# Multiple-Based Air- and Ground-Launch for Inspection, Rescue, and Other Space Missions

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**Orbital rendezvous, or suborbital and orbital injection at preselected altitude, heading and phasing, with short reaction times, may be critical for inspection, rescue, and other space missions. This study explores effects on reaction time, of number of launch bases, warning time, alert status, and launch system characteristics including both air-launch, and ground-launch utilizing impulsive and aerodynamic ascent turns. Analysis is based on the class of launch-base deployment consisting of equidistant bases along a 180° great-circle arc. Results indicate that a chain of four bases can reduce maximum reaction times from 15–20 hr using existing bases, to 2–6 hr. Only marginal gains result from increasing the number of bases beyond four, air-launch cruise velocity beyond Mach ~1, and/or elaborating alert status beyond fueled ground alert. Ground-launch can achieve reaction times up to ~2 hr shorter than air-launch but only at ascent vehicle gross weight penalties up to 380% for hydrogen-oxygen vehicles. Four- or six-base deployments could be implemented using existing bases plus one or two new bases in Australia. If usable for landing, as well as launch, such a chain of bases could be attractive for other missions, which might require a limited number of orbits, or return to a specific base.**

## Nomenclature

$I_{sp}$ = specific impulse, sec
$n$ = number of bases
$R$ = radius of earth (3440 naut miles)
$r$ = radius of action of aircraft (with or without in-flight refueling)
$T$ = maximum time from warning to rendezvous
$t$ = time
$v$ = cruise velocity of aircraft
$\lambda$ = stage structure factor, (empty weight less payload)/(gross weight less payload)

### Subscripts

$ar$ = ascent and rendezvous
$c$ = climb to cruise altitude
$g$ = ground get-ready from warning to liftoff
min = minimum achievable from warning to rendezvous
$w$ = warning before first pass through a potential rendezvous point

## Introduction

THE capability for launching spacecraft to rendezvous with a target satellite or into a suborbital or orbital trajectory of preselected altitude, heading and phasing, within a short time after decision and at tolerable performance penalties for maneuver, may be a critical determinant of effectiveness for inspection, rescue, and other space missions. Alternative modes for accomplishing these operations are as follows. 1) Basing concept: existing bases, or existing plus additional bases; 2) launch mode: air launch (subsonic, supersonic, or hypersonic) and ground launch (impulsive dog-leg, or aerodynamic ascent turn); 3) rendezvous mode: direct or parking orbit.

This list describes, in effect, a matrix of alternatives, portions of which have been considered by previous studies. Rosenzweig[1] explored the effects on probable times to rendezvous of using both existing bases at ETR and WTR and an additional equatorial base, with hypersonic air-launch, and ground-launch with a nominal dog-leg capability, and assuming direct rendezvous. Jackson[2] demonstrated increases in launch window for direct rendezvous which can be achieved by hypersonic launch platforms. Fey[3] evaluated the use of aerodynamic maneuvers during ascent to provide launch offset for orbital rendezvous.

This study explores parametrically the effects on system reaction time, and maneuvering penalties, of warning time and launch system characteristics including both air-launch and ground-launch modes, alert status, number of bases, and cruise velocity. Only near-orbit missions are considered, since the extended transit times to far orbits tend to minimize the relative importance of reductions in reaction time and turning penalties, achievable by use of mobile launch platforms and ascent maneuvers.

All considerations are based on a single fundamental class of launch site deployment, namely, a series of launch bases along a great circle providing continuous launch coverage within a 180° segment of that great circle, where the number of bases is allowed to vary parametrically. This deployment geometry is selected because it is characterized by the fact that any near-orbit satellite must pass over such a chain of bases at least once every orbital period. This characteristic not only provides significant reductions in times from warning to rendezvous, but in conjunction with a few reasonable assumptions it renders the problem amenable to hand calculation, and leads to straightforward results which can be clearly stated and provide useful insights. The results are presented in the form of minimum, expected, and maximum rendezvous reaction times, and maneuver performance penalties, for various numbers of bases, for air-launch using both Mach ~1 and Mach ~3 launch platforms, for ground-launch using both impulsive and aerodynamic turning, and for unfueled, fueled, and airborne alert status. Reaction times and intercept opportunities using this basing concept are compared with results from Ref. 1, which assumed use of existing bases and also an additional equatorial base. Finally, for illustrative purposes, typical 4-base and 6-base deployments are shown against a world map.

