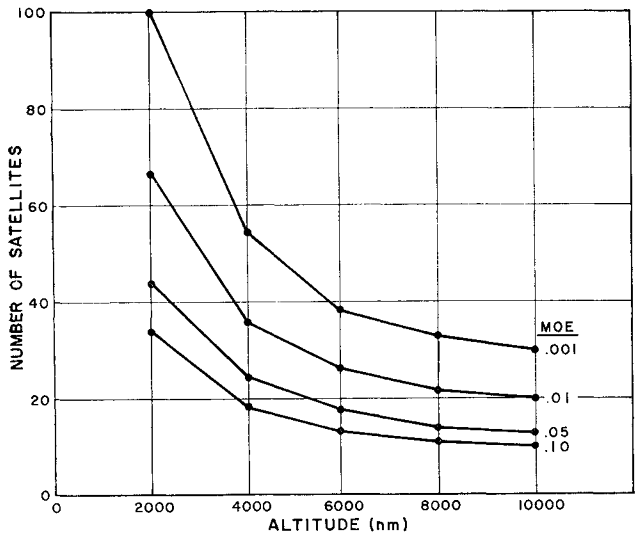

Fig. 1 Minimum number of satellites required as a function of altitude and desired measure of effectiveness. Note: Costs of achieving all orbits are equal.

meaning, the integer approach is attempted. In actuality, a linear programing solution will generally conform quite closely to the one obtained using integer programing techniques.

Example 1

The first problem selected for the purpose of illustrating the outlined technique of obtaining a minimum-cost satellite overlay consists of seven links that form a global belt of stations having a small variation in latitude. These links are: Japan $\xrightarrow{1}$ Midway $\xrightarrow{2}$ Hawaii $\xrightarrow{3}$ California $\xrightarrow{4}$ Washington, D. C. $\xrightarrow{5}$ Azores $\xrightarrow{6}$ France $\xrightarrow{7}$ Turkey. It is assumed that all links require the same MOE. That is, the satellite overlay will provide a probability of outage which is less than 0.01 ($A_k = 0.01$). Inclination angles of 0°, 30°, 45°, 60°, and 90° and discrete altitudes from 2000 to 10,000 naut miles at 2000-naut-mile intervals were chosen. Assumed cost values used in this problem are found in Table 1. Values for P_{ijk} were obtained using the technique outlined previously. The results for this example show a mix consisting of a single altitude and inclination. The optimum orbit is 6000 naut miles at 30° inclination. The system overlay required 35 satellites at a total cost of $105,000,000. Results obtained by linear programing rather than integer programing gave 34.78 satellites at an orbit of 6000 naut miles and 30° inclination; rounding this off, results are identical. This is not the case for example 2 below.

Example 2

Slightly different cost figures are assumed (see Table 1), and the orbit altitude is fixed at 6000 naut miles. The inclination angle was permitted to vary as in example 1. The P_{ijk} (for $H = 6000$ naut miles) and A_k are the same as those in example 1. The results show an optimum mix of 27 satellites at a 60° and one satellite in a polar orbit (90°) for a total cost of $66,000,000. The linear program results for this problem indicate 25.56 satellites at a 60° and 2.01 satellites at 90°. Roundoffs to the next highest integers which guarantee satisfaction of the constraint equation give 26 at 60° and 3 at 90°, which would raise the cost by $3.7,000,000 or 6% compared to the integer-program results. The cost estimates of example 2 were used in the integer program to obtain minmum cost mixes of satellites in various fixed altitude configurations; results are given in Table 2.

Example 3

The minimum number of satellites required to satisfy all coverage conditions simultaneously was also obtained. The method in this case assumes equal costs for placements of satellites. Under this assumption, minimum cost criteria will result in the minimum number of satellites for a specified MOE. Results are shown in Fig. 1 for each of the altitudes.

Conclusion

A method has been developed using integer programing techniques for optimizing a satellite configuration to satisfy global communication systems using minimum cost criteria. The technique may also be applied to any satellite overlay used to optimize presence of two satellites in the line-of-sight path of ground observers, as in navigational or satellite weather systems. Several examples have been presented, both for satisfying minimum cost criteria and for minimum number of satellites.

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Venus Swingby Mode for Manned Mars Missions

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A PROMISING new method for reducing Earth return velocities from Mars stopover or flyby missions is the Venus swingby mode, which utilizes the gravitational field of Venus to decelerate the spacecraft on the return leg, or to accelerate it on the outbound leg, to achieve a more favorable calendar date for return from Mars. Earth entry velocities are reduced from a maximum of 70,000 to 50,000 fps or less, without increases in mission propulsion requirements. Venus swingby modes have been examined previously by Ross[1] and others in connection with the 1970–1972 Mars-Venus dual planet flybys; it is the purpose of this note to show the general applicability of the Venus swingby technique to both Mars stopover and flyby missions for all mission opportunities (14 opportunities were examined, covering the period from 1971 to 1999).

