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# DEFINITION OF LATERAL-RANGE AND LIFT-DRAG-RATIO REQUIREMENTS FOR RETURN TO BOTH OPTIMUM AND NONOPTIMUM RECOVERY SITES

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## SUMMARY

The problem of return from near-earth circular orbits to both optimum and non-optimum recovery sites has been analyzed in detail in terms of lateral-range-angle and lift-drag-ratio requirements. A technique of analysis has been developed which permits the rapid determination of the variation of the lateral-range angle with time for a given set of mission constraints (recovery-site latitude and longitude and orbit inclination) through the application of a single equation. The lateral range is defined as the latitude of a given recovery site referred to the orbital plane of a spacecraft. Emphasis has been placed on land recovery; however, the results are equally applicable to water recovery.

In particular, the equation for lateral-range angle has been applied with the necessary restrictions to define the optimum location of one, two, three, or four recovery sites and the maximum lateral-range-angle requirements necessary to reach these recovery sites for a range of orbit inclinations from $-90^\circ$ to $90^\circ$. The lift-drag ratio required to reach the recovery networks has been determined as a function of the lateral-range angle. The effects of wait time in orbit on the lateral-range-angle and lift-drag-ratio requirements are presented for optimum recovery sites for both quick return (return during any orbit) and for return after a preselected number of delay orbits. Also, the increase in lateral-range angle required as a result of deviations from the optimum latitude location is included for quick return from an orbit inclination range from $-90^\circ$ to $90^\circ$ to recovery sites located in the full latitude range from $-90^\circ$ to $90^\circ$.

The analysis indicates that optimum multiple recovery sites must be at the same latitude (but not necessarily in the same hemisphere) for any of several possible schemes of longitudinal spacing. Wait time in orbit can be very effective in reducing the lateral-range angle, particularly if a preselected number of delay orbits is considered a mission constraint so that a new definition of the optimum latitude of recovery sites may be made. If optimum longitudinal spacing restrictions are maintained, deviations from the optimum latitude result in rapid increases in the lateral-range angle. On the basis of the present analysis, however, a vehicle with a lift-drag ratio of 2.0 would be capable of return during any orbit with any orbital inclination to a network of three properly located recovery sites. Several examples of the application of the analysis techniques developed herein are given in the appendixes.

# INTRODUCTION

Attempts to define requirements for future entry vehicles must, of necessity, be limited by present projections of future space missions. One such mission is the manned space station. Numerous studies (refs. 1 to 7, for example) which are applicable to the problem of return from a space station in a near-earth orbit have been conducted.

Several studies (refs. 1 and 2) have demonstrated that the use of propulsive power during entry to augment aerodynamic maneuvering (in gaining lateral range) is relatively inefficient for vehicles with low lift-drag ratios and generally unnecessary for vehicles with high lift-drag ratios (although some specific missions may require propulsion). Thus, the primary emphasis has generally been placed on the attainment of any necessary lateral range by aerodynamic maneuvering.

References 3 and 4 treat, in a general fashion, the problem of return from near-earth orbital missions to a specified latitude. Boehm (ref. 3) considers the probability of recall to a given latitude for the full range of orbital inclinations and lateral-range capabilities up to 2000 nautical miles. Stern and Chu's analysis (ref. 4) is similar to that of Boehm but takes the basic approach of defining the distance along a parallel of latitude to which a vehicle with a given lateral-range capability may return. However, neither multiple recovery sites nor optimized locations were considered in these analyses.

Other studies (refs. 1 and 5 to 7) have considered recovery area requirements for return from near-earth orbits. Baradell and McLellan (ref. 1) consider the restricted case of return to multiple sites from polar orbits while Martikan (ref. 5) considers only return to the central Texas area. Boyle (ref. 6) describes recovery areas for one to six orbital recalls per day with ballistic vehicles. Some consideration is also given to multiple recovery areas but the emphasis is on water recovery. For instance, a water landing is required for four of the five areas considered for return from a $29^\circ$ orbital inclination. Campbell and Capuzzo (ref. 7) conducted a more general analysis in which the earth was divided into recovery zones classified as preferred, secondary, undesirable, and unacceptable, on the basis of geopolitical consideration. This analysis considered orbital inclinations of $0^\circ$, $30^\circ$, $60^\circ$, and $90^\circ$ and was primarily concerned with the definition of the recall capabilities of several specific vehicles to these zones.

However, in the studies reviewed, no consideration has been given to the optimization of the recovery site location for orbital return to land bases. It is the basic purpose of this report to treat the problem of return from near-earth circular orbits to optimally located recovery sites. Primary emphasis is on land recovery; however, the results presented are equally applicable to water recovery. In particular, the optimum spacing of one, two, three, and four recovery sites, the corresponding maximum lateral-range angle, and maximum hypersonic lift-drag-ratio requirements for a full range of orbit inclination angles of $-90^\circ$ to $90^\circ$ are presented. The optimum spacing (both latitudinal

and longitudinal location) of recovery sites is defined as that spacing which will minimize the lateral range required to reach a scheduled recovery site or network of sites from a given orbit inclination. Optimum spacing requirements are presented for both "quick" return (i.e., return from any orbit) and for return after a preselected number of delay orbits. Physical examples of recovery sites which are located near optimally for quick return are presented. Also, the effects of a delay-orbit capability on lateral-range-angle and lift-drag-ratio requirements are presented for the optimum recovery-site location dictated by quick-return restrictions.

Finally, the increases in lateral-range requirements resulting from deviations from the optimum latitude location for one, two, three, and four recovery sites are presented for a latitude range from $-90^\circ$ to $90^\circ$ and an orbit inclination range from $-90^\circ$ to $90^\circ$.

The results presented herein for recovery-site selection and for maximum lateral-range-angle requirements are universal in nondimensional form and are thus applicable to entry to any planet. In order to convert lateral-range requirements into lift-drag-ratio requirements, however, it was necessary to consider the further restriction of earth entry from low circular orbits.

## SYMBOLS

| | |
|---|---|
| A,B,... | locations of recovery sites on earth's surface |
| $C_D$ | drag coefficient |
| D | drag |
| k | function of m (see eq. (14)) |
| L | lift |
| m | number of recovery sites |
| n | number of delay orbits |
| $r_e$ | radius of earth |
| S | planform area of vehicle |
| t | time |

| W | weight of entry vehicle |
|---|---|
| y | lateral range (see eq. (10)) |
| $\alpha$ | inclination of orbital plane to equatorial plane (or inclination of plane of approach trajectory to equatorial plane) |
| $\Delta\theta$ | longitudinal spacing of recovery site |
| $\epsilon$ | deviation from optimum location |
| $\theta$ | longitude |
| $\dot{\theta}$ | angular rotation rate of earth |
| $\lambda$ | latitude |
| $\lambda'$ | lateral-range angle (latitude of landing site referenced to orbit plane) |
| $\tau$ | orbital period |

Subscripts:

| A,B,... | recovery sites |
|---|---|
| i | intersection (see fig. 2) |
| s | instantaneous shift of prime landing site (see fig. 2) |
| $\theta$ | longitude |
| $\lambda$ | latitude |
| hyp | hypersonic |
| max | maximum |
| min | minimum |
| opt | optimum |

4

req          required

1,2          maximum positive and negative lateral-range-angle requirements, respectively

## GEOMETRICAL ANALYSIS

The geometry of the problem as considered herein is shown schematically in figure 1(a). In this paper, the lateral-range angle is defined by the latitude angle $\lambda'$ referred to the orbital plane. In order to determine $\lambda'$ in terms of the known quantities $\lambda$, $\theta$, and $\alpha$, consider the spherical triangle ABC (on the earth's surface) shown in figure 1(b), defined by a general point B on the earth's surface and the longitude and latitude of point B. Point O then represents the center of the earth, and plane OAC is the equatorial plane. In order to refer the latitude of point B to the orbital plane, triangle ABC' is shown with $\alpha$ representing the inclination of the orbital plane to the equatorial plane. Therefore, plane OAC' is the orbital plane. Angle $\phi$ is the angle between the longitudinal reference radius and the earth radius to the general point B on the earth's surface. Angle $\gamma$ represents the spherical angle between arcs b and c. The latitude $\lambda'$ and the longitude $\theta'$ of point B are referred to the orbital plane.

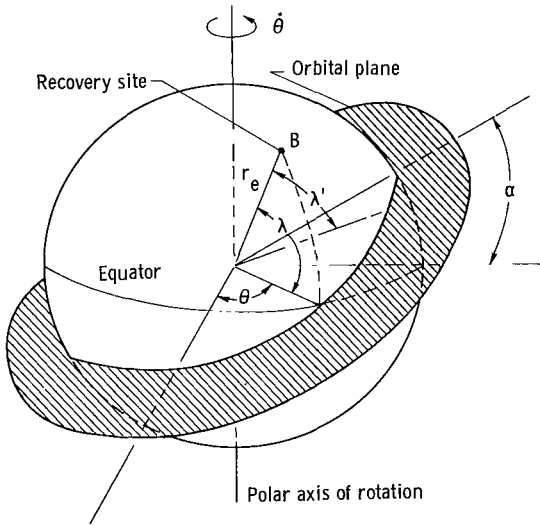In spherical triangle ABC', the following relation must hold:

$$\frac{\sin a'}{\sin A'} = \frac{\sin c}{\sin C'} \tag{1}$$

But C' is the angle between the planes in which $\lambda'$ and $\theta'$ are measured. Thus, C' must be a right angle by definition of longitude and latitude. Also, from figure 1(b), it can be seen that
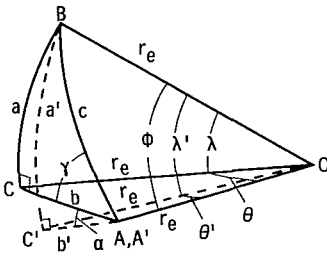
$$\left. \begin{aligned} A' &= \gamma + \alpha \\ c &= \phi \\ a' &= \lambda' \end{aligned} \right\} \tag{2}$$

Equation (1) may now be rewritten by substituting equations (2) so that

$$\sin \lambda' = \sin(\gamma + \alpha)\sin \phi \tag{3}$$



(a) Sketch of geometrical model.



(b) Sketch of spherical triangle on earth's surface.

Figure 1.- Problem geometry.

The angle $\phi$ is a function of longitude and latitude such that

$$\cos \phi = \cos \lambda \cos \theta$$

or

$$\sin \phi = \sqrt{1 - \cos^2\lambda \cos^2\theta} \tag{4}$$

Substituting equation (4) into equation (3) and expanding yields

$$\sin \lambda' = (\sin \gamma \cos \alpha + \cos \gamma \sin \alpha)\sqrt{1 - \cos^2\lambda \cos^2\theta} \tag{5}$$

but

$$\cos \gamma = \frac{\sin \theta \cos \lambda}{\sqrt{1 - \cos^2\lambda \cos^2\theta}} \tag{6}$$

and

$$\sin \gamma = \frac{\sin \lambda}{\sqrt{1 - \cos^2\lambda \cos^2\theta}} \tag{7}$$

Substituting equations (6) and (7) into equation (5) and reducing results in

$$\sin \lambda' = (\sin \lambda \cos \alpha + \cos \lambda \sin \alpha \sin \theta) \tag{8}$$

In order to include the lateral-range variation with time due to the rotation of the earth, the longitude term must include the time dependence; that is, $\sin \theta$ for a rotating earth is given by $\sin(\dot{\theta}t + \theta)$. Finally, equation (8) becomes

$$\lambda' = \sin^{-1}\left[\sin \lambda \cos \alpha + \cos \lambda \sin \alpha \sin(\dot{\theta}t + \theta)\right] \tag{9}$$

The selection of a starting point from which time and longitude may be referred is arbitrary and will not affect the lateral-range requirements determined from equation (9). In the application of equation (9), the intercept of the orbital plane and the equatorial plane is assumed to be alined with the zero earth (planet) longitude line. With this assumption, east longitudes are considered positive and west longitudes, negative. Also north latitudes are considered positive and south latitudes, negative. Once the latitude referred to the orbital plane $\lambda'$ is known, the lateral range in nautical miles may be determined by

$$y = r_e\lambda' \tag{10}$$

The basic assumptions made in the derivation of equation (9) are

(1) a spherical earth

(2) negligible earth wobble (nodal regression)

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In application of equation (9), the rotation rate of the earth will be assumed to be 15°/hour. The position of the vehicle on its orbit is not significant in the present analysis.