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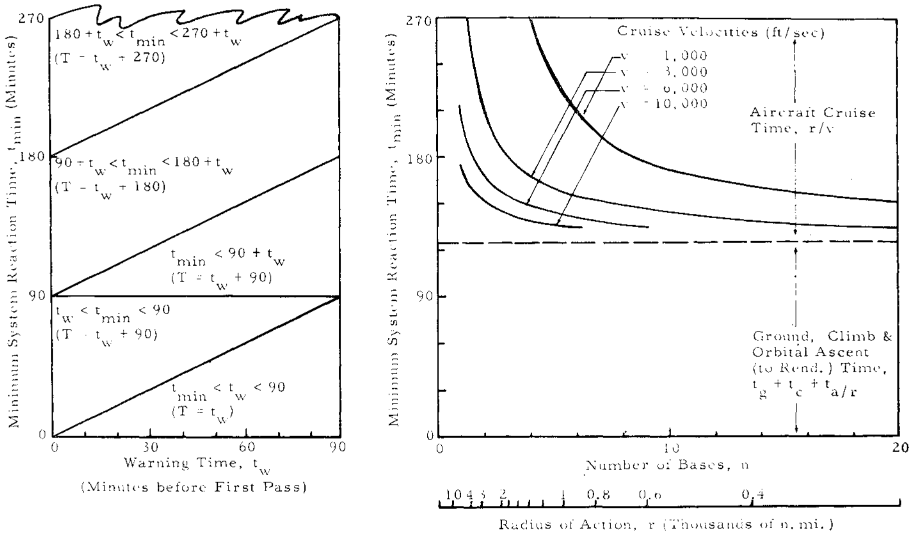


**Fig. 1 Parametric relations for rendezvous from air-launch (unfueled ground alert).**

## Analysis

### Reaction Times from Warning to Rendezvous

For a nonrotating earth, any great-circle arc subtending a central angle of $\pi$ rad is crossed at least once by the ground trace of any earth satellite. Two exceptions occur when the satellite orbit plane and the great-circle plane are coincident, in which case the ground trace lies along the great-circle arc, and perpendicular, in which case the ground trace intersects the end points of the great-circle arc at orbital half-period. If effects of earth rotation were considered, the interval between crossovers could increase to infinity in the limiting case where the earth rotation period is equal to the orbital period. For near orbits, where orbital periods are much shorter than the earth rotation period, the interval between crossovers could be increased through earth rotation by as much as one-half orbital period due to arc line end effects, but this effect can be eliminated simply by increasing the arc length somewhat beyond $\pi$ rad.

Consider a series of launch bases spaced at equal distances along the great-circle arc described previously. A satellite whose ground trace crosses this great-circle arc is the rendezvous target for a vehicle operating out of the base closest to the point of crossover. The crossover location and angle determine a distance of closest approach or offset, from the launch base, which is assumed to be traversed by a mobile platform in the case of air-launch, or by implusive dog-leg or aerodynamic turn in the case of ground-launch. This analysis will assume that such a minimum offset condition will obtain once every 90 min, which is a close approximation for circular near orbits up to $\sim$500 naut miles altitude. Because of the effective radius of action, $r$, in both air-launch and ground-launch cases, this 90-min period can be reduced to as little as $\sim$45 min in special cases when target orbit planes are close to the plane of the line of bases. It will also be assumed that range safety regulations, and guidance and navigation technologies, are sufficiently permissive to allow full utilization of launch vehicle offset and azimuth capability for both air- and ground-launch, that there is equal probability of warning time between zero and 90 min before crossover, and that there is equal probability of crossover at any target orbit inclination angle. These assumptions should be borne in mind in considering the results, since their validity will be affected to some degree by specific operational and deployment situations in the light of which this investigation may be considered.

#### *Air-launch*

Elementary geometry gives

$$n = \pi R/2r \tag{1}$$

For air-launch at $r$ from a base, it is evident that

$$t_{min} = t_g + t_c + r/v + t_{ar} \tag{2}$$

Combining Eqs. (1) and (2),

$$t_{min} = (\pi R/2nv) + (t_g + t_c + t_{ar}) \tag{3}$$

Equation (3) expresses the minimum achievable total time for ground get-ready, climb, cruise, ascent and rendezvous, consistent with the launch aircraft alert status and cruise velocity. The time between warning and rendezvous, however, can be significantly longer depending on when warning is received. For example, if warning is received too late for the next pass through a potential rendezvous point (i.e., $t_w < t_{min}$), then rendezvous must wait completion of another full orbit even if the launch aircraft can be ready at the launch point earlier. Since by definition $t_w$ is less than one orbital period ($t_w < 90$ min), the following conditions are possible (all times expressed minutes):

$$\text{if } t_{min} < t_w < 90 \text{ then } T = t_w \tag{4}$$

$$\text{if } t_w < t_{min} < 90 \text{ then } T = t_w + 90 \tag{5}$$

$$\text{if } t_w < 90 < t_{min} \text{ then } T = t_w + 90 \text{ (for } t_{min} < 90 + t_w) \tag{6a}$$

$$= t_w + 180 \text{ (for } 90 + t_w < t_{min} < 180 + t_w) \tag{6b}$$

$$= t_w + 270 \text{ (for } 180 + t_w < t_{min} < 270 + t_w)\text{, etc.} \tag{6c}$$

