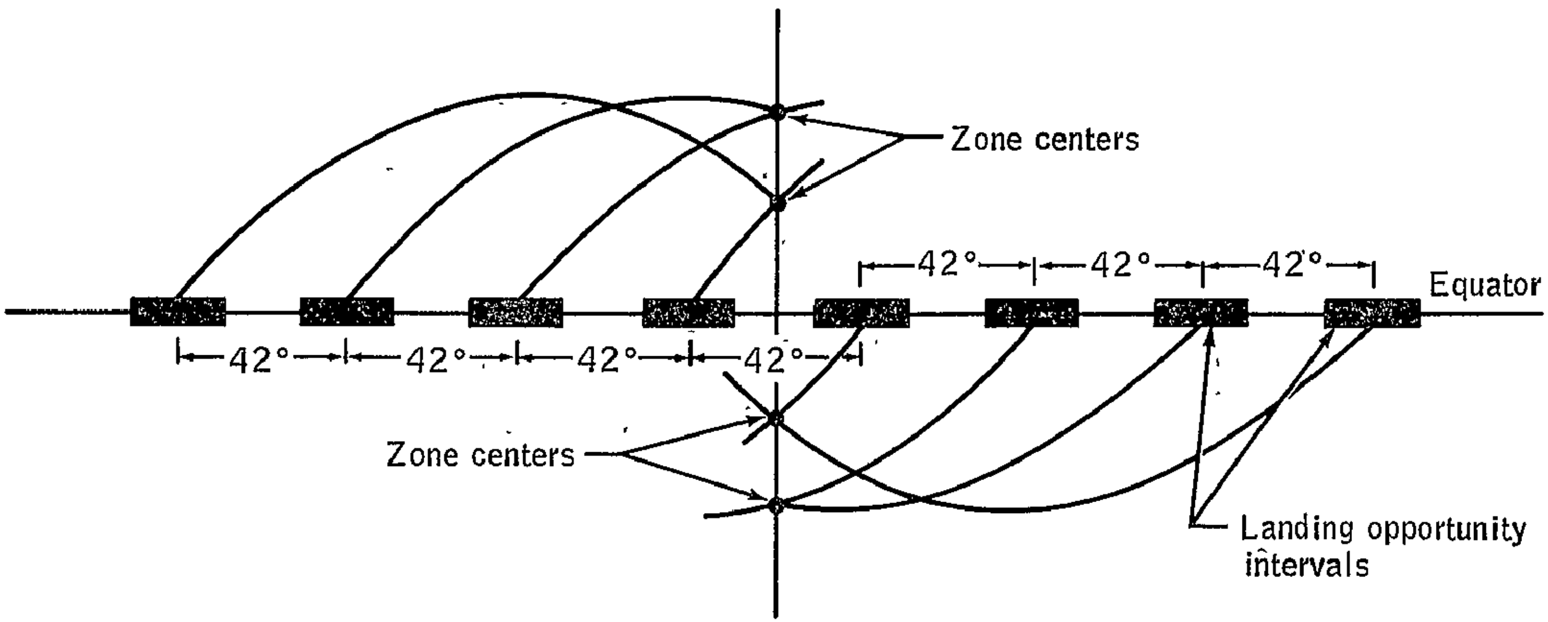


Figure 20.- Four zones on same longitude — optimum landing-opportunity-interval spacing.