Launch opportunities for Mars missions are associated with Mars-Earth oppositions, and precede by three to four months the opposition dates, which occur on the average every 26 months. Because of the eccentricity of the Mars orbit, the mission trajectory profiles change from one opposition to the

Received April 27, 1964; revision received June 25, 1964. Material presented in this note was developed during a study of the manned Mars landing and return mission for the NASA Ames Research Center under Contract No. NAS 2-1409. The helpful comments of C. A. Syvertson and H. Hornby of the Ames staff are gratefully acknowledged.

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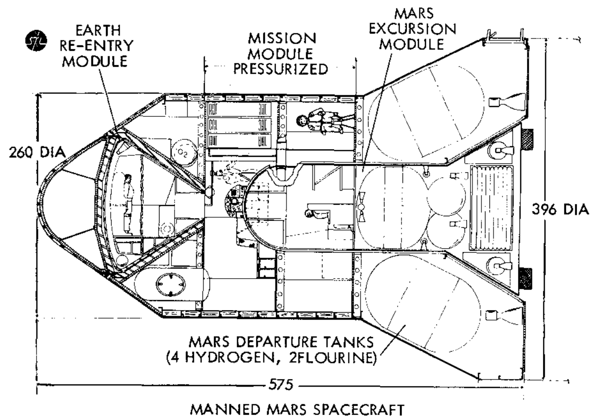

Fig. 1 Manned Mars spacecraft.

next. Earth entry velocities are particularly sensitive, and range from 46,000 fps in a favorable opposition, such as 1971, to 70,000 fps in an unfavorable opposition, such as 1980. The cyclic pattern of mission profile variations repeats every 15 yr, or every seven oppositions. The slight inclination of the Mars orbit causes the transfer trajectories to rotate out of the ecliptic, but this effect is small except in one or two special cases and was not found to constrain the selection of optimum trajectories.

Direct Missions

The direct flights used as a basis for comparison with the Venus swingby modes were based on a 10-day stopover mission to Mars. The spacecraft departs from an Earth parking orbit and, after a 4- to 6-month transit, is decelerated into a 500-km circular parking orbit at Mars by means of aerodynamic braking (similar mission characteristic velocities are obtained with retro capture). A surface landing on Mars is made by means of an excursion module that returns to the parking orbit for rendezvous with the main spacecraft. After a 6- to 8-month return trip, the craft enters the Earth's atmosphere for landing by means of an Apollo or M-2-type Earth entry module after jettisoning the main spacecraft mission module. A typical spacecraft layout is shown in Fig. 1.

Weight-scaling laws, based on the spacecraft design shown in Fig. 1, were used in performing optimization analyses to select the best combination of calendar date, total trip time, and leg time to minimize total spacecraft weight on Earth orbit. The results, shown in Fig. 2, indicate that Earth arrival velocities increase rapidly during the late 70's when opposition occurs as Mars nears its aphelion. Since aerodynamic entry system weights are relatively small compared to equivalent propulsion system weights, and the mission module is about four times as heavy as the Earth entry module, the mission is biased heavily in favor of reduced propulsion system requirements at the expense of high Earth arrival velocities. Aero entry systems capable of operating at these high velocities (70,000 fps) will be exceptionally difficult to develop, primarily for reasons of navigation and control.

Aerodynamic entry speeds at Earth return can be reduced in several ways, all of which result in increased spacecraft gross weight. Biasing the trajectory optimization to reduce

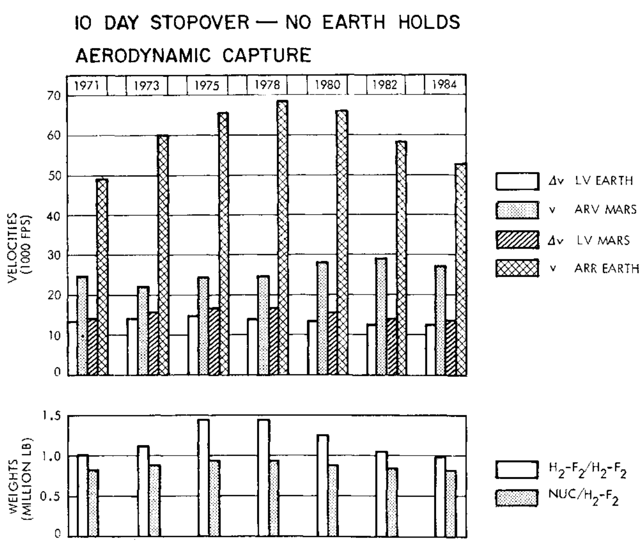

Fig. 2 Manned Mars stopover mission characteristics.