These relationships are shown diagrammatically in Fig. 1.

Using the assumed values for $t_g$, $t_c$, and $t_{ar}$, shown in Table 1, Eqs. (1–6c) are plotted in Fig. 1 for unfueled ground alert. For fueled ground alert and airborne alert, the results are exactly similar, but shifted downward along the $t_{min}$ scale by 60 and 95 min, respectively, as would be evident from Table 1. To show more clearly the effects of $n$, $v$, and $t_w$ on $T$, Fig. 1 is recast as Fig. 2a which shows $T$ directly as a function of probability, assuming that there is equal probability that $t_w$ will take any value between 0 and 90 min. Figures 2b and 2c show the fueled ground alert and airborne alert cases. These figures show $T$ for several values of $n$, and for $v$ = 1000 and 3000 fps. From Fig. 1 it is clear that $T$ is relatively insensitive to increases of $v$ above 3000 fps. Also shown in Fig. 2 are comparable values of $T$ for air-launch from 0.318$r$, the average or expected cruise radius, as well as from $r$, the maximum cruise radius.

The value of 0.318$r$ for the expected cruise radius is obtained in the following manner. If it is assumed that target orbits are distributed longitudinally at random, then it is expected that the orbital traces will cross the great circle

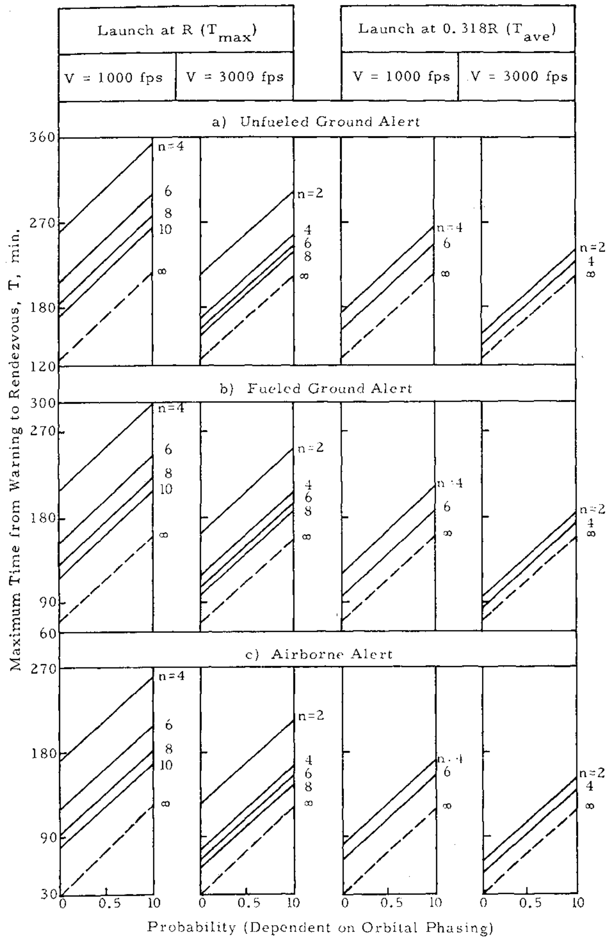


**Fig. 2 Maximum and average times from warning to rendezvous.**

connecting the bases at an average of $r/2$ from the nearest base, and, if it is assumed that target orbit inclinations are distributed randomly, then it can be shown that the expected distance of closest approach, or offset, is $r/\pi$, which is $0.318r$.

The minimum, expected, and maximum times from warning to rendezvous can be read directly from Fig. 2. The minimum time corresponds to the dashed curves in these figures, which represent the case for an infinite number of bases, or alternatively for the fortunate instances where the orbits pass directly over an existing base so that no offset is required, and to the most favorable phasing situation corresponding the zero probability extremity of the dashed curves. The expected times for a specified number of bases are given by the 0.5 probability points on the curves representing launch at 0.318 radius of action. The maximum times are given by 1.0 probability points on the curves representing launch at maximum radius of action.