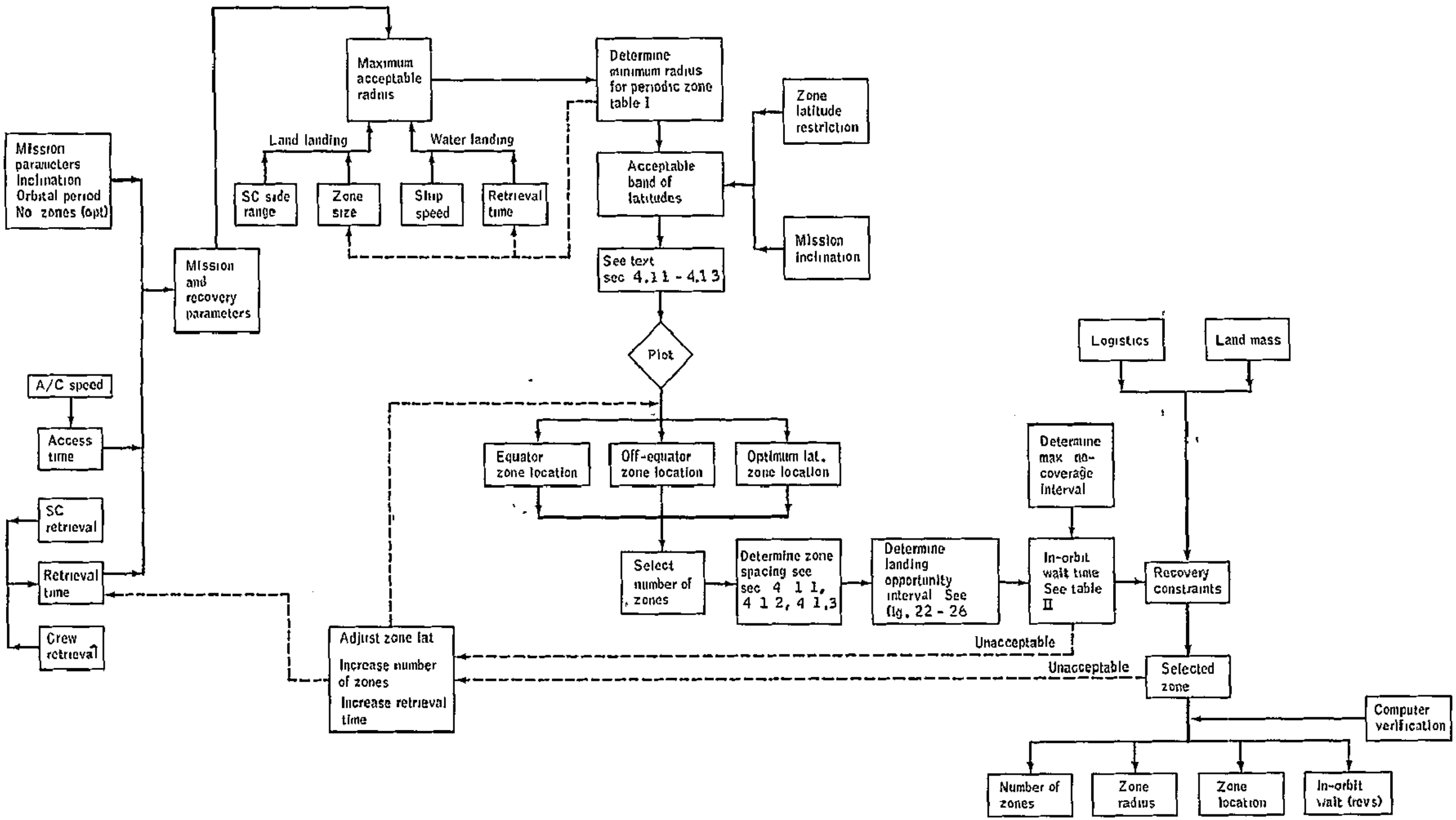


Figure 21 - Flowgram for the analysis of periodic landing zones