## DEFINITION OF OPTIMUM LOCATION REQUIREMENTS OF RECOVERY SITES FOR QUICK-RETURN CAPABILITY

The optimum spacing (both latitude and longitude location) of recovery sites has been defined as that spacing which will minimize the lateral-range angle $\lambda'$ required to reach a scheduled site or network of recovery sites on return from a given orbit inclination. Equation (9) describes the sinusoidal variation of this lateral-range angle $\lambda'$ with time for a given set of governing conditions ($\alpha$, $\lambda$, $\theta$). Variation of the longitudinal location of a recovery site affects the lateral range by shifting the curve of the variation of lateral-range angle with time, so that, for different values of $\theta$, the maximum and minimum values of $\lambda'$ occur at different times. For quick return, the vehicle must be capable of return at some time during any orbit of the 24-hour period. The lateral-range-angle requirement necessary to insure this capability is the maximum requirement which occurs during the 24-hour period. Equation (9) represents a sinusoidal variation of $\lambda'$ with time for which the relative location of the $\lambda' = 0$ axis of the curve is determined by the value of $\lambda$ for a given orbit inclination. In order to minimize the maximum value of $\lambda'$ for the time when a given site is the prime recovery site, a given site must be the prime recovery site for the minimum possible time daily. Therefore, each site of a recovery network must be the prime site for an equal amount of time during the 24-hour period — that is, each site must be the prime site for a time of

$$t = 24/m \text{ hours} \tag{11}$$

daily. This requirement results in a longitudinal spacing restriction of $\Delta\theta = 360°/m$ if each site of the multiple-recovery-site network is to be located in the same hemisphere. Equivalent, alternative longitudinal spacing schemes can result by locating one or more sites in opposite hemispheres with a 180° shift in longitude. (A detailed discussion of alternative longitudinal spacing schemes is presented subsequently in this section.)

The optimum longitudinal and lateral spacing of recovery sites may now be defined with the aid of figures 2 to 4 which describe the variation of $\lambda'$ with time for typical spacing techniques for two, three, and four recovery sites. An orbit inclination of 30° was selected for these examples for illustrative purposes. The solid curves in figures 2 to 4 indicate the time during a 24-hour period for which each site is the prime recovery site. These curves were generated by assuming equal latitude (but not necessarily the same hemisphere) of multiple recovery sites within a given recovery network and by utilizing the longitudinal spacing just discussed. Although it has not been proven thus far,
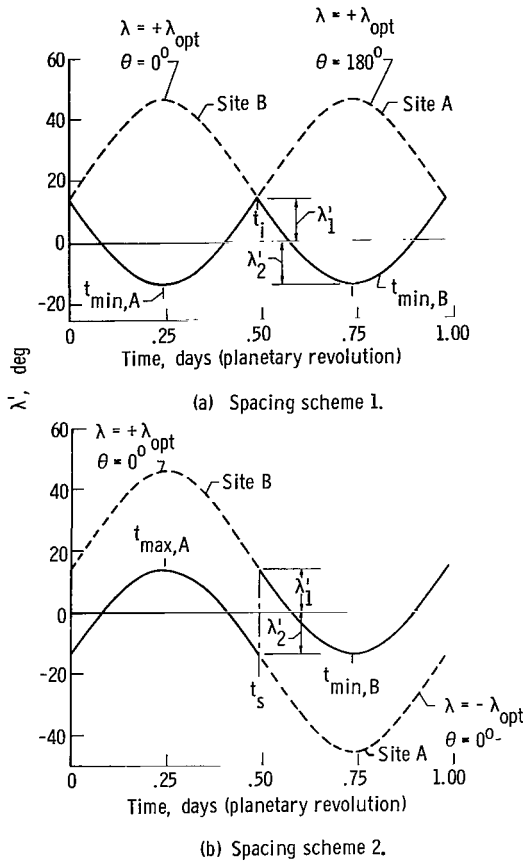
(a) Spacing scheme 1.



(b) Spacing scheme 2.

Figure 2.- Requirements for return to two optimally spaced recovery sites, $\alpha = 30°$. Solid lines indicate time each site is the prime recovery site.

this spacing technique comprises optimum spacing of recovery sites and the proof of this is presented in the following discussion.

With the restriction of equation (11), an instantaneous change from one prime recovery site to another must be made at either the time of intersection $t_i$ (see fig. 2(a)) or the time of shift $t_s$ (see fig. 2(b)). Analysis of figure 2 clearly indicates that if either recovery site A or B were required to be the prime site for a time greater than $24/m$ hours (12 hours in the case of $m = 2$, fig. 2), then the lateral-range angle required to insure quick-return capability would necessarily be greater than those in the figure $\left(\left|\lambda_1'\right| = \left|\lambda_2'\right| = \text{Maximum lateral-range angle required}\right)$.

Optimum Latitude Location

The symmetry of the geometrical problem dictates that the latitudes of multiple recovery sites be equal in magnitude although not necessarily in the same hemisphere. The minimum lateral-range-angle requirement results when

$$\left|\lambda'\right|_{t_{min,A}} = \left|\lambda'\right|_{t_{min,B}} = \left|\lambda'\right|_{t_i} \quad \text{or} \quad \left|\lambda'\right|_{t_s} \tag{12}$$

In equation (12), the subscript $t_{min}$ indicates the time for which the slope of the curve of the variation of $\lambda'$ with $t$ is zero and $\lambda'$ has the smallest absolute value $\big($i.e., $t_{min,A}$ and $t_{min,B}$ in fig. 2(a) and $t_{max,A}$ and $t_{min,B}$ in fig. 2(b)$\big)$. For a given orbit inclination $\alpha$ and for a given number of sites $m$, the restrictions of equations (11) and (12) together with the general equation (9) require that the magnitude of the optimum latitudes of multiple sites A, B, C, . . . be equal. Analysis of figure 2(a) indicates that if $\lambda_A \neq \lambda_B$, $\lambda'$ will not be minimized. For the case of $m = 2$ and the restrictions of equations (11) and (12), equation (9) may be solved to show that the optimum latitude of recovery sites must be

$$\left|\lambda_{opt}\right| = \tan^{-1}\left(\frac{\tan \alpha}{2}\right) \tag{13}$$

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Therefore, for $\alpha = 30^O$

$$\left|\lambda_{opt}\right|_A = \left|\lambda_{opt}\right|_B = 16.1^O$$

If the latitude of either site A or B were allowed to be less than $16.1^O$, then the value of $\lambda'$ at time $t_{min,A}$ or $t_{min,B}$ would be greater than the value of $\lambda_2'$ indicated in figure 2(a). Similarly, if the latitude of either site A or B were allowed to be greater than $16.1^O$, then the value of $\lambda'$ at time $t_i$ would be greater than the value of $\lambda_1'$ indicated in figure 2(a). For the latter case, the value of $\lambda'$ at time $t_{min,A}$ or $t_{min,B}$ would be reduced to less than $\lambda_2'$. However, the requirements for quick return would be governed by $\lambda'$ at $t = t_i$ and the lateral-range-angle requirements would be greater than those for optimum location $\left(\left|\lambda_{opt}\right| = 16.1^O\right)$. Equation (13) may be written generally as

$$\left|\lambda_{opt}\right| = \tan^{-1}(k \tan \alpha) \tag{14}$$

where k is a function of m.



(a) Spacing scheme 1.

(b) Spacing scheme 2.

Figure 3.- Requirements for return to three optimally spaced recovery sites, $\alpha = 30^O$. Solid lines indicate time each site is the prime recovery site.



(a) Spacing scheme 1.

(b) Spacing scheme 3.
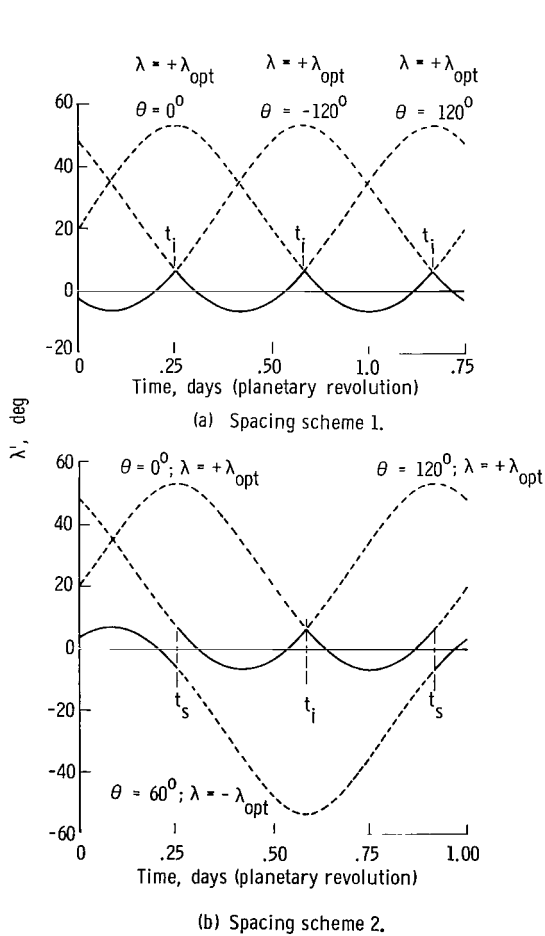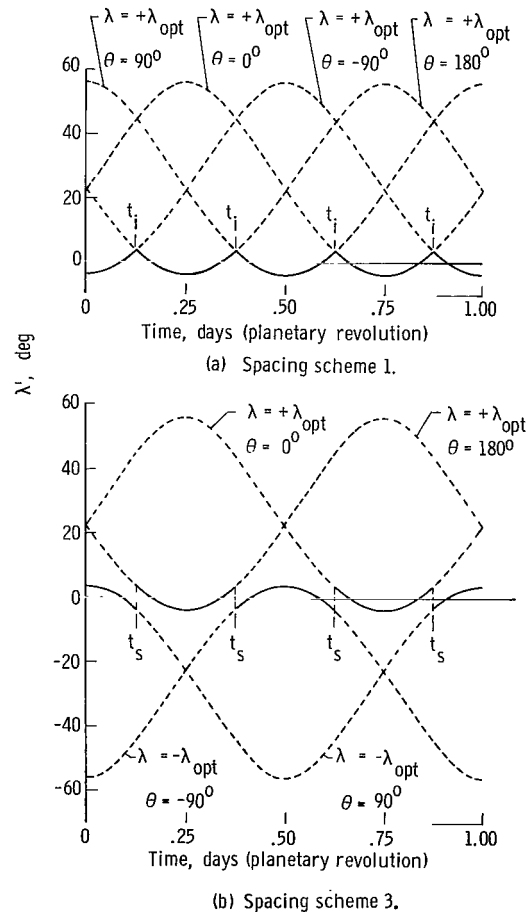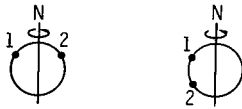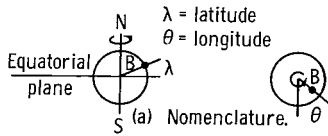
Figure 4.- Requirements for return to four optimally spaced recovery sites, $\alpha = 30^O$. Solid lines indicate time each site is the prime recovery site.

Equation (14) may be used with the proper value of k to determine the optimum latitude for any orbit inclination for return to networks of recovery sites with m = 2, 3, or 4. The following table lists the appropriate values of k and the optimum values of latitude for the two-, three-, and four-site recovery networks for return from a $30^{\circ}$ orbit determined from equation (14) and plotted in figures 2 to 4:

| Number of recovery sites, m | k | Optimum latitude for return from a $30^{\circ}$ orbit inclination, $\|\lambda_{opt}\|$, deg |
|---|---|---|
| 2 | 0.5000 | 16.1 |
| 3 | .7500 | 23.4 |
| 4 | .8535 | 26.2 |



Figure 5.- Optimal spacing techniques of multiple recovery sites.