### *Ground-launch*

In principle, the analysis of times from warning to rendezvous for a ground-launch is identical to that for air-launch, with the following qualifications. For ground-launch utilizing impulse dog-leg, the times required for aircraft climb and cruise associated with the air-launch case can be avoided, with the result that Eq. (3) for the ground-launch case with impulse turn becomes

$$t_{\min} = t_g + t_{ar} \tag{7}$$

For the ground-launch case utilizing aerodynamic maneuver during ascent, an additional increment of time must be included for the aerodynamic maneuver. Based on data given in Ref. 3, it is estimated that the maneuver time required for a representative turn angle, say 45°, is in the same order as the time $t_c$ for aircraft climb, ~20 min. Although this time can be expected to vary depending on the degree of offset required in each particular rendezvous case, the variation is estimated not to exceed ± ~10 min, which is considered negligible for purposes of this investigation. Thus, for the ground-launch case utilizing aerodynamic maneuvering during ascent, Eq. (3) becomes

$$t_{\min} = t_g + t_c + t_{ar} \tag{8}$$

By comparing Eqs. (7) and (8) with Eq. (3), it becomes apparent that reaction times for ground-launch as well as air-launch can be obtained readily from the curves in Fig. 2. For ground-launch utilizing aerodynamic maneuver during ascent, the reaction times correspond to the dashed curves, where the minimum, expected, and maximum times are represented by the 0, 0.5, and 1.0 probability conditions. The corresponding reaction times for ground-launch utilizing impulsive dog-leg can be obtained by subtracting 20 min from the foregoing values.

### Ascent Vehicle Gross Weights and Maneuver Penalties

The reductions in reaction time which can be achieved with ground-launch by substituting for offset capability, rocket or combined rocket-aerodynamic maneuvers at low propulsive efficiency, for air-breathing cruise at high propulsive efficiency, impose performance penalties. Any comparison of air-launch and ground-launch modes must consider these penalties, since they can result in significant increases in launch gross weight and ultimately in systems costs.

The total velocity penalties associated with impulsive dog-leg and aerodynamic maneuvers from ground-launch are given as a function of effective offset distance in Ref. 3. The penalties associated with aerodynamic maneuvers by a high lift/drag ratio upper stage ($L/D = 3$) are in the order of half those associated with dog-leg turns, but are still significant. For purposes of this analysis, the total velocity requirement for ascent to orbit from ground-launch is taken to be the sum of a representative ascent velocity gain (30,500 fps including losses) plus the offset velocity penalties given in Ref. 3 for aerodynamic $L/D = 3$. For air-launch, it is assumed that the entire offset requirement is met by the air-breathing launch platform, so that no impulsive maneuver penalties are imposed. The total velocity gain required for ascent to orbit from air-launch is reduced from the representative ground-launch value of 30,500 fps by the altitude and speed advantages inherent in air-launch. Based on trajectory optimizations not described here, which consider air-launch with pull-up maneuvers, ascent total velocity requirements of 27,000 and 24,000 fps are assumed for air-launch velocities of 1000 fps and 3000 fps, respectively.

Using the above velocity requirements, gross weights were computed for six approximately optimized ascent vehicles whose basic characteristics are outlined in Table 2. The results are given as a function of offset in Fig. 3, which shows that the gross weight penalties for hydrogen-oxygen ascent vehicles are in the order of 40 to 85% at zero offset, depending on vehicle concept, and increase rapidly as offset increases. At offset distances greater than zero, it appears that aero-

**Table 1 Assumed times for reaction operations, min**

| Alert status | $t_g$ | $t_c$[a] | $t_{ar}$[b] |
|---|---|---|---|
| Ground (unfueled) | 75 | 20 | 30 |
| Ground (fueled) | 15 | 20 | 30 |
| Airborne | ... | ... | 30 |

[a] Approximately independent of $v$.
[b] Could be as high as 60–90 min if Hohmann transfer used.