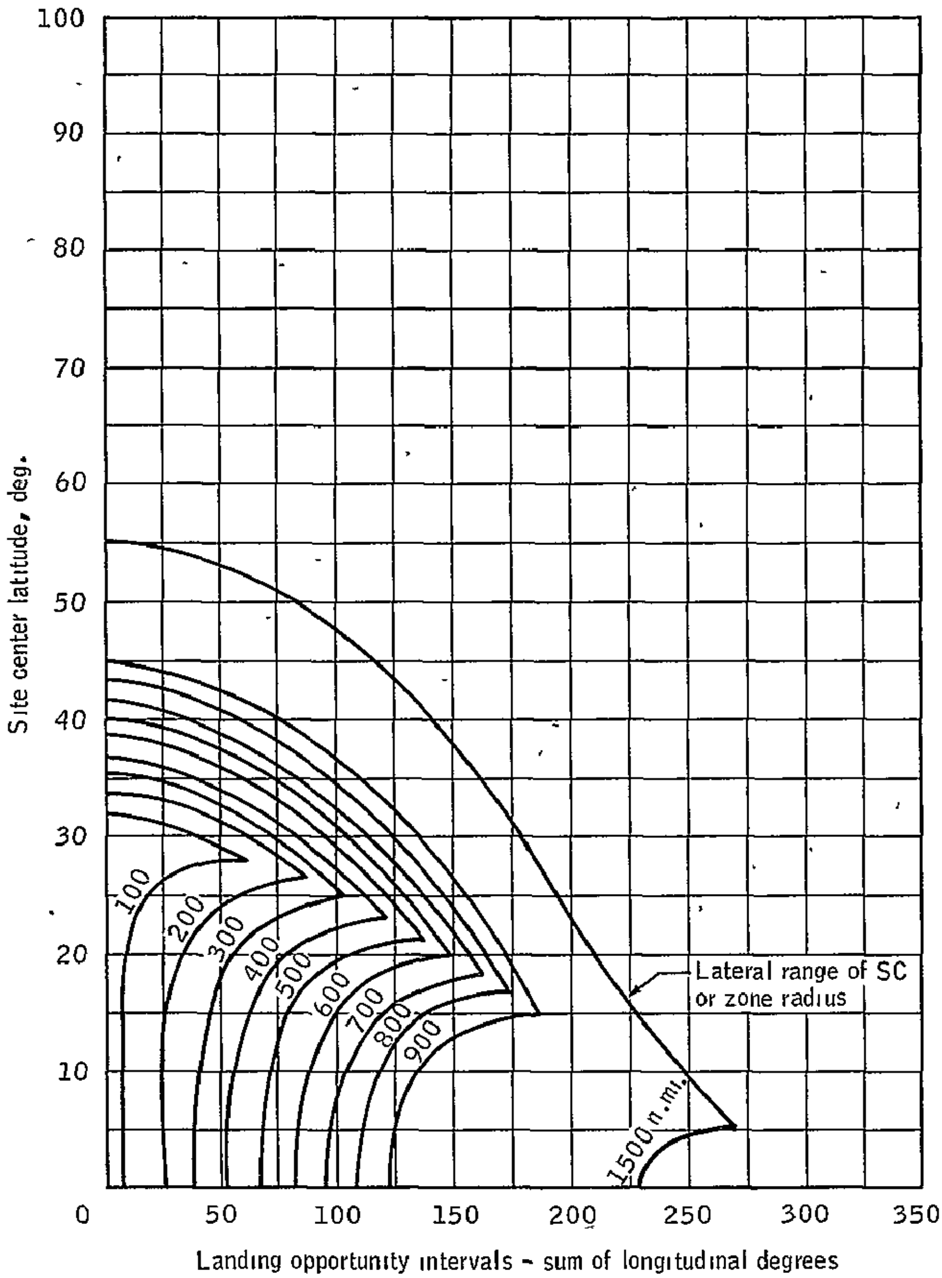


Figure 22.- Landing site accessibility, 30° inclination.