## Optimum Longitude Spacing

As was stated previously, the latitude of each site in an optimum recovery network must be equal in magnitude although not necessarily in the same hemisphere. Several schemes of longitudinal spacing combinations of multiple sites which meet the optimum restriction of minimizing lateral-range requirements are available. These spacing combinations are shown schematically in figure 5 for two, three, and four recovery sites. Figure 5(a) shows the appropriate nomenclature.

It has been shown by Baradell and McLellan in reference 1 that for one recovery site, the optimum latitude of the site must be either $0^{\circ}$ or $90^{\circ}$ for $|\alpha| \leq 45^{\circ}$ or $|\alpha| \geq 45^{\circ}$, respectively. Note that longitude considerations for one recovery site are unimportant since the variation of $\lambda'$ with time is cyclic for each daily rotation of the earth.

Two recovery sites.- From figure 5(b), it can be seen that the utilization of two optimally spaced recovery sites dictates either a $180^{\circ}$ longitudinal spacing with both sites in the

same hemisphere (scheme 1), or both sites at the same longitude but in opposite hemi-spheres (scheme 2).

Three recovery sites.- Three recovery sites may also be optimally spaced in either of two ways as illustrated in figure 5(c):  all sites in the same hemisphere with a longitudinal spacing of 120° (scheme 1), or two sites in one hemisphere with a 120° lon-gitudinal spacing and the third site in the opposite hemisphere spaced 60° longitudinally from the first two (scheme 2).

Four recovery sites.- Four recovery sites may be optimally spaced in either of four ways as illustrated in figure 5(d):  all sites in the same hemisphere with a 90° lon-gitudinal spacing (scheme 1), two sites at one longitude but in opposite hemispheres with a second pair in opposite hemispheres located 90° longitudinally from the first pair (scheme 2), sites in alternate hemispheres with 90° longitudinal spacing (scheme 3), or three sites in one hemisphere with 90° longitudinal spacing in conjunction with a fourth site in the opposite hemisphere at the same longitude as the middle site of the other three sites (scheme 4).

## RESULTS AND DISCUSSION

### Optimal Latitude, Maximum Lateral-Range, and Maximum Hypersonic-Lift-Drag-Ratio Requirements for Quick-Return Capability

The definition of optimal spacing and the equations necessary to determine the corresponding lateral-range requirements were outlined in the previous section.  In order to relate the lateral-range requirements to a specific required vehicle L/D capability, the variation of lateral range with $(L/D)_{hyp,max}$ of the vehicle must be determined.  The variation of lateral-range angle with $(L/D)_{hyp,max}$ considered here-inafter is shown in figure 6.

Although lateral-range capability is not strongly dependent on orbital altitude for orbits restricted to lie below the Van Allen radiation belts, it was necessary to select a set of conditions for the computation of figure 6. Descent from a 150-nautical-mile orbit was assumed to be initiated by the applica-tion of a velocity decrement
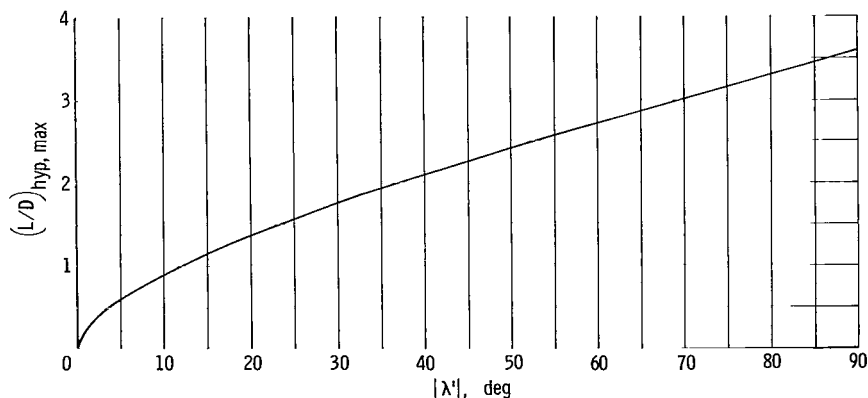


Figure 6.- Lateral-range angle obtainable by aerodynamic maneuvering.

of 296 knots which results in an entry velocity of approximately 15 158 knots and an entry angle of approximately $2^o$. Entry is initiated at the trimmed attitude for maximum L/D and a constant bank angle. At the bottom of the pullup, a constant-altitude maneuver is initiated by bank-angle control with additional side range obtained by maintaining the lift vector to the same side during the maneuver. At the end of the constant-altitude maneuver, a second constant-bank-angle maneuver is flown either to landing or until a heading angle of $90^o$ is reached at which point a zero-bank-angle maneuver is initiated. The actual values of the bank angle used during the constant-bank-angle portions of the entry trajectory are dependent on the vehicle L/D and were systematically varied to obtain the maximum lateral-range angle for each value of L/D. Finally, the effect of rather large variations in the ballistic coefficient $W/C_D S$ on the lateral range is generally small (see, for example, ref. 1). Consequently in the computation of lateral-range capability, values of $W/C_D S$ were used which were considered to be reasonable for the particular L/D under consideration. For this investigation, $W/C_D S = 9576$ N/m$^2$ was used for the higher range of L/D and $W/C_D S = 3591$ N/m$^2$ was used for the lower range of L/D.

The conditions necessary to insure quick return to one, two, three, or four recovery sites are given in figure 7 for $0^o \leq |\alpha| \leq 90^o$. In figure 7, the magnitudes of $|\lambda_{opt}|$ and the resulting $|\lambda'_{max}|$ and the corresponding $(L/D)_{hyp,max}$ (from fig. 6) are presented. As shown previously, the longitudinal spacing technique for recovery sites and the choice of hemispheres for the sites have no effect on the magnitudes of $|\lambda_{opt}|$ or $|\lambda'|$. Hence, the recovery sites may be selected by either of the longitudinal spacing schemes discussed previously to yield the results in figure 7. Here it can be seen that the maximum value of $|\lambda'|$ and $(L/D)_{hyp,max}$ vary significantly with the number of recovery sites (i.e., L/D = 2.27 for m = 1 whereas L/D = 0.58 for m = 4).

It must be stressed that $|\lambda'|_{max}$ and $(L/D)_{hyp,max}$ shown in figure 7 for varying orbital inclinations are calculated for the optimum latitude for each orbit inclination. The calculation results in varying optimum latitudes for the varying orbit inclinations. Therefore, the variation of $|\lambda_{opt}|$ with $|\alpha|$ is shown at the top of figure 7. In order to satisfy the maximum lateral-range-angle and lift-drag-ratio requirements shown in figure 7, a slight variation in the orbit inclination of a given mission would require a change in the latitude of the recovery sites



Figure 7.- Optimum requirements for quick-return capability.

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in accordance with the variation of $\left|\lambda_{opt}\right|$ with $|\alpha|$. Therefore, consideration of a single optimum recovery site is of particular interest because of the requirement that the site be located either on the equator or at a pole, depending on the orbit inclination. That is, a vehicle with an L/D of 2.27 could return from any orbit in the range $0^{\circ} \leqq |\alpha| \leqq 45^{\circ}$ to a prepared equatorial recovery site and from any orbit inclination in the range of $45^{\circ} \leqq |\alpha| \leqq 90^{\circ}$ to a prepared polar recovery site.

It should be noted here that the optimum latitude of recovery sites for return from a polar orbit would be $90^{\circ}$. (See fig. 7.) Such a location is meaningless for three or four polar recovery sites. Hence, the present analysis does not apply to polar orbits for either three- or four-site recovery networks. The problem of optimum location of multiple recovery sites for return from a polar orbit has been considered in reference 1 and is not therefore treated herein.

If the least desirable orbit inclination is defined as that $|\alpha|$ which requires the maximum lateral-range capability for quick return to optimally located sites, then the magnitude of the least desirable orbit inclination may be determined analytically by the equation

$$\frac{d(\alpha - \lambda)}{d\alpha} = 0 \tag{15}$$

where $\lambda$ is given by equation (14) for m = 2, 3, and 4. These least desirable inclinations are listed in the following table:

| Number of recovery sites, m | Least desirable orbit inclination, $|\alpha|$, deg |
|---|---|
| 1 | 45.0 |
| 2 | 54.7 |
| 3 | 49.1 |
| 4 | 47.3 |

### Physical Examples of Near Optimally Spaced Recovery Sites for Quick-Return Capability

In order to illustrate the results of utilization of the optimal spacing techniques established previously in this report, physical examples of near optimally spaced recovery sites for quick-return capability are presented in tables I and II. Also presented in these tables are the L/D requirements for both exact optimum spacing and for slight deviations from the optimal spacing made necessary by geographical restrictions. These tables clearly indicate the increased L/D requirements resulting from deviations from

optimum locations. The examples of recovery sites presented in this section have been selected completely from general geographic consideration without regard to such items as local terrain and world politics. These examples are presented purely for illustration and discussion purposes and are not meant to be considered as suggested recovery locations for any future mission. Only land recovery sites are presented and no consideration has been directed toward water recovery.

TABLE I.- TYPICAL EXAMPLES OF LOCATIONS OF NEAR OPTIMALLY SPACED RECOVERY SITES
FOR QUICK RETURN FROM A 30° ORBIT INCLINATION

| Number of sites in recovery network, m | Recovery locations (latitude, longitude) | Spacing scheme | $\|\lambda_{opt}\|$ | $\epsilon_\lambda$ | $\epsilon_\theta$ | $(L/D)_{req}$ | $(L/D)_{opt}$ |
|---|---|---|---|---|---|---|---|
| 1 | Galápagos Islands (0°, -91.5°) | 1 | 0° | ---- | ---- | 1.78 | 1.78 |
| | Colombia (0°, -70° to -75°) | 1 | | ---- | ---- | 1.78 | |
| | Brazil (0°, -52° to -70°) | 1 | | ---- | ---- | 1.78 | |
| 2 | Guadeloupe (16.1°, -61.5°) + Philippines (16.1°, 120°) | 1(+λ) | 16.1° | ---- | 1.5° | 1.11 | 1.10 |
| | Arnhem Land, Australia (-16.1°, 135°) + Brazil (-16.1°, -45°) | 1(-λ) | | ---- | ---- | 1.10 | |
| | Mariana Islands (16.1°, 145.5°) + Australia (-16.1°, 145.5°) | 2 | | ---- | ---- | 1.10 | |
| | Guadeloupe (16.1°, -61.5°) + Brazil (-16.1°, -61.5°) | 2 | | ---- | ---- | 1.10 | |
| 3 | Libya (23.4°, 15°) + Mexico (23.4°, -105°) + Volcano Islands (24°, 136.5°) | 1(+λ) | 23.4° | 0.6° | 1.5° | 0.75 | 0.72 |
| | Loyalty Islands (-22°, 167°) + Madagascar (-23°, 47°) + Chile (-23.4°, -70°) | 1(-λ) | | 1.4° | 3° | 0.80 | |
| | Libya (23.4°, 13°) + Brazil (-23.4°, -47°) + Mexico (23.4°, -107°) | 2 | | ---- | ---- | 0.72 | |
| | Bechuanaland, So. Africa (-23.4°, 25°) + India (23.4°, 85°) + Australia (-23.4°, 145°) | 2 | | ---- | ---- | 0.72 | |
| 4 | Laysan Island (26°, -171.5°) + Florida (26.2°, -81.5°) + Algeria (26.2°, 8.5°) + Burma (26.2°, 98.5°) | 1 | 26.2° | 0.2° | ---- | 0.54 | 0.53 |
| | San Felix Island (-26.2°, -80°) + Florida (26.2°, -80°) + Southwest Africa (-26.2°, 15°) + Libya (26.2°, 10°) | 2 | | ---- | 5° | 0.58 | |
| | Laysan Island (26.0°, -171.5°) + San Felix Island (-26.2°, -80°) + Libya (26.2°, 10°) + Australia (-26.2°, 114°) | 3 | | 0.2° | 14° | 0.69 | |
| | Laysan Island (26°, -171.5°) + Florida (26.2°, -81.5°) + Algeria (26.2°, 8.5°) + San Felix Island (-26.2°, -80°) | 4 | | 0.2° | 1.5° | 0.55 | |

Return to near optimum recovery-site networks from a 30° orbit inclination.- A 30° orbit inclination has been chosen as a typical example since considerable interest has been generated about this inclination in connection with manned space-station missions. For a 30° orbit inclination, a single optimum recovery site would be located on the equator. Table I indicates several recovery areas which would meet the optimum requirements. Also available would be the African land area located on the equator.