**Table 2 Summary of vehicle parameters assumed**

| | E-R,[a] $H_2$-$O_2$ | | E-E, $H_2$-$O_2$ | | E-E, storable | |
|---|---|---|---|---|---|---|
| Stages | 2 | 3 | 2 | 3 | 2 | 3 |
| Stage III | | | | | | |
| $I_{sp}$, sec | ... | 450 | ... | 450 | ... | 310 |
| $\lambda$ | ... | 0.30 | ... | 0.085 | ... | 0.055 |
| Stage II | | | | | | |
| $I_{sp}$, sec | 450 | 450 | 450 | 450 | 310 | 310 |
| $\lambda$ | 0.30 | 0.11 | 0.11 | 0.11 | 0.055 | 0.095 |
| Stage I | | | | | | |
| $I_{sp}$, sec | 440 | 440 | 440 | 440 | 300 | 300 |
| $\lambda$ | 0.09 | 0.09 | 0.09 | 0.09 | 0.065 | 0.065 |

[a] E-R = expendable-reusable; E-E = expendable-expendable.

dynamic maneuvers during ascent can reduce these penalties somewhat, but they are still quite significant.

## Results and Discussion

The minimum, expected, and maximum times from warning to rendezvous are summarized in Fig. 4 for the various air-launch and ground-launch cases considered. Because ground-launch can reduce reaction times by as much as approximately one orbital period or more as compared to some cases of air-launch, reaction times have also been shown for ground-launch incorporating a delay interval of one orbital period, to explore the degree to which this delay eases the severity of performance degradations for turning maneuvers. The minimum, expected, and maximum gross weight penalties for ground-launch and offset maneuvers, as compared to the various air-launch modes considered, are summarized in Fig. 5. One orbit delay interval does not produce appreciable reductions in expected and minimum offset penalties but can significantly reduce the maximum penalties, which represent the worst case conditions for which the ascent vehicles must be designed. The gross weight penalties shown here are for impulsive dog-legs performed 90° downrange from the launch site, and may be reduced somewhat for aerodynamic turns utilizing a lifting upper stage. The maximum penalty reductions achievable thereby are indicated in Fig. 3.

It should be emphasized that a thorough comparison of air-launch and ground-launch modes must look beyond the analysis of reaction times and ascent vehicle gross weights given here, to evaluate comparative costs and reliabilities of construction and operations associated with fixed launch sites vs mobile launch platforms.

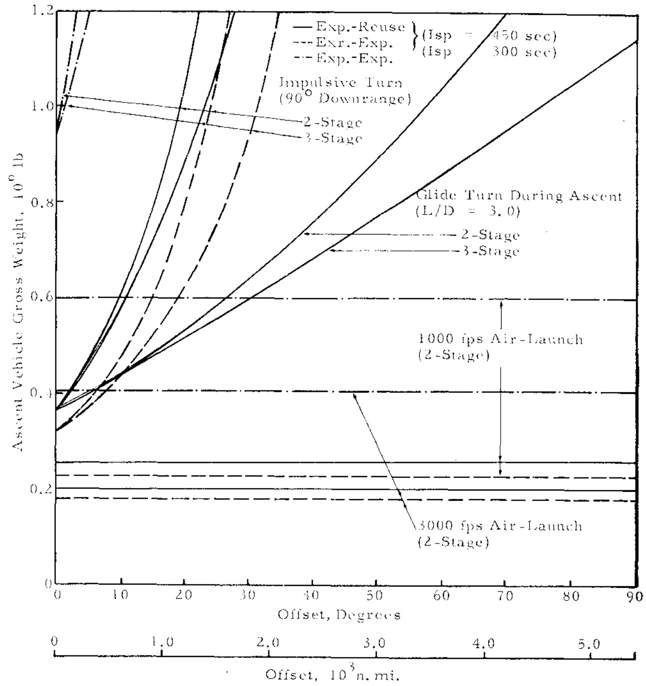


**Fig. 3 Ascent vehicle gross weight vs offset (useful payload = 10,000 lb).**

For a comparison with ground-launch from other combinations of typical launch sites [Eastern Test Range (ETR), Western Test Range (WTR), and a hypothetical equatorial site on a Pacific island], Table 3 shows the results of a previous study (Ref. 1) of ground- and air-launch, where air-launch was assumed to be restricted to ETR and WTR, and to cruise velocities of 6000 fps. For comparison between the (ETR + WTR) and the 180° basing concept, the times from warning to rendezvous for 180° basing were