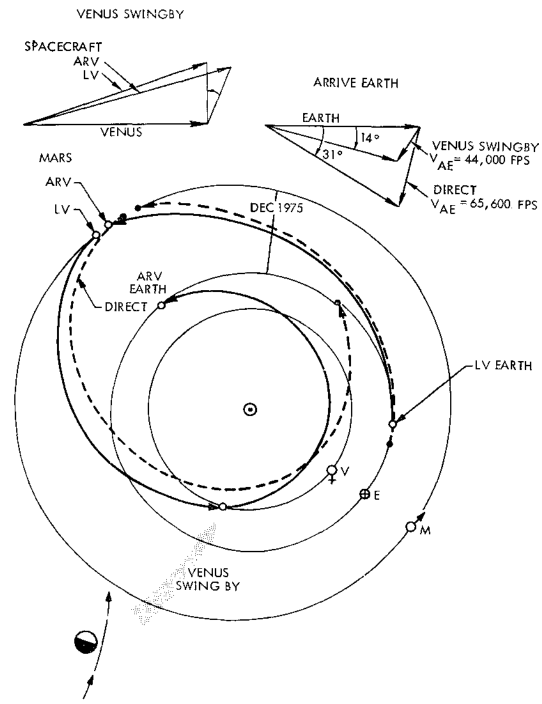

Fig. 3 Venus swingby return mode (1975 mission).

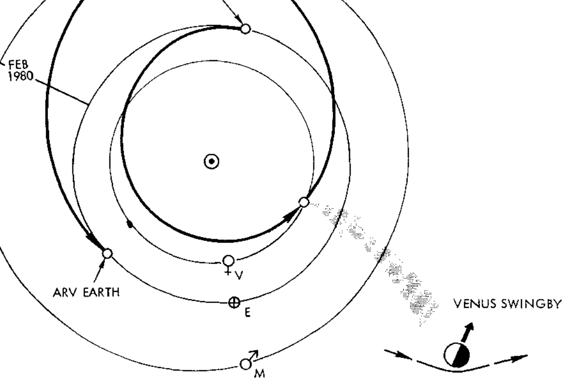

Fig. 4 Venus swingby outbound mode (1980 mission).

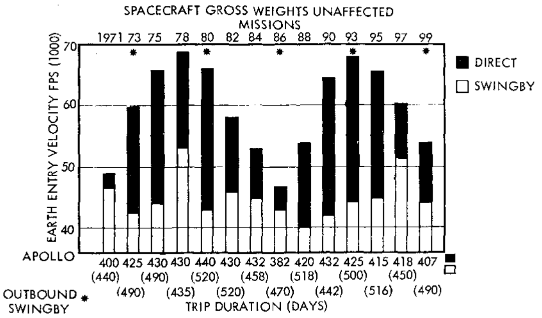

Fig. 5 Effect of Venus swingby mode on Earth entry velocities (Mars stopover mission).

the Earth entry speed from 65,600 to 60,000 fps (for the 1975 mission) increases the gross weight from 1.43 to 1.70 $\times$ 10^6 lb (24%). Use of a retrorocket to reduce speed by the same amount increases gross weight to 1.61 $\times$ 10^6 lb (13%). Reducing the Earth entry speed to 50,000 fps by means of retro propulsion increases gross weight from 1.43 to 2.05 $\times$ 10^6 lb (43%).