For both a two-site and a three-site recovery network, two examples of each combination of spacing schemes are shown. Note that for the three-site combination of Loyalty Islands, Madagascar, and Chile, deviations from the latitude- and longitude-spacing requirements of 1.4° and 3°, respectively, result in an increase in the required value of L/D of 0.08.

One example of each spacing scheme is given in table I for the case of a four-site recovery network. The best combination found for scheme 3 had errors of $\epsilon_\lambda = 0.2°$ and $\epsilon_\theta = 14°$, which resulted in an increase in the required value of L/D of 0.16.

The typical examples of recovery networks shown in table I illustrate the relatively low L/D requirements that may be obtained with a small number of recovery sites if they can be optimally spaced. Also indicated are the relatively large increases in L/D which will result from small deviations from optimum spacing.

Further results which include the restriction that one site lie in the United States are presented in appendix A.

TABLE II.- TYPICAL EXAMPLES OF LOCATION OF NEAR OPTIMALLY SPACED TWO-SITE RECOVERY NETWORKS FOR QUICK RETURN FROM VARYING ORBIT INCLINATIONS

| Orbit inclination, deg | Recovery locations (latitude, longitude) | Spacing scheme | $\|\lambda_{opt}\|$ | $\epsilon_\lambda$ | $\epsilon_\theta$ | $(L/D)_{req}$ | $(L/D)_{opt}$ |
|---|---|---|---|---|---|---|---|
| 0 | Galápagos Island (0°, -91.5°) | --- | 0° | ----- | --- | 0 | 0 |
| | Brazil (0°, -52° to -70°) | --- | | ----- | --- | 0 | |
| 15 | Brazil (-7.6°, -40°) + New Guinea (-7.6°, 140°) | 1 | 7.6° | ----- | --- | 0.76 | 0.76 |
| | British Guiana (7.6°, -59°) + Brazil (-7.6°, -59°) | 2 | | ----- | --- | 0.76 | |
| 30 | Australia (-16.1°, 135°) + Brazil (-16.1°, -45°) | 1 | 16.1° | ----- | --- | 1.10 | 1.10 |
| | Saudi Arabia (16.1°, 48°) + Madagascar (-16.1°, 48°) | 2 | | ----- | --- | 1.10 | |
| 45 | Texas (26.6°, -97.5°) + India (26.6°, 82.5°) | 1 | 26.6° | ----- | --- | 1.31 | 1.31 |
| | Florida (26.6°, -80°) + San Felix Island (-26.3°, -80°) | 2 | | 0.3° | --- | 1.33 | |
| 60 | Gough (-40.5°, -10°) + New Zealand (-40.9°, 172°) | 1 | 40.9° | 0.4° | 2° | 1.36 | 1.35 |
| | New Jersey (40.9°, -74°) + Chile (-40.9°, -74°) | 2 | | ----- | --- | 1.35 | |
| 75 | Alaska (61.8°, -164°) + Sweden (61.8°, 16°) | 1 | 61.8° | ----- | --- | 1.07 | 1.07 |
| | Greenland (61.8°, -45°) + South Orkney Islands (-61.8°, -45°) | 2 | | ----- | --- | 1.07 | |
| 90 | North Pole (90°, –) | --- | 90° | ----- | --- | 0 | 0 |
| | South Pole (-90°, –) | --- | | ----- | --- | 0 | |

Return to two-site recovery networks from varying orbit inclinations.- Typical examples of near optimally located two-site recovery networks are given in table II for return from orbit inclinations of 0°, 15°, 30°, 45°, 60°, 75°, and 90°. Note that for return from either an equatorial or polar orbit, one recovery site located on the equator or a pole is sufficient to insure quick return for a ballistic vehicle. For the other orbit inclinations considered, examples of each spacing scheme are included in table II. From table II, it can be seen that two-site recovery networks can generally be located optimally, regardless of the orbit inclination. However, it should be stressed that each combination of sites considered here is assumed to support return from only one orbit inclination. The increases in L/D required to permit a given network of recovery sites to support return from a range of orbit inclinations are discussed subsequently.

## Delay Orbit Effects

The results discussed up to this point have been restricted to the requirements which must be met to insure the capability to return from any orbit during the 24-hour period (quick return). Spacing techniques have been defined which will, for a given number of recovery sites, minimize the lateral-range and L/D requirements necessary to guarantee this quick-return capability. One means of gaining a further reduction in the L/D requirement is the use of wait time in orbit. That is, the mission of interest must have the further restriction that a given delay of n orbits will be permissible in order to define the vehicle L/D necessary to return to a network of recovery sites. In order to ascertain delay orbit effectiveness in reducing lateral-range requirements, a definite time factor (the time required for the completion of one orbit relative to some longitudinal point on earth) must be introduced. For the present analysis, this time factor has been chosen to be 1.6 hours based on a circular orbit with an altitude of 150 nautical miles (278 kilometers) in accordance with the restrictions of figure 6.

Delay orbit effectiveness in reducing lateral-range requirements may be considered in two primary ways within the present analysis. First, if the recovery sites are located by the quick-return consideration presented heretofore, then a given delay orbit capability results in a decrease in the required lateral-range requirements as compared with the quick-return requirements. As a typical example of this technique of employing delay orbits, the effects of a two-delay orbit capability on the lateral-range requirements for return to two optimally located recovery sites (quick-return restriction) from a 30° orbit inclination are shown in figure 8(a). Inspection of figure 8(a) indicates that, because of the relative slopes of the curves, delay orbit capability is much more effective in reducing lateral-range requirements in the region of the intersection of curves than in the region of the minimum of either curve. However, this analysis is concerned with the maximum lateral-range requirements. Therefore, for recovery sites located optimally

for quick-return considerations, the delay orbit effectiveness in reducing lateral-range requirements is governed by the effects in the region of the minimum of the curve of $\lambda'$ plotted against $t$. (Note that in referring to the minimum of the curves of $\lambda'$ plotted against $t$, the geometric maxima or minima which have the lowest absolute value are indicated.)

The second technique of considering delay orbit effects is devised so that maximum effectiveness in reducing lateral-range requirements may be achieved. This technique requires a new definition of the optimum latitude of the recovery sites which is dependent upon the number of delay orbits considered permissible for a given mission. The longitudinal spacing requirements are considered to be unaffected by delay orbit capability. A typical example of this technique of considering delay orbit effects is illustrated in figure 8(b) for a two delay orbit capability and return to two optimally located recovery sites from a 30° orbit inclination. The optimum latitude for a preselected delay orbit capability (n = 2, in fig. 8(b)) can be determined from equation (9) under the restriction that



(a) Recovery sites at optimum latitude for quick-return capability.



(b) Recovery sites at optimum latitude for preselected wait time of n = 2.

Figure 8.- Delay orbit effects. $\alpha = 30°$; m = 2; n = 2. (Solid line indicates site is prime recovery site.)

$$\left|\lambda'_A\right|_{t=\text{Time for }\lambda'_{min}+1.6} = \left|\lambda'_A\right|_{t=t_i-1.6} \tag{16}$$

where $t$ is in hours.

The differences in the two techniques may now be illustrated by comparison of figures 8(a) and 8(b). For return from a 30° orbit to two optimally located recovery sites, the optimum latitude of the sites would be 16.1° for quick return or 20.9° for a preselected wait time of two delay orbits. For a quick-return capability, the lateral-range requirement would be 13.9°. (See fig. 7.) With recovery sites located optimally at $\lambda = 16.1°$ for quick return, a wait time of two delay orbits would decrease this lateral-range requirement to 11.5°, a decrease of 2.4°. For a preselected wait time of two delay orbits and for the resulting optimum latitudes of 20.9°, the lateral-range requirement is reduced to 6.8°, a decrease of 7.1° from the quick-return requirements. This example, then, illustrates that if a given delay orbit capability can be specified for a given mission, recovery sites can be so located as to reduce greatly the L/D requirement below that required for a quick-return latitude location. Therefore, the determination of the vehicle L/D capability necessary to carry out a given mission is intimately tied in with the overall mission requirements.
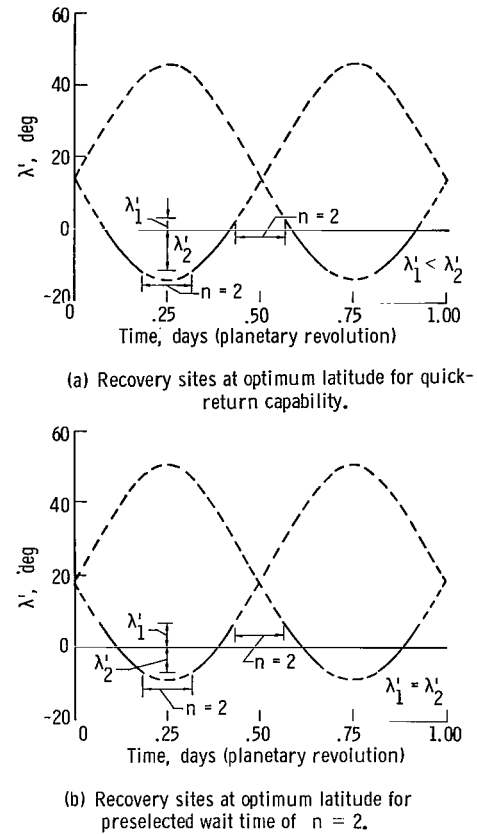
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The restriction given by equation (16) can be written in general form for the determination of $\lambda_{opt}$ as

$$\left| \lambda'_A \right|_{t_{min}+\frac{n\tau}{2}} = \left| \lambda'_A \right|_{t_i(or\ t_s)-\frac{n\tau}{2}} \tag{17}$$

where $n$ is the number of delay orbits and $\tau$ is the orbital period. From the restriction of equation (17) the relationship for $\left| \lambda_{opt} \right|$ may be written for a given number of delay orbits $n$ as

$$\left| \lambda_{opt} \right| = \tan^{-1} \left[ \frac{\sin(90^o - 12n) + k'}{2} \tan \alpha \right] \tag{18}$$

where

| m | k' |
|---|---|
| 2 | sin 12n |
| 3 | sin(30$^o$ + 12n) |
| 4 | sin(45$^o$ + 12n) |

With the restriction of low circular orbits (i.e., $\tau = 1.6$), the effects of delay orbits have been calculated for both techniques of evaluating delay orbit effectiveness in reducing lateral-range requirements. The results are shown in figures 9 to 12 for return from any orbit inclination to one to four optimally located recovery sites.

For $0^o \leq \left| \alpha \right| \leq 45^o$, the optimum latitudes and hence the lateral-range and $L/D$ requirements are the same for the two techniques of considering delay orbit effects in return to one optimally located recovery site (fig. 9). That is, for $\left| \alpha \right| \leq 45^o$, the recovery site is always located on the equator. However, for the range of orbit inclinations defined by $45^o \leq \left| \alpha \right| \leq \left| \alpha* \right|$, delay orbits allow substantial decreases in $\lambda'$ and in the $L/D$ requirements for the case of a preselected delay orbit capability but have no effect on the requirements necessary to reach the recovery site located by quick-return considerations. The orbit inclination $\left| \alpha* \right|$ is defined as that orbit inclination for which the lateral-range requirements necessary to return to either an equatorial or a polar recovery site are equal for a given number of preselected delay orbits. That is, if the preselected number of delay orbits is specified, then an equatorial site would be optimum for $\left| \alpha \right| \leq \left| \alpha* \right|$. The angle $\left| \alpha* \right|$ may be defined as

$$\left| \alpha* \right| = \tan^{-1} \left[ \frac{1}{\sin \left( 90^o - \frac{\dot{\theta}\tau n}{2} \right)} \right] \tag{19}$$

Hence, the differences in lateral-range requirements for the two techniques in this orbit inclination range of $45^o \leq \left| \alpha \right| \leq \left| \alpha* \right|$ are a result of a polar site being required for

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quick-return considerations while an equatorial site is required for the preselected delay orbit capability considerations. The polar site (for quick-return restrictions) is equidistant from the maximum latitude of each orbital trace regardless of time, and, therefore, delay orbits are completely ineffective in altering lateral-range requirements. For the range of orbit inclinations given by $|\alpha^*| \leq |\alpha| \leq 90°$, the optimum recovery site is polar for both techniques of delay orbit considerations. Hence, in this range, delay orbits also have no effect on lateral-range requirements.