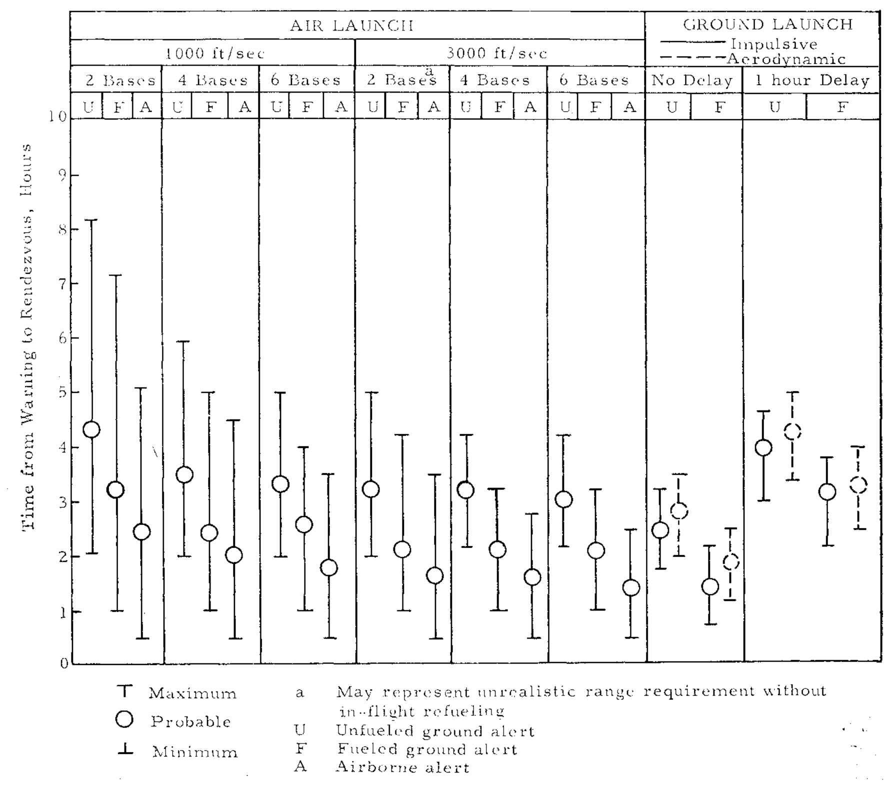


**Fig. 4 Times from warning to rendezvous.**

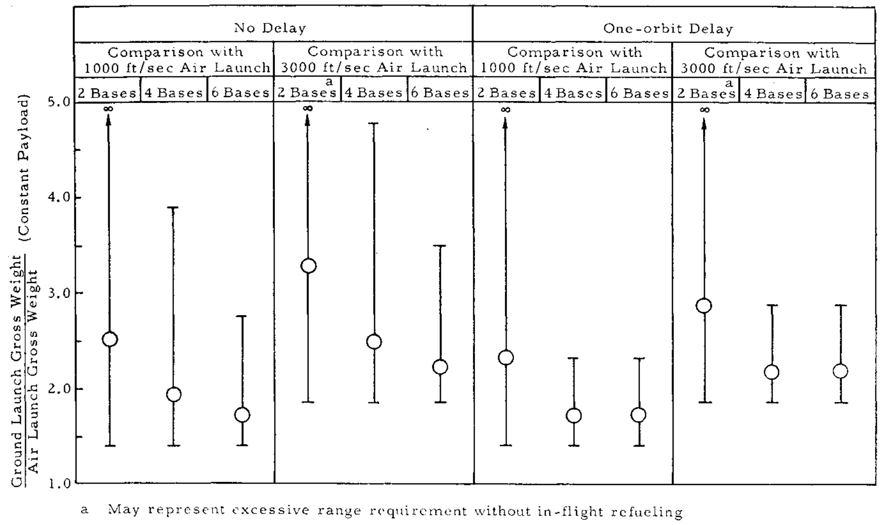


**Fig. 5 Maneuver penalties for ground-launch (based on 2-stage $H_2$-$O_2$ expendable launch vehicle and impulsive turn; gross weight reduced for aerodynamic turn, see Fig. 4).**

computed for V = 6000 fps and are also shown. Since the previous study assumed a 15-min countdown for both ground- and air-launch (equivalent to assuming $t_g$ = 15 for fueled ground alert), all results of Table 3 can be compared on the fueled ground alert basis. Reduction of reaction times by using the 180° basing concept, from the levels associated with existing bases, are summarized in Table 4 together with the number of intercept opportunities made available by the new basing concept, before the first opportunity using existing bases. This comparison shows that for the 4- and 6-base cases subsonic air-launch can reduce reaction times by 11 to 16 hr, but that going to supersonic air-launch or ground-launch produces only marginal additional gains. Also, the gains achieved by increasing the number of bases from 4 to 6 appear marginal.

Figures 6 and 7 show typical 4- and 6-base arrangements oriented around existing U.S. Air Force bases, and requiring 1 and 2 additional bases in Australia, for the 4- and 6-base cases, respectively. All arrangements cover somewhat more than 180° to allow for end effects.

