INITIAL MASS SAVINGS ASSOCIATED WITH THE VENUS SWINGBY MODE OF MARS ROUND TRIPS

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ABSTRACT

Trajectory data is presented for round trip stopover missions to Mars during which the spacecraft is accelerated by Venus' gravitational field on either the outbound or inbound leg. The manner of presentation allows the analyst to determine the arrival and departure speeds at Earth and Mars, and the dates of passage and passage distances at Venus. Representative vehicle systems are analyzed to compare the initial mass on Earth orbit requirements of the Venus swingby modes with the direct round trips. It is shown that in many instances the swingbys require less than half the initial mass associated with the direct trips and that Earth entry speeds are reduced to not more than 50,000 ft/sec. These benefits can be realized at an expense of no more than a 25 percent increase in total mission time.

1. Introduction

It has been shown (Ref. 1) that Earth entry speeds associated with round trip stopover missions to Mars can be significantly reduced by employing Venus swingbys. This paper analyzes the swingby mode with a view toward its usefulness in reducing powered flight performance requirements, thereby reducing the initial mass needed on Earth orbit.

The velocity requirements for short duration round trip stopover missions to Mars are essentially periodic within an Earth-Mars synodic cycle. These requirements are at a minimum during the 1969 and 1971 launch opportunities since arrival occurs near Mars' perihelion; maximum requirements exist during the 1975 and 1978 opportunities since arrival

occurs near Mars' aphelion. However, an examination of single leg trajectory data (Ref. 2) indicates that if the outbound and inbound legs of a round trip could be optimized separately then arrival and departure hyperbolic excess speeds at both Earth and Mars of less than 0.10 to 0.15 EMOS (Earth Mean Orbital Speed of approximately 97,700 ft/sec) could be attained.* These speeds are only slightly higher than the Earth departure speeds, for instance, of 0.08 to 0.12 EMOS needed for Hohmann transfers to heliocentric radii equal to Mars' perihelion and aphelion radii, respectively.

Rather than consider further the single leg speed requirements, if instead the single leg flight times are examined, the cause of the increase in energy requirements associated with standard round trip missions becomes clear. The flight time for a near-Hohmann outbound leg is such that, at Mars arrival, Earth is ahead of Mars in heliocentric longitude, i.e., arrival occurs after opposition. This makes it clearly impossible to employ a near-Hohmann inbound leg; the required heliocentric transit angle must greatly exceed 180 degrees. Thus, it is never possible to leave Earth on a minimum energy outbound leg and arrive at Mars soon enough to leave Mars on a minimum energy inbound leg. This disparity between the desired arrival and departure times at Mars is a maximum during the unfavorable launch periods. This is illustrated in Figure 1 which compares the relative position of Earth and Mars at Mars arrival, based on two Hohmann transfers, one arriving at perihelion (representative of 1969 and 1971 missions) and the other arriving at aphelion (representative of 1975 and 1978 missions). Notice that for the aphelion transfer Earth would be 98 degrees ahead of Mars, or the equivalent of arrival three months after the opposition date. Even for the perihelion transfer, Earth would be over 50 degrees ahead of Mars at arrival. This increase of almost 50 degrees in the inbound leg transit angle is the primary cause of the increase in energy requirements for round trip missions during those years recognized as "unfavorable."

*This independent optimization of each leg is possible if one considers the conjunction class round trips wherein the outbound leg takes place near one opposition and the inbound leg takes place near the following opposition. These trips suffer the disadvantage, however, of total mission times of up to 950 days.

From the foregoing statements, it is apparent that if the arrival time at Mars could in some way be altered so that Earth were closer to (or even behind) Mars in heliocentric longitude, i.e., if arrival could occur before opposition, then the speed requirements for the round trip stopover missions could be markedly reduced and perhaps rendered less sensitive to the year of the trip. In this context, further examination of the interplanetary trajectory data reveals that the single leg speed requirements between Earth and Venus (Ref. 2) and between Venus and Mars are comparable to those between Earth and Mars. Of particular significance, the dates at which these low speed trajectories occur differ widely since minimum energy trajectories between