From consideration of figure 10(a), it can be seen that, for two-site recovery networks, increasing the number of preselected delay orbits results in decreasing optimum latitude changes. For example, in going from quick return to a preselected delay time of one orbit, the maximum shift in the optimum latitude is approximately $4°$, but, in going from a preselected delay time of three orbits to four orbits the maximum shift in the optimum latitude is less than $1°$. Comparison of figures 10(a) and 10(b) indicates that two or more delay orbits are necessary to gain significant reductions in $\lambda'$ and $L/D$ for quick-return considerations while only one delay orbit results in significant reductions in $\lambda'$ and $L/D$ for the preselected delay orbit capability considerations. Figures 10(a) and 10(b) also indicate that four delay orbits are sufficient to reduce the $L/D$ requirements to zero for the

(a) Optimum latitude for preselected delay orbit capability.

(b) Optimum latitude for quick-return capability.
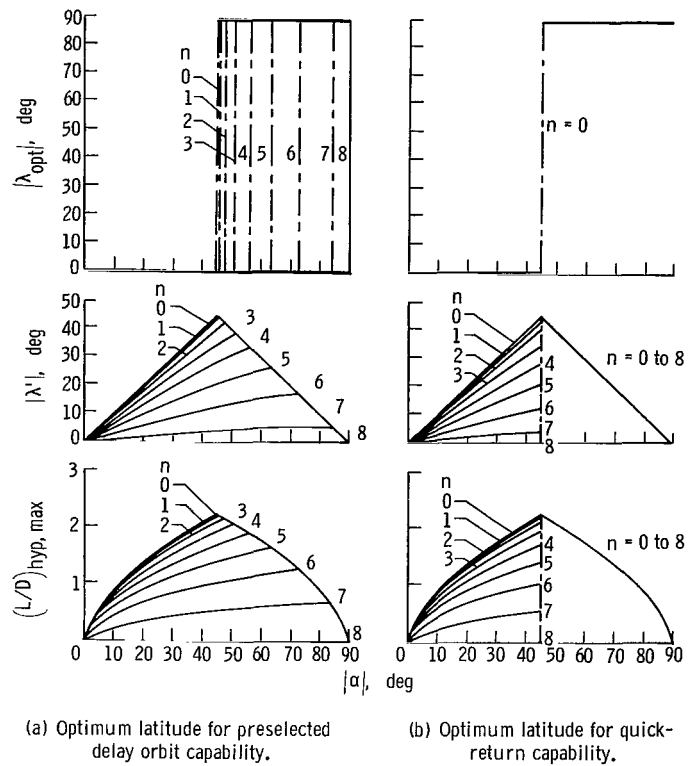
Figure 9.- Delay-orbit effects for return to one optimally located recovery site.

(a) Optimum latitude for preselected delay orbit capability.

(b) Optimum latitude for quick-return capability.
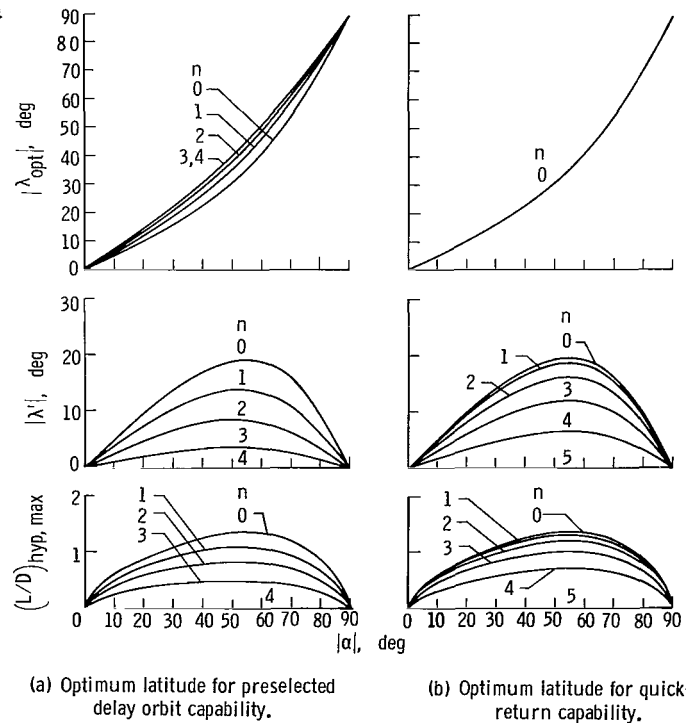
Figure 10.- Delay-orbit effects for return to two optimally located recovery sites.

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(a) Optimum latitude for preselected delay orbit
capability.

(b) Optimum latitude for quick-return
capability.

Figure 11.- Delay-orbit effects for return to three optimally located recovery sites.



(a) Optimum latitude for preselected delay orbit
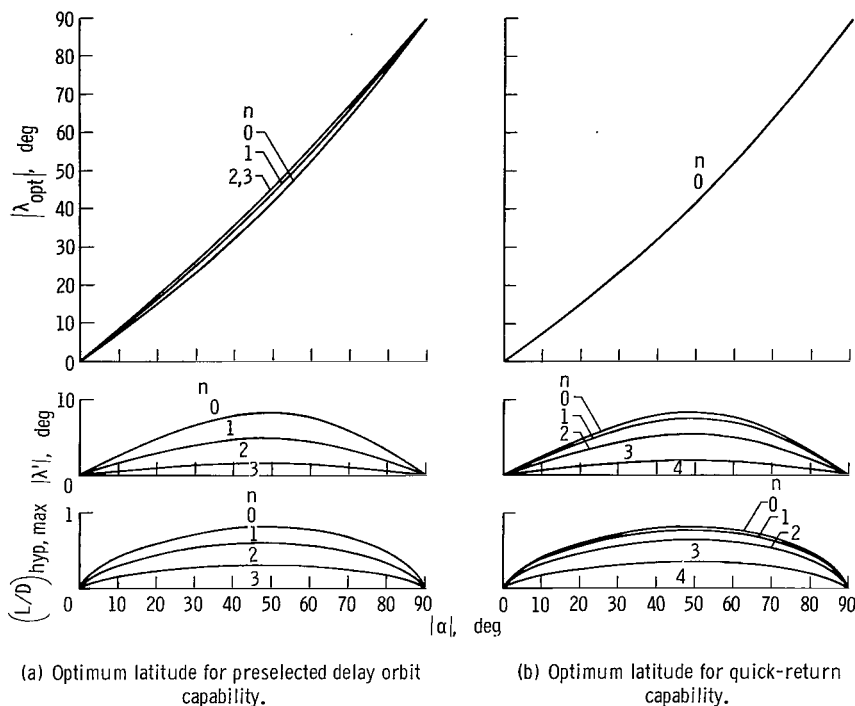capability.

(b) Optimum latitude for quick-return
capability.

Figure 12.- Delay-orbit effects for return to four optimally located recovery sites.

preselected delay orbit capability considerations whereas for quick return a maximum wait time of five delay orbits is required for equivalent $L/D$ reductions.

As the number of sites within a recovery network increases (see figs. 10 to 12), the deviations in optimum latitudes for the preselected delay orbit considerations from the values dictated by quick-return requirements become decreasingly smaller and the lateral-range and $L/D$ requirements decrease.

## Deviations From Optimum Latitudes

The previous discussion has been concerned with the requirements necessary to return to optimally located recovery sites. There are, of course, many situations which can result in making deviations from the optimum spacing conditions mandatory. These situations can include such factors as world politics and local terrain. If deviations from the longitudinal spacing requirements become necessary, then an infinite number of possibilities of spacing techniques become available. For this case, the reader may select desirable
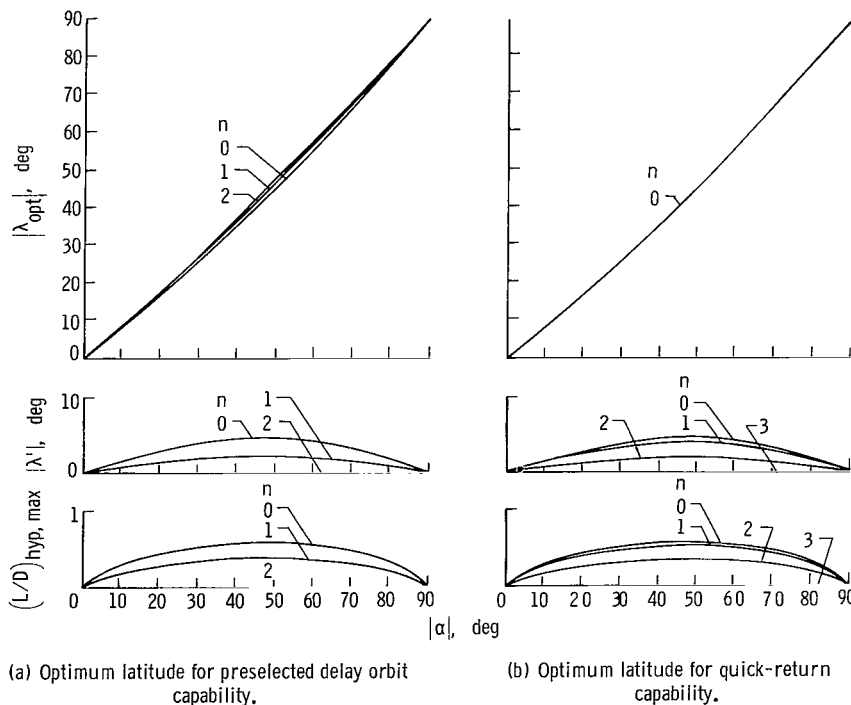
networks of recovery sites and apply equation (9) to determine requirements for return to these recovery combinations. For example, it has been shown that under the constraint of a four-site recovery network, with three of the sites located in North America (two in the United States and one in Mexico) and one emergency recovery site in India, a vehicle with a lift-drag-ratio capability of 1.25 would be capable of recall during any orbit, while in a 30° orbit inclination. (See appendix B.) If, however, the longitudinal spacing requirements are considered to be fixed (see fig. 5), then the effects of latitude deviations from the optimum location on the lateral range and $L/D$ requirements may be calculated. It must be noted that for multiple recovery-site networks, the latitudes of the sites are considered to be equal even though they are not the optimum value. The results of these calculations are illustrated in figures 13 to 16 for return to one to four recovery sites. In these figures, the full latitude range of $0° \leq |\lambda| \leq 90°$ is covered to include any possible site latitude in combination with the optimum longitudinal spacing. The results indicated in figures 13 to 16 are further restricted to the definition of those requirements necessary to insure a quick-return capability to the nonoptimally located recovery sites. The envelopes of the optimum landing sites are indicated in figures 13 to 16 by the dashed curves. These curves, of course, correspond to those presented previously in figure 7.

The results for one recovery site, indicated in figure 13, have been presented previously by Baradell and McLellan in reference 1 and are included only for completeness. No further comments are therefore considered necessary.

The material presented in figures 13 to 16 covers too broad a range to permit any but general observations. Rather, it would be more meaningful to discuss the application of this material. Analysis of these figures illustrates very clearly the increases in $\lambda'$ and $L/D$ requirements which result when deviations from optimum latitude locations become necessary.