## Observations

The results of this study lead to the following indications:

1) For both air-launch, and ground-launch utilizing ascent propulsive maneuvers for offset, a 180° multiple-basing concept can reduce maximum times from warning to rendezvous in any near-earth orbit from 15 to 20 hr (for existing bases) to 2 to 6 hr maximum (1.5 to 3.5 probable). With regard to reaction time, the number of bases is not critical with respect to ground-launch, but it may be critical with respect to air-launch. For air-launch, reductions in reaction time appear significant when the number of bases is increased from 2 to 4, but only marginal when the number of bases is increased beyond 4. Also, only marginal reductions in reaction time can be achieved by increasing air-launch cruise velocity beyond ~Mach 1. For both air-launch and ground-launch, it appears that worthwhile improvements in reaction time can be achieved by going from unfueled ground alert to fueled ground alert status, and while similar gains may be achievable for air-launch by going to airborne alert, the inevitable high operational costs associated with airborne alert probably restrict the value of this alternative to very special situations.

2) Times from warning to rendezvous associated with the 4-base air-launch approach range from 3.5 to 5 hr maximum and 2 to 3 hr probable. The times from warning to rendezvous for ground-launch are more nearly independent of the number of bases, and range from 2 to 3 hr maximum and 1.5 to 2.5 hr probable where launch is not delayed. These reductions of 0.5 to 2 hr in reaction time are achieved through ground-launch only by paying ascent vehicle design gross weight penalties from 160 to 380%. If launch is delayed one orbit, the corresponding reaction times are increased to 4

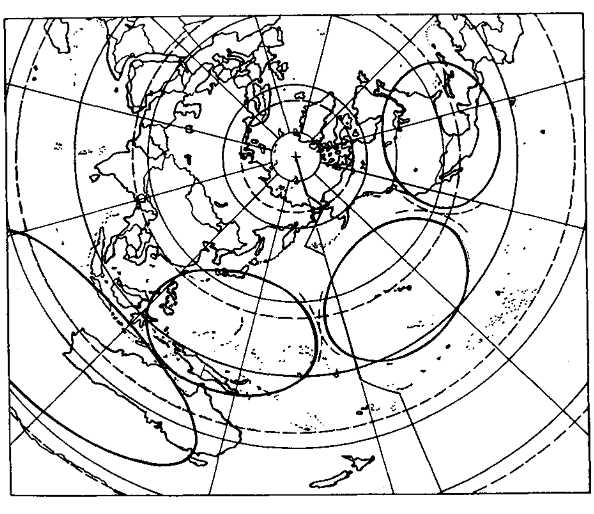

**Fig. 6 Typical 4-base arrangement (r = 1350 naut miles; bases at Bergstrom AFB, Hickam AFB, Guam and Perth; full coverage if r extended where shown by dashed curves).**

**Table 3 Comparison of air-launch and ground-launch maximum times from warning to rendezvous (fueled ground alert for air-launch; 15 min countdown time for ground-launch; air-launch cruise velocity ~6000 fps)**

| Probability | 1.00 | | | 0.75 | | |
|---|---|---|---|---|---|---|
| Orbit inclination | 35° | 65° | 90° | 35° | 65° | 90° |
| Ground-launched | | | | | | |
| ETR | 20.5 | 15.5 | ... | 13.4 | 9.6 | ... |
| WTR | ... | ... | ... | ... | ... | 18.6 |
| Equatorial | 13.1 | 13.1 | 13.1 | 9.6 | 9.6 | 9.6 |
| ETR + Eq. | 13.1 | 11.4 | 13.1 | 6.7 | 6.5 | ... |
| WTR + Eq. | ... | ... | 24.6 | ... | ... | 8.5 |
| Air-launched | | | | | | |
| ETR + WTR (Ref. 1) | | | | | | |
| r = 1500 naut miles | 13.0 | 10.6 | 8.2 | 5.8 | 4.0 | 4.8 |
| r = 2500 naut miles | 8.4[a] | 8.2[a] | 6.0[a] | 2.5[a] | 2.6[a] | 2.3[a] |
| Air-launched | | | | | | |
| (This study) | (Independent of target orbit inclination) | | | | | |
| 2 bases (r = 2700 naut miles) | 3.3[a] | | | 2.9[a] | | |
| 4 bases (r = 1350 naut miles) | 3.0 | | | 2.8 | | |

[a] Probably represents excessive range requirement without in-flight refueling.