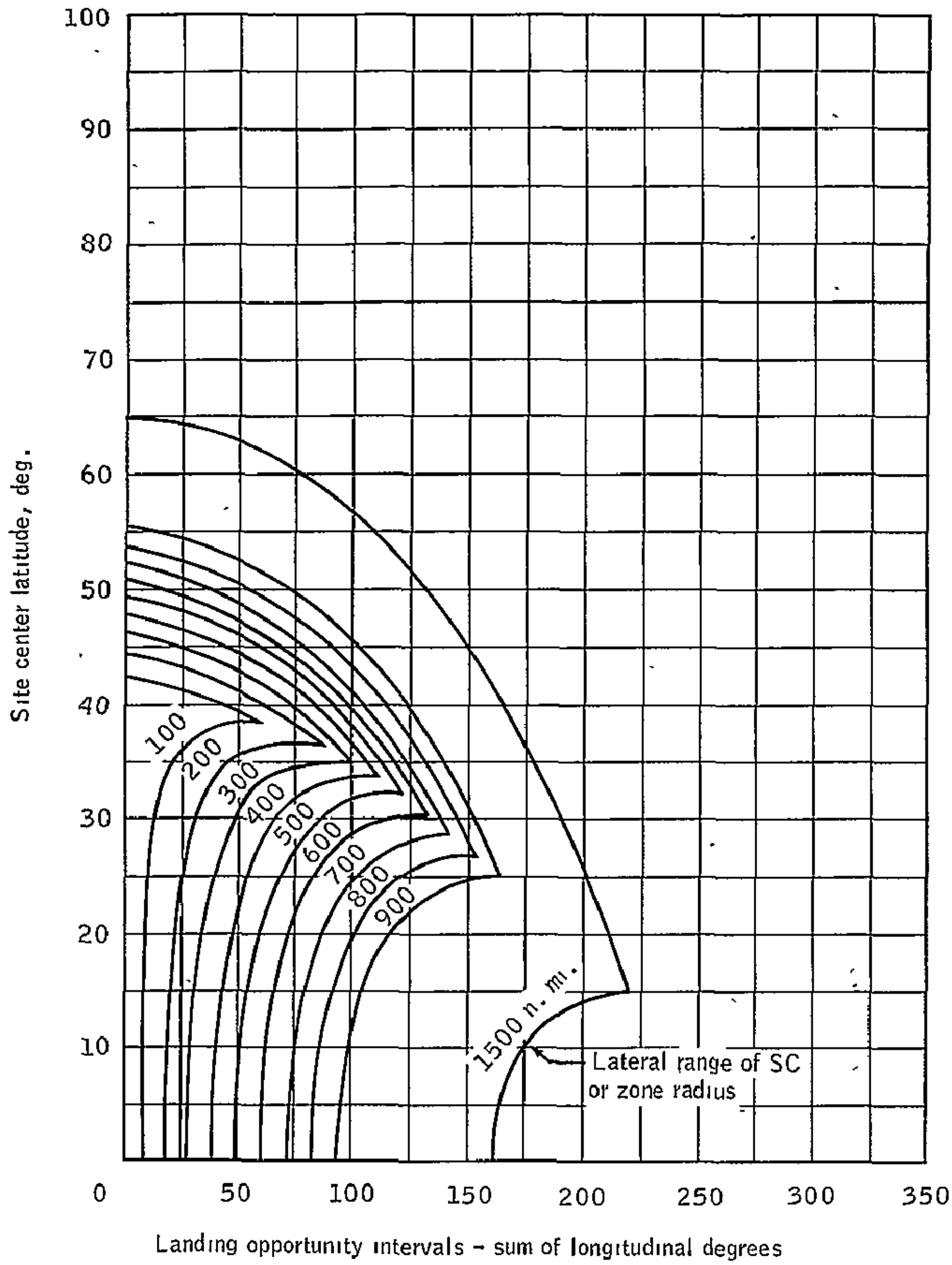


Figure 23 - Landing site accessibility, 40° inclination