The networks of recovery sites considered heretofore were optimally located and, therefore, were considered to support return from only one orbit inclination. It may very well be desirable to have a given network of recovery sites support return from a range of orbit inclinations. If the sites can be located with the optimal longitudinal spacing, then figures 13 to 16 may be used to determine the necessary $\lambda'$ and
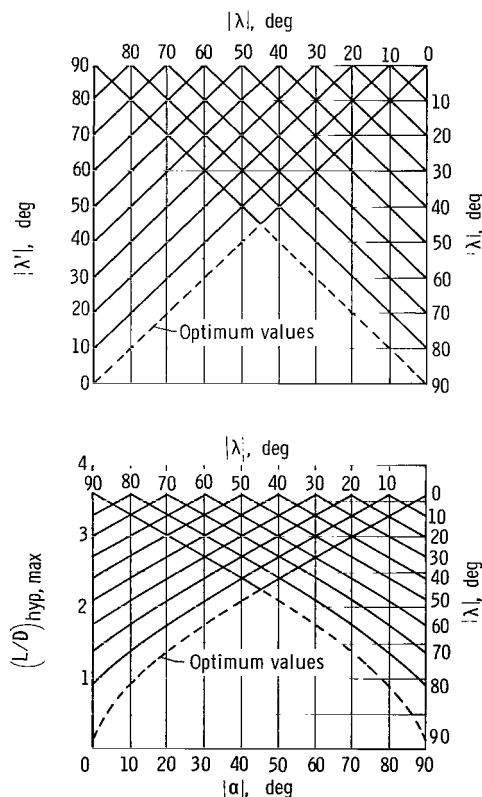


Figure 13.- Requirements for quick-return capability to one recovery site located at nonoptimum latitudes.

L/D requirements for quick return from any number of (or any range of) orbit inclinations. As an example of this type of application, consider the L/D required for quick return to a network of recovery sites located at a latitude of 30° from a range of orbit inclinations of 30° to 60°. For these restrictions, return to a one-site recovery network would require an L/D of 3.6. (See fig. 13.) Return to a two-site recovery network would require an L/D of 1.77. (See fig. 14.) Similarly, return to a three- or four-site recovery network would require an L/D of either 1.77 or 1.25. (See figs. 15 and 16, respectively.)
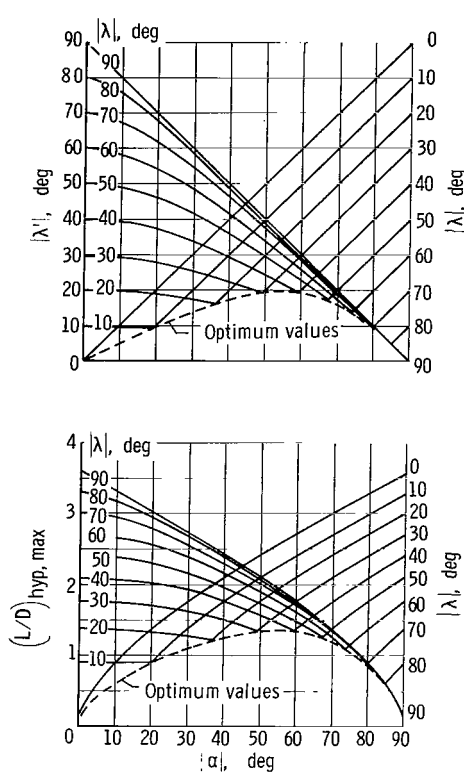


Figure 14.- Requirements for quick-return capability to two recovery sites located at nonoptimum latitudes.
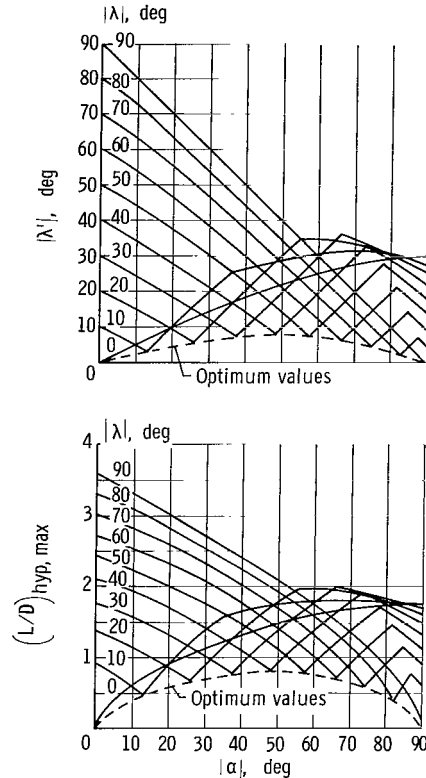
Figure 15.- Requirements for quick-return capability to three recovery sites located at nonoptimum latitudes.

In addition, a given mission may involve as part of its objectives an orbit plane change. For such a mission, return capability must be insured from each of the orbit inclinations in which the vehicle is designed to function. Under these considerations, figures 13 to 16 may be used to determine $\lambda'$ and L/D requirements for quick-return capability.

Finally, the results of the previous section on delay orbit effects have demonstrated that, in order to gain maximum delay orbit effectiveness in reducing $\lambda'$ and L/D requirements, it is necessary to redefine the optimum latitude of the landing sites. Referring to figures 9 to 12, the (a) part of each figure defines the optimum latitude and

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the $\lambda'$ and L/D requirements for return from a given orbit inclination after a number of preselected delay orbits. If it is desired to determine the $\lambda'$ and L/D requirements necessary to achieve quick-return capability to the networks of sites which are located for optimal return after a preselected wait time, these requirements may be obtained from figures 13 to 16 for the latitude and orbit inclination of interest. For example, in figure 10(a) it can be seen that a preselected wait time of three orbits (for return to two recovery sites) from a 40° orbit inclination requires a recovery-site latitude of approximately 30°. The corresponding L/D requirement (also from fig. 10(a)) is 0.50. The L/D requirement for quick-return capability to these sites at a latitude of 30° from a 40° orbit inclination is shown in figure 14 to be 1.5. (Note that if the sites were located according to the optimal restrictions for quick-return capability (see fig. 10(b) for $\underline{n} = 0$ or fig. 7), a latitude of 22.8° and an L/D requirement of 1.26 would result.)



Figure 16.- Requirements for quick-return capability to four recovery sites located at nonoptimum latitudes.

## Quick Return From Any Orbit Inclination

It seems reasonable to anticipate that the trend of reentry vehicle development will eventually include relatively sophisticated lifting vehicles. Achievement of operational vehicles of relatively high L/D capability will allow the definition of a single network of recovery sites which can support return from any orbital inclination. The lateral-range and L/D requirements necessary to insure quick return to such recovery-site networks may be obtained from figures 13 to 16 by considering the maximum requirements necessary over the full orbit inclination range for each latitude. These requirements are plotted in figure 17.

As was shown in reference 1, an L/D capability of 3.6 will permit quick return to a single recovery site regardless of the site latitude or the orbital inclination. For two-site recovery networks, a latitude of 45° will give the minimum L/D requirement (L/D = 2.27) for return from any orbit inclination.

An interesting result indicated in figure 17 is that three-site recovery networks can support return from any orbit inclination by a vehicle with an L/D capability of 2.0 if the networks can be located within the latitude range of 0° to 35°. Several three-site networks which would be possible in this latitude range are described and analyzed in detail in appendix C. Since these requirements include the quick-return-capability restriction, an L/D of 2 appears to be the upper limit necessary to support return from any scientific manned space mission with the nominal recovery site located in the
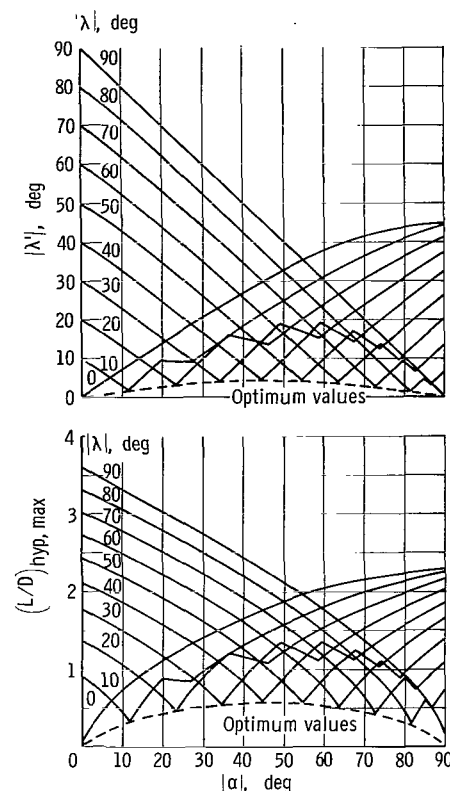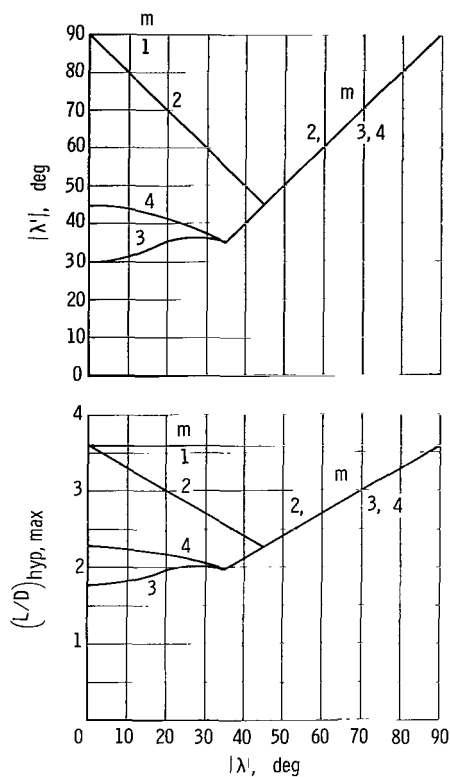
Figure 17.- Requirements for quick-return capability from any orbit inclination to one to four recovery sites located at any constant latitude.

United States if the longitudinal spacing constraints can be met. (See appendix C.) However, other specific missions may have constraints peculiar to the mission which will make higher values of L/D necessary.

Figure 17 also shows that for recovery sites located in the latitude range from $0^O$ to $35^O$, three-site recovery networks require a lower L/D to support return from any orbit inclination than four-site recovery networks. This result stems from the maximum L/D requirements in this latitude range being determined by the polar orbits. (See figs. 15 and 16.) For the special case of polar orbits, the previously derived longitudinal spacing restrictions for three-site recovery networks are optimum. (See ref. 1.) However, the longitudinal spacing of the four-site recovery networks is actually equivalent to the optimum spacing of two recovery sites so that a higher L/D is required for quick return to a four-site recovery network than to a three-site recovery network. For a discussion of optimum spacing for return from polar orbits, see reference 1.

## APPLICABILITY OF ANALYSIS TO OTHER PLANETS

Much of the analysis presented in this report is concerned only with geometry, and the results have been, therefore, presented in geometrical terms (i.e., lateral-range requirements in degrees of surface arc). This material is not, then, earth oriented and may be applied for any planet of interest. In particular, the results of figures 2, 3, 4, 5, 7, 13, 14, 15, 16, and 17 have this general applicability except for the L/D requirements which are earth oriented. The results of the remaining figures generally are derived from consideration of delay orbits which depend on an orbital period and are, therefore, primarily earth oriented. Finally, in consideration of other planets, the angle $\alpha$ may be defined generally as the angle between the approach trajectory and the equatorial plane of the target planet.

## CONCLUSIONS

An analysis of the problem of return from near-earth circular orbits in terms of recovery-site location, lateral-range requirements, and the corresponding lift-drag-ratio requirements has led to the following conclusions:

1. Optimum location of multiple recovery sites requires that the latitudes of the sites be equal but not necessarily in the same hemisphere. (Two schemes of longitudinal spacing are available for two- or three-site recovery networks, and four schemes are available for four-site recovery networks.)

2. Under the restrictions of conclusion 1, an optimum latitude of recovery sites may be defined for a recovery network consisting of a specified number of sites supporting quick-return capability from a given orbital inclination if each of the sites is required to be the prime site for an equal period of time daily.

3. Considerations of wait time in orbit indicate that delay orbits can be very effective in reducing lateral-range and hence lift-drag-ratio requirements, with the largest reductions being available when the preselected delay orbit capability is defined prior to the location of recovery sites. If the preselected wait time in orbit is made a mission constraint, then a new definition of the optimum latitude of recovery sites will result.

4. If optimum longitudinal spacing restrictions are considered to be upheld, deviations from the optimum latitude location result in rapid increases in lateral-range requirements.

5. As an example of how the technique of analysis can be applied, the following two conclusions may be drawn:

(a) Under the constraint of a four-site recovery network with three of the sites located in North America (two in the United States and one in Mexico) and one emergency site in India, a vehicle with a lift-drag-ratio capability of 1.25 would be capable of recall during any orbit, while in a $30^\circ$ orbit inclination.