Mars Stopover Missions with Venus Swingby

The gravitational field of Venus can be used to reduce the heliocentric velocity vector of the spacecraft as it passes by Venus, resulting in a more nearly tangential approach to Earth. The advantages of the Venus swingby return modes can be demonstrated for the 1975 mission, which is a typically unfavorable year for a direct return. In the direct return mode the spacecraft passes inside the orbit of Venus to effect the rendezvous with Earth (Fig. 3) at a relative heliocentric flight path angle of 31°, which results in an entry velocity of 65,600 fps. By adjusting the return trajectory slightly, the spacecraft can be made to rendezvous with Venus, and if a dark side passage is made at an altitude of about 3300 km, the spacecraft heliocentric velocity is reduced by 15,000 fps. The resulting Venus-to-Earth trajectory approaches Earth at a relative heliocentric path angle of only 14° so that the entry velocity is reduced to 44,000 fps. For many of the 14 opportunities in the 1971–1999 period, the spacecraft does not pass close by Venus on the return trip. However, the angular rate of travel of Venus is rapid compared to that of Mars (by a factor of four when Mars is near its aphelion), and the spacecraft can be parked on Mars for relatively short periods of time to await a favorable rendezvous. In addition, the mission trajectory paths can be adjusted to effect a more favorable position for Venus rendezvous, which can be effected before or after perihelion passage of the spacecraft. Altogether, about two-thirds of the mission opportunities can effectively utilize the Venus swingby return mode to reduce Earth entry velocities.

In the remaining opportunities, Venus swingbys can be effected by "reversing" the trajectory, that is, by following long (>180°) transfers out to Mars, and returning to Earth by short (<180°) transfers. This mode is normally precluded because the Earth-departure propulsion requirements are excessive, but can be reduced to near-optimum values, if, subsequent to Earth departure, the whip effect of Venus is used to accelerate the spacecraft toward Mars (Fig. 4). The net result is again a reduction of the Earth entry velocities to less than 45,000 fps.

Results of the 14 opportunities are given in Fig. 5. Very significant reductions due to Venus swingby are apparent, even in the favorable years. In those cases in which Venus rendezvous is made before perihelion passage, trip time is extended to about 500 days. If rendezvous is effected after perihelion passage, little extension in trip time results. Spacecraft gross weight is essentially unaffected.

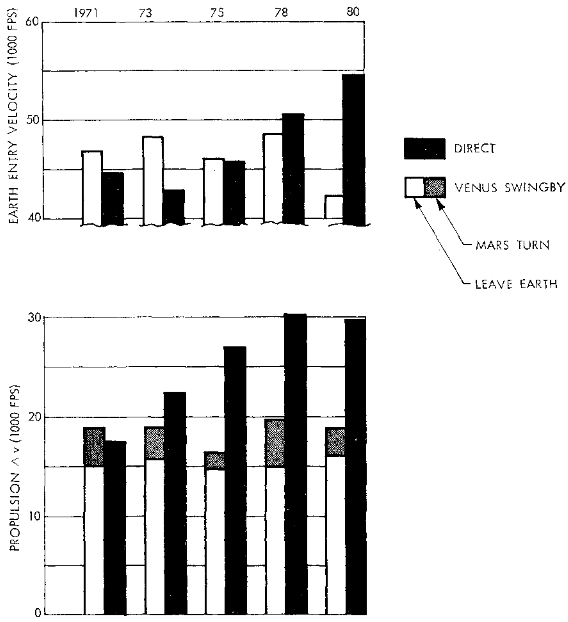

Fig. 6 Effect of Venus swingby modes on characteristic velocities (Mars flyby mission).

In certain cases it is possible to reduce the spacecraft gross weight penalty associated with the unfavorable years by proper selection of trajectory paths. In 1980, for example, using a Venus swingby on the outbound leg, total propulsion ΔV (to leave Earth and to leave Mars) is 27,600 fps, which compares with 27,500 fps for the 1971 opportunity. Earth entry velocity is maintained at 41,500 fps, which also is less than that for the favorable years. Trip duration is extended to 495 days, which results in a 3.5% increase in gross weight because of increased life support system weight.

Mars Flyby Missions with Venus Swingby

Spacecraft arrive and depart from Mars near the aphelions of transfer trajectories; during the Mars passage they are moving at a relatively low velocity. This suggests that the Mars stopover missions described previously can be "converted" to Mars flyby missions by the use of moderately powered turns during the Mars passages (the gravitational field of Mars is augmented by propulsive maneuvering). As in the case of the Mars stopover missions, the Venus swingby mode is used to reduce Earth departure and Earth return velocities to near-minimum values. Hence, a class of Mars flyby missions can be derived which have much reduced characteristic velocities compared to those of the Earth-Mars-Earth direct flyby missions (Fig. 6). Propulsion requirements (which determine spacecraft gross weight) and Earth entry system design requirements are reduced to approximately those of the favorable years (1971 and 1986). Examination of missions through a cycle of favorable to unfavorable opportunities indicates that velocity requirements with the Venus swingby mode remain approximately the same. Powered turns at Mars vary between 1600 and 5000 fps.

Conclusions

It is concluded that Venus swingby modes can be applied systematically to all Mars stopover or flyby missions with significant reductions in characteristic velocities compared to those of direct Earth-Mars-Earth mission modes.

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