**Table 4 Reductions of reaction time using modified basing concept with air-launch and ground-launch (fueled ground alert: probability = 1.0 for 35° and 65°, 0.75 for 90°)**

| Target orbit inclination | Interceptor basing | | Reduction of $T$, hr, using 180° basing concept | | | Earlier intercept opportunities using 180° basing concept | | |
|---|---|---|---|---|---|---|---|---|
| | | | Air-launch | | Ground-launch | Air-launch | | Ground-launch |
| | Existing | 180° concept (No. bases) | Mach ~1 | Mach ~3 | (no delay) | Mach ~1 | Mach ~3 | (no delay) |
| 35° | ETR | 4 | 15.6 | 17.2 | 17.9 | 10 | 11 | 12 |
| | | 6 | 16.5 | 17.3 | 17.9 | 11 | 11 | 12 |
| ~90° | WTR | 4 | 13.7 | 15.3 | 16.0 | 9 | 10 | 11 |
| | | 6 | 14.6 | 15.5 | 16.0 | 9 | 10 | 11 |
| 65° | ETR | 4 | 10.6 | 12.2 | 13.9 | 7 | 8 | 9 |
| | | 6 | 11.5 | 12.3 | 13.9 | 7 | 8 | 9 |

to 5 hr maximum and 3.5 to 4.5 hr probable, and the gross weight penalties are reduced to 120 to 180%, when compared to 4-base air-launch approaches. It would appear questionable whether any reaction time savings are worth the gross weight penalties associated with ground-launch, but a conclusive comparison of air-launch and ground-launch must be based on more detailed evaluation of the comparative costs, reliabilities, and operational flexibility of fixed launch sites and mobile launch platforms as applied to specific missions.

3) The reduction of reaction times associated with the 4-base concept produces corresponding numbers of additional rendezvous opportunities before the first opportunity, which would appear using existing bases. The numbers of earlier launch opportunities resulting from this basing concept are 7 to 10 for air-launch at 1000 fps, 8 to 11 for air-launch at 3000 fps, and 9 to 12 for ground-launch. If the first rendezvous attempt fails as a result, for example, of vehicle malfunction or target evasive maneuvers or counteraction, multiple-basing allows several more attempts before the first rendezvous could be attempted from existing bases. There may be many realistic scenarios where the time savings could be critical in rescue, such as failure of a life-support or power subsystem, uncontrolled spinup, freezing of a vent valve in a pressurized vessel, or failure of re-entry equipment during orbital decay, and there may be military situations in which the orbit approaches over-flight of hostile territory where it could be subject to ground fire or capture. The range 10 to 18 hr savings corresponds to 7 to 12 orbital passes, during which time a hostile satellite could accomplish much in the way of military testing, photo reconnaissance, or satellite inspection, capture, and negation.

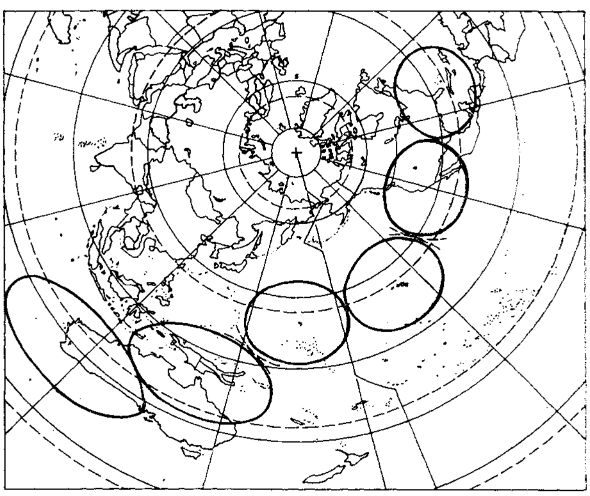

**Fig. 7 Typical 6-base arrangement ($r$ = 900 naut miles; bases at ETR, WTR, Hickam AFB, Wake, Cape York, and Perth; full coverage if $r$ extended where shown).**

4) Suitable location of a chain of 4 or 6 bases covering more than 180° could be achieved utilizing 3 or 4 existing U.S. military air bases with 1 or 2 new bases in Australia. Locating the chain of bases primarily across the Pacific Ocean effectively surrounds most of the bases by water, reducing potential restrictions on launch azimuth resulting from range safety considerations, and increasing the capability for polar and retrograde, as well as posigrade, orbits.

5) If landing or recovery is possible at each base in the chain, then for missions requiring a given number of orbits, launch can be from one base with recovery or landing either at the same base, after the first orbit (if launch offset and re-entry maneuvering are sufficient to allow for earth rotation), or at bases farther along the chain if more orbits are required. This may be attractive if landing is required at a specific base.

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