(b) Under the constraint of a three-site recovery network with the nominal site in the United States and with optimum longitudinal spacing restrictions, a vehicle with a lift-drag-ratio capability of 2.0 would be able to return during any orbit with any orbit inclination.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 18, 1966.

## APPLICATION OF ANALYSIS TECHNIQUE TO

## A SPECIFIC ORBIT INCLINATION

In order to maintain generality, a minimum number of restrictions were applied to the analysis presented herein. However, by using this analysis as a basic foundation, much more detailed results may be obtained through the imposition of additional constraints. It is the purpose of this appendix to outline methods by which additional information may be generated.

Two constraints are added to serve as typical examples which seem to merit considerable interest. The first constraint is the consideration of a single orbit inclination of 30°. This inclination was chosen because of its apparent importance in current manned space-station mission considerations. The second constraint is that at least one of the recovery sites within a given network be located within the United States.

Under the first constraint, effects of recovery-site latitude on the L/D requirements for quick return from a 30° orbit may be generated for one to four recovery sites from figures 13 to 16. These requirements are shown in figure A1. (Note that the values of L/D indicated in fig. A1 were obtained by assuming that the longitudes of the recovery sites meet the optimum longitudinal spacing requirements.) This figure again illustrates the rapid increase in L/D which results when the latitude of the recovery sites is displaced from the optimum value.
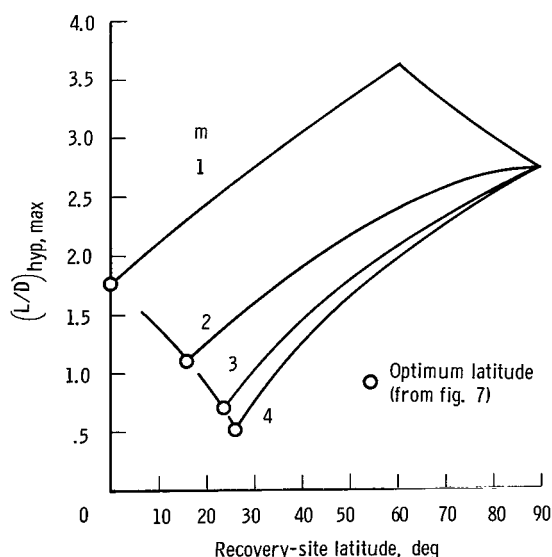


Figure A-1.- Requirements for quick return from a 30° orbit inclination.

Figure A1 illustrates that it would be possible for a vehicle with an L/D of 1.0 to return to a network of either three or four recovery sites and that these sites must be located within a relatively restricted latitude band. Also, a vehicle with an L/D of 0.5 would possess quick-return capability only to four recovery sites located at a latitude of approximately 26.2° (the optimum value).

### Delay Orbit Considerations

Under the first constraint, the effects of wait time for return from a 30° orbit may also be condensed into one convenient figure which illustrates very clearly the advantages of delay orbits in reducing L/D requirements. These delay orbit effects are shown in figure A2 for the two techniques
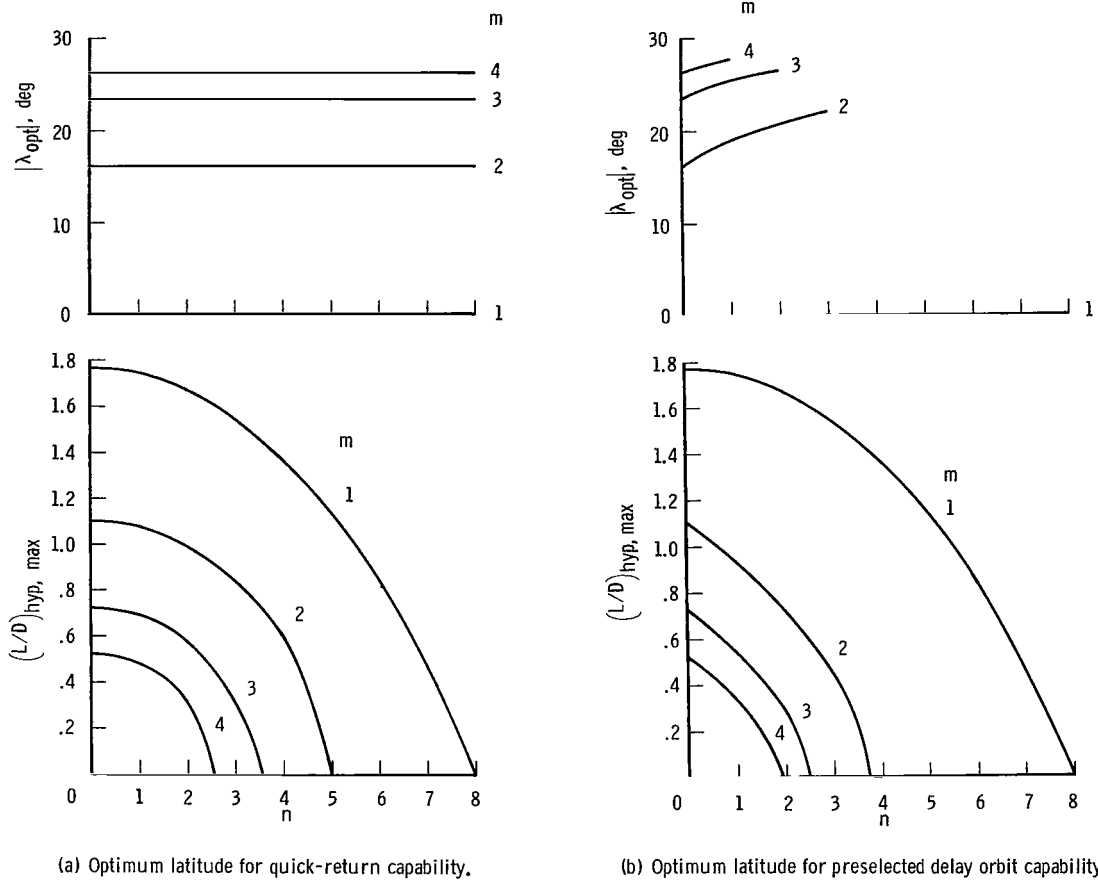
(a) Optimum latitude for quick-return capability.

(b) Optimum latitude for preselected delay orbit capability.

Figure A-2.- Delay orbit effects for return from a $30^\circ$ orbital inclination to optimally located recovery sites.

of determining optimum latitude locations (that is, optimum latitude location for either quick-return capability or for return after a preselected number of delay orbits). The number of delay orbits necessary for return to one to four recovery-site networks for several classes of lifting vehicles have been taken from figure A2 and are presented in the following table:

| L/D | Maximum number of delay orbits, $n_{max}$, for — | | Required number of sites, m, in recovery network |
|---|---|---|---|
| | $\lambda_{opt}$ determined by quick-return restriction | $\lambda_{opt}$ determined by preselected delay orbit restriction | |
| 2.0 | 0 | 0 | 1 to 4 |
| 1.0 | 0 | 0 | 3 or 4 |
| | 2 | 1 | 2 |
| | 6 | 6 | 1 |
| 0.5 | 1 | 1 | 4 |
| | 3 | 2 | 3 |
| | 5 | 3 | 2 |
| | 7 | 7 | 1 |

Quick Return to Nominal Recovery Sites

The final selection of recovery sites will be strongly influenced by many varied considerations such as geopolitical constraints. The sites considered in this section will be required to lie on land. In addition, the nominal recovery site (that site to which the entry vehicle would return under all except emergency conditions) has been restricted to be located within the islands of Hawaii or the continental United States. The restriction of a nominal recovery site to be located within the United States can, depending upon the number of sites within the recovery network, result in rather large deviations from the optimum latitude location. The latitudes, however, of a network of multiple recovery sites are considered to be equal (but not necessarily within the same hemisphere) and are determined by the selection of the nominal recovery sites. Furthermore, optimal longitudinal spacing has been included as a restriction in the selection of these networks of recovery sites. Three nominal sites have been selected: Edwards Air Force Base, California; south Texas; and the Hawaiian Islands. (The particular island selected is allowed to change depending on the number of recovery sites.)

Retaining the restriction that the entry vehicle be capable of returning during any orbit from a 30° orbital inclination, the effect of increasing the number of recovery sites on the L/D requirements is presented in figure A3. Of the three nominal sites considered, use of a Hawaiian Island site yields the lowest L/D requirement in all cases.

This result was to be expected since the optimum latitudes for return from a 30° orbit are generally less than the lowest extremes of the continental United States.

From figure A3, a vehicle with an L/D of 2.5 to 3 would be capable of return to one recovery site, whereas a vehicle with an L/D capability of 1.5 would possess quick-return capability to a network of two recovery sites. A vehicle with an L/D of 1.0 could return during any orbit to three recovery sites with the nominal site in either Texas or Hawaii. Finally a vehicle with an L/D of 0.5 would be adequate for quick return if four sites are available, one of which is Laysan Island in Hawaii.
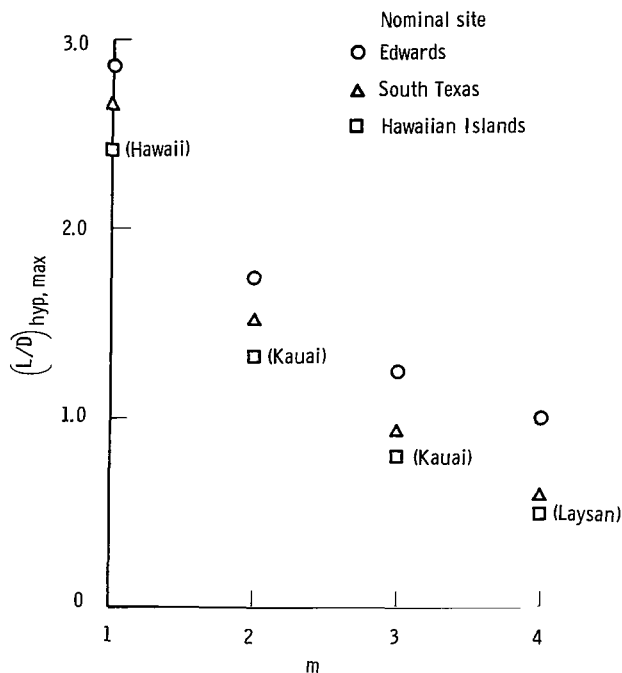


Figure A-3.- Requirements for quick return from a 30° orbit inclination to networks of recovery sites with the nominal recovery area located in the United States.

# APPENDIX A

For completeness, table AI lists the complete combinations of recovery networks presented in figure A3. Note that the four-site combinations with nominal sites in Texas and California are not included in table AI because of geographical restrictions. That is, geography requires that one of the recovery sites be a water recovery area. Thus, these combinations are not considered further.

TABLE AI.- POSSIBLE RECOVERY-SITE NETWORKS WITH THE

NOMINAL SITE IN UNITED STATES

| Recovery sites for — | | |
|---|---|---|
| m = 2 | m = 3 | m = 4 |
| Kauai Island* and Libya | Laysan (or Kauai) Island,* India, and Australia | Laysan Island,* South Florida, Algeria, and San Felix Island (Chile) |
| South Texas* and India | South Texas,* Libya, and Muko Jima Retto | |
| Edwards AFB* and Iran | Edwards AFB,* Algeria, and Argentina | |

*Nominal site.

The four-site recovery network with a Hawaiian Island as a nominal site (which requires an L/D capability of approximately 0.5) is particularly attractive because two of the four sites are located within the United States (from table AI, Florida and Laysan Island). The relatively low L/D requirement associated with this combination is rather fortuitous, and is a result of these sites being located almost exactly optimally for quick return from a $30^\circ$ orbital inclination.