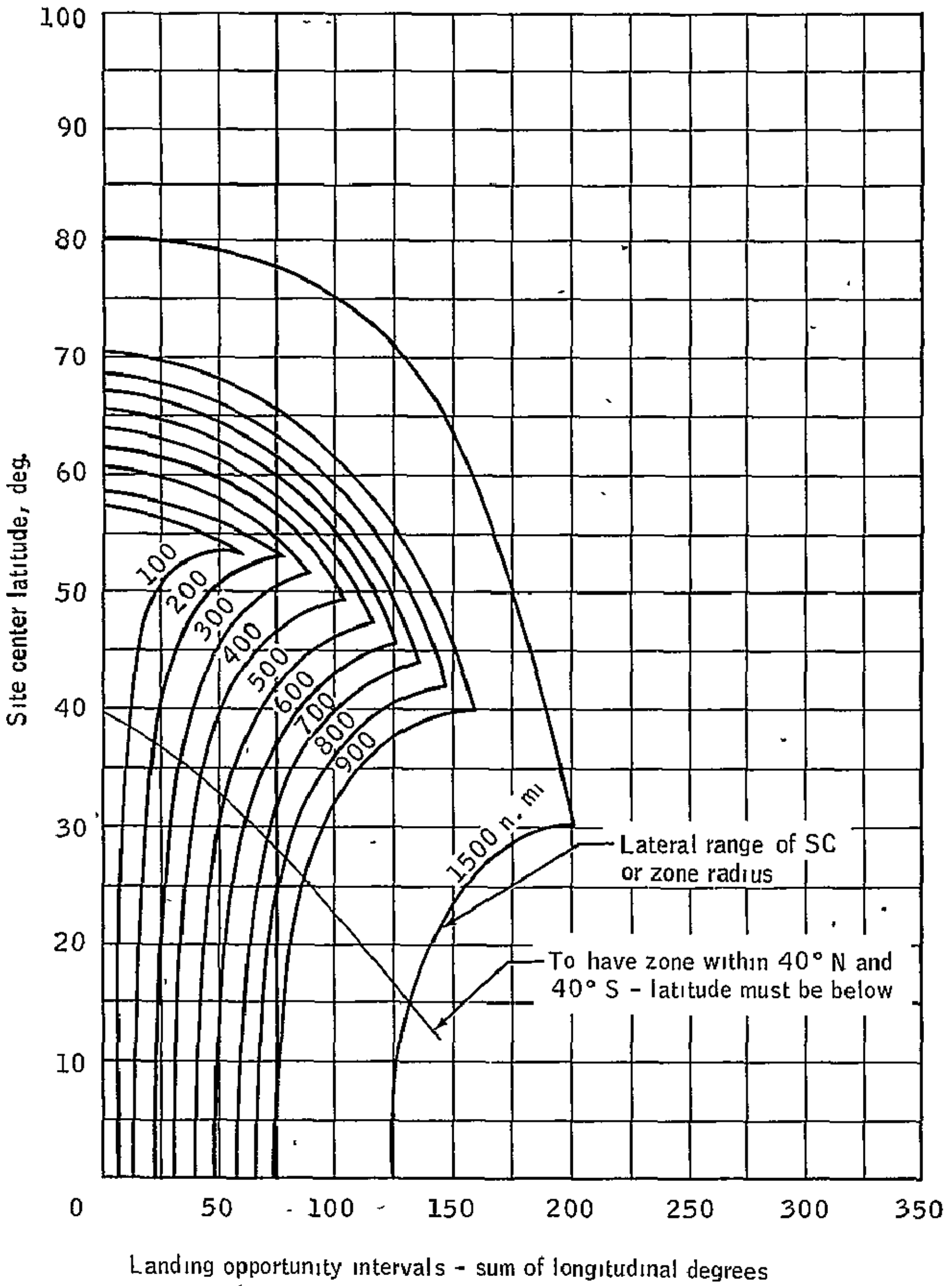


Figure 24 - Landing site accessibility, 55° inclination.