# APPENDIX B

## VEHICLE RECALL CAPABILITY TO A RECOVERY NETWORK WITH MULTIPLE

## SITES IN NORTH AMERICA FROM A 30° ORBIT INCLINATION

It has been stated previously herein that if large deviations from the optimum longitudinal spacing restrictions were desired, then analysis of return requirements could be accomplished by application of equation (9) to the network of sites of interest. For this type of application, it is usually advantageous to define the recall capability (percentage of orbits per day in which the vehicle can return) of a specific class of lifting vehicle to the network of sites considered. Therefore, consider the recall capability of several classes of lifting vehicles to a network of three primary recovery sites consisting of south Florida, south Texas, and Baja California. These sites are located at a latitude of 26.5° in consideration of the 30° orbit inclination. The relative locations of these sites are indicated in figure B1.
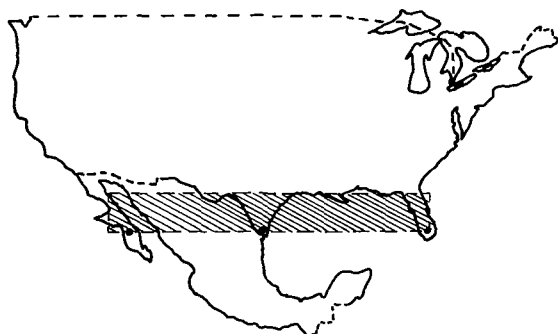
The recall capabilities of a wide range of lifting vehicles to each site and to the combination of the recovery sites are given in table BI. The percentages indicated in table BI are based on 15 orbits per day (that is, $\tau = 1.6$ hours). Note



Figure B-1.- Location of three recovery sites and of recovery area band.

TABLE BI.- RECALL CAPABILITY TO SELECTED RECOVERY SITES FROM A 30° INCLINED ORBIT

OF SEVERAL CLASSES OF LIFTING ENTRY VEHICLES

| L/D capability | Florida | | Texas | | Baja California | | Florida, Texas, and Baja California | |
|---|---|---|---|---|---|---|---|---|
| | Number of return orbits per day | Recall capability, % (a) | Number of return orbits per day | Recall capability, % (a) | Number of return orbits per day | Recall capability, % (a) | Number of return orbits per day | Recall capability, % (a) |
| 0.35 | 2 | 13.33 | 1 | 6.67 | 2 | 13.33 | 5 | 33.33 |
| .50 | 4 | 26.67 | 4 | 26.67 | 4 | 26.67 | 6 | 40 |
| .75 | 4 | 26.67 | 5 | 33.33 | 5 | 33.33 | 6 | 40 |
| 1.00 | 5 | 33.33 | 6 | 40 | 6 | 40 | 7 | 46.67 |
| 1.25 | 6 | 40 | 7 | 46.67 | 7 | 46.67 | 8 | 53.33 |
| 1.50 | 7 | 46.67 | 8 | 53.33 | 8 | 53.33 | 9 | 60 |
| 2.00 | 10 | 66.67 | 10 | 66.67 | 10 | 66.67 | 12 | 80 |

[a]Percentages based on 15 orbits per day.

that if the return requirements are not too stringent, the relatively low $L/D$ class of vehicle may be adequate for the mission considered.

It would be desirable to compare the vehicle recall capability to a combination of specific sites with the vehicle recall capability to a large recovery area (for which the mode of touchdown is not considered important). In figure B1 a recovery area is indicated which extends across the lower United States and northern Mexico. This region covers a latitude range from $26.5^{\circ}$ to $30^{\circ}$. The resulting recall capabilities to this recovery area are compared with the recall capabilities to the three specific primary recovery sites in table BII. From this table, it can be seen that practically no advantage is gained by the consideration of the large recovery area for the vehicles considered. However, it should be pointed out that advantages would become apparent for return to the recovery area if $L/D$ values of less than 0.35 were considered. Table BII indicates that careful selection of recovery sites can result in reduced recovery operation requirements without reducing vehicle recall capability.

TABLE BII.- RECALL CAPABILITY FROM A $30^{\circ}$ INCLINED ORBIT OF SEVERAL

CLASSES OF LIFTING ENTRY VEHICLES – A COMPARISON OF A

THREE-SITE RECOVERY NETWORK WITH A RECOVERY AREA

BAND ACROSS THE UNITED STATES AND NORTHERN MEXICO

| L/D capability | Florida, Texas, and Baja California | | Band across lower United States and upper Mexico (a) | |
|---|---|---|---|---|
| | Number of return orbits per day | Recall capability, % (b) | Number of return orbits per day | Recall capability, % (b) |
| 0.35 | 5 | 33.33 | 5 | 33.33 |
| .50 | 6 | 40 | 6 | 40 |
| .75 | 6 | 40 | 7 | 46.67 |
| 1.00 | 7 | 46.67 | 7 | 46.67 |
| 1.25 | 8 | 53.33 | 8 | 53.33 |
| 1.50 | 9 | 60 | 9 | 60 |
| 2.00 | 12 | 80 | 12 | 80 |

[a]Latitude band: $26.5^{\circ}$ to $30^{\circ}$; longitude band: $-81^{\circ}$ to $-114^{\circ}$.

[b]Percentages based on 15 orbits per day.

Careful selection of an emergency recovery site can very effectively increase the recall capability of the classes of vehicles considered. To obtain maximum increases in recall capability, the emergency site must be located longitudinally so that the return capability during a given orbit is not duplicated by the return capability to one of the primary sites. Since classes of vehicles which possess a given $L/D$ capability are of concern here, the best latitude for an emergency site is easily obtainable through the

application of figure 6. That is, a given L/D capability indicates a specific lateral-range capability as shown in the following table:

| L/D | $\lambda'$, deg |
|------|------|
| 0.35 | 1.8 |
| .50 | 3.5 |
| .75 | 7.2 |
| 1.00 | 11.7 |
| 1.25 | 17.0 |
| 1.50 | 22.9 |
| 2.00 | 36.5 |

The latitude of an emergency site supporting return by a given class of lifting vehicle should be determined from the relation

$$\lambda = \alpha - \lambda' \tag{B1}$$

with the following constraints:

(1) if $|\alpha| - |\lambda'|$ is negative, an equatorial site should be utilized.

(2) if $|\lambda'| \geqq 90^o - |\alpha|$, a polar site should be utilized.

Definition of the latitude of an emergency site by equation (B1) will result in maximum increased recall capability.

The recall capabilities for the basic combination plus one emergency site in either India, Hawaii, or Edwards AFB, California, are given in table BIII. It can be seen from table BIII that Edwards AFB offers no advantage as an additional emergency site to the basic combination of primary sites. An emergency site in the Hawaiian Islands would increase recall capability but not nearly as effectively as a single emergency site in India. From table BIII it can be seen that a vehicle with an L/D capability of 1.25 would be able to return during any orbit while in an orbit inclined $30^o$ if one emergency site in India were added to the basic three-site recovery network. Note that the vehicles with an L/D capability of 1.5 and 2.0, determination of the latitude by equation (B1) was unnecessary since the latitude of $13.1^o$ gave a quick-return capability.

Equation (B1) can also be used to locate the prime (North American) recovery sites for orbit inclinations greater than $30^o$. (For $\alpha = 30^o$, however, the best latitude for L/D > 0.5 would be below the lowest extremes of the United States.) As an example, the maximum recall capabilities for return from a $45^o$ orbit by a vehicle with an L/D of 1.0 would result for a choice of latitude of

$$\lambda = 45^o - 11.7^o = 33.3^o$$

where $11.7^o$ is the $\lambda'$ capability corresponding to a lift-drag ratio of 1.0.

TABLE BIII.- SCHEDULED RETURN FROM AN ORBIT INCLINED 30° TO A RECOVERY NETWORK CONSISTING OF FLORIDA, TEXAS, AND BAJA CALIFORNIA PLUS ONE EMERGENCY RECOVERY SITE

| L/D capability | Basic network of Florida, Texas, and Baja California | | Three-site recovery network plus one emergency site in – | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | California (Edwards AFB) | | Hawaiian Islands | | India | |
| | Number of return orbits per day | Recall capability, % (a) | Number of return orbits per day | Recall capability, % (a) | Number of return orbits per day | Recall capability, % (a) | Number of return orbits per day | Recall capability, % (a) |
| 0.35 | 5 | 33.33 | 5 | 33.33 | 5 | (Hawaii) 33.33 | 8 | ($\lambda = 28°$) 53.33 |
| .50 | 6 | 40 | 6 | 40 | 7 | (Kauai) 46.67 | 9 | ($\lambda = 26.5°$) 60 |
| .75 | 6 | 40 | 6 | 40 | 9 | (Kauai) 60 | 12 | ($\lambda = 22.6°$) 80 |
| 1.00 | 7 | 46.67 | 7 | 46.67 | 10 | (Hawaii) 66.67 | 14 | ($\lambda = 18.3°$) 93.33 |
| 1.25 | 8 | 53.33 | 8 | 53.33 | 11 | (Hawaii) 73.33 | 15 | ($\lambda = 13.1°$) 100 |
| 1.50 | 9 | 60 | 9 | 60 | 12 | (Hawaii) 80 | 15 | ($\lambda = 13.1°$) 100 |
| 2.00 | 12 | 80 | 12 | 80 | 14 | (Hawaii) 93.33 | 15 | ($\lambda = 13.1°$) 100 |

[a]Percentages based on 15 orbits per day.

# APPENDIX C

## POSSIBLE THREE-SITE RECOVERY NETWORKS FOR RETURN
## FROM ANY ORBIT INCLINATION

It has been shown in the main body of this report (see fig. 17) that a three-site recovery network with optimum longitudinal spacing (if located in the latitude range of $0°$ to $35°$) could support quick return by a vehicle with an $L/D$ of 2.0 from any orbit inclination. The three-site recovery networks shown in table AI meet these requirements. These networks are:

(1) Edwards AFB, Algeria, and Argentina

(2) South Texas, Libya, and Muko Jima Retto

(3) Laysan Island (or Kauai Island), India, and Australia

The $L/D$ requirements for quick-return capability to these networks as a function of orbit inclination are shown in figure C1. From this figure, the $L/D$ requirements necessary for quick return from any orbit inclination or range of orbit inclinations may be obtained.

Considerations of the effects of wait time in orbit on reducing these $L/D$ requirements are strongly dependent upon orbit inclination. In order to illustrate these effects, the effectiveness of wait time is shown in figure C2 for the combination of Hawaii, India, and Australia. In figure C2 orbit inclination increments of $15°$ are presented. Analysis
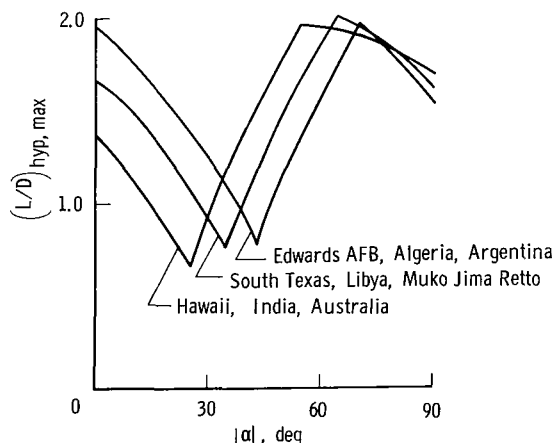
Figure C-1.- Requirements for quick return to possible three-site recovery networks from any orbit inclination.
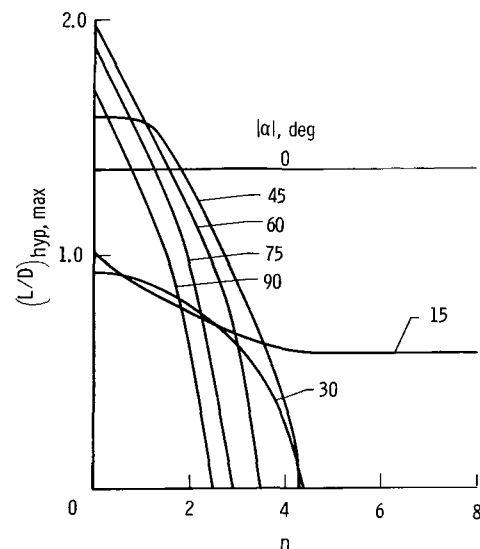
Figure C-2.- Delay orbit effects for return to the three-site recovery network of Hawaii, India, and Australia (latitude, $19.5°$) for return from varying orbit inclinations.

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of figure C2 indicates that delay orbits are very effective in reducing maximum $L/D$ requirements except for the lower range of orbit inclinations $\left(|\alpha| = 0^\circ \text{ to } 15^\circ\right)$. A maximum wait time of five orbits is sufficient to decrease the $L/D$ required to zero for orbit inclinations of $30^\circ$ and above.

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