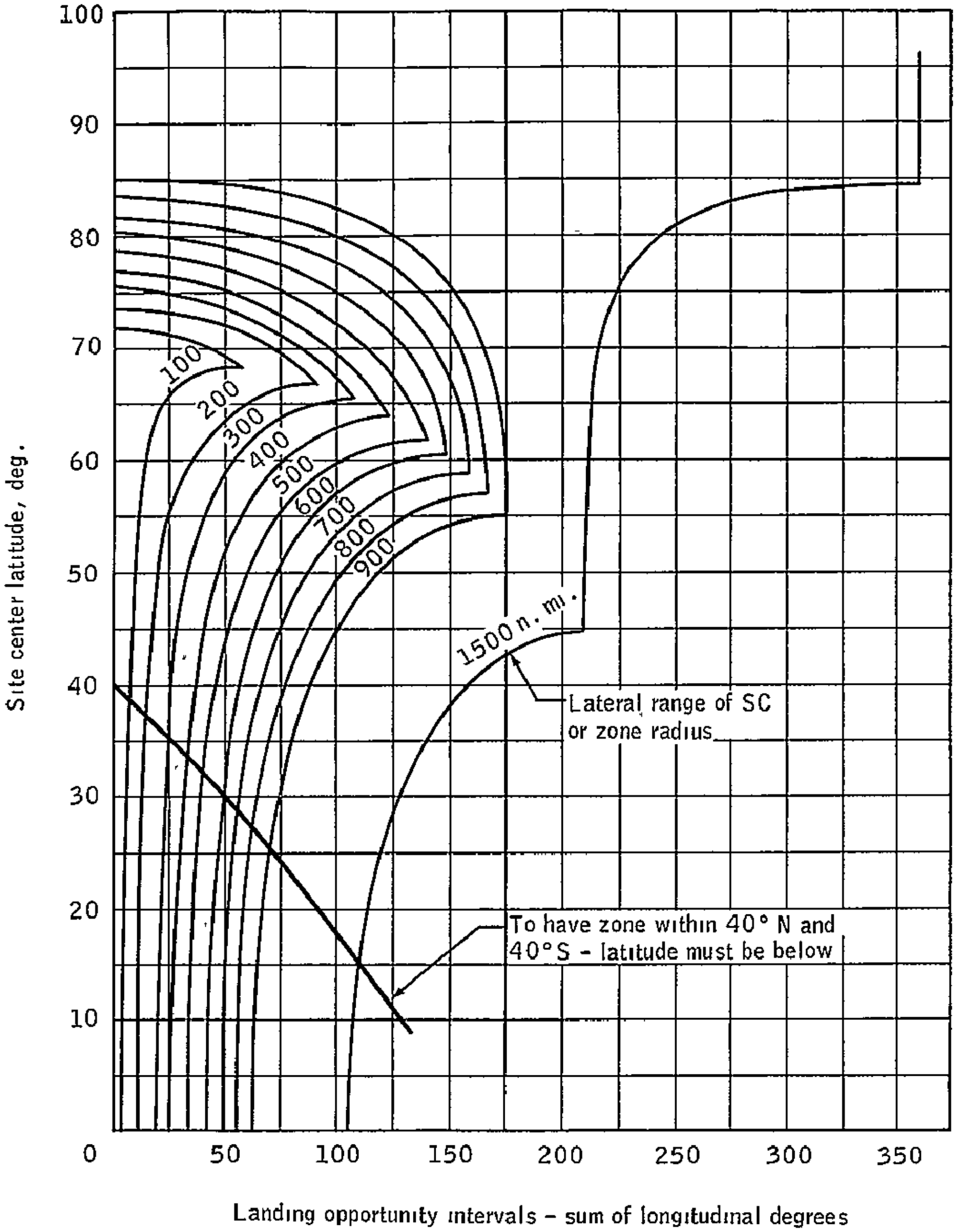


Figure 25.- Landing site accessibility, 70° inclination.

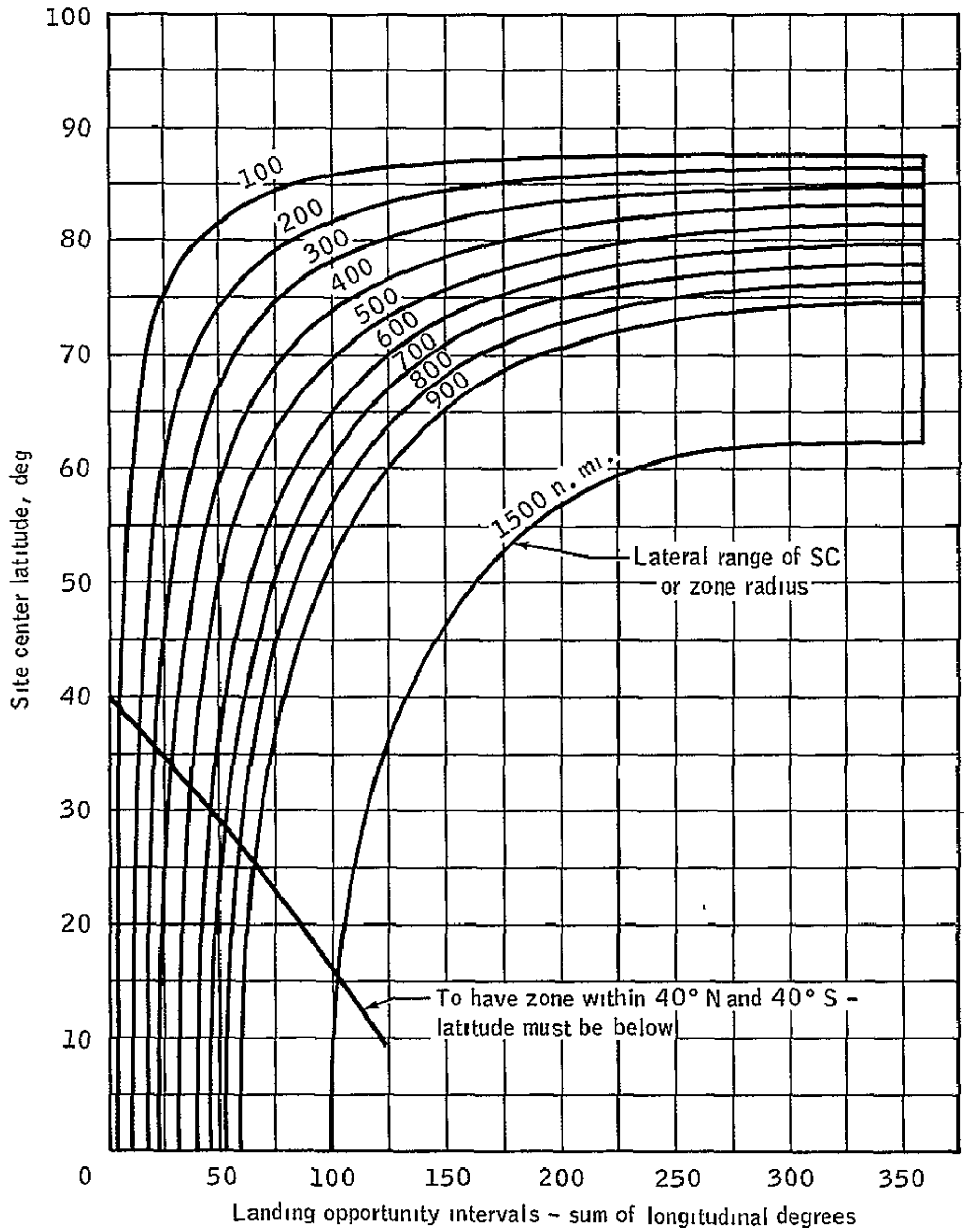


Figure 26 - Landing site accessibility, 90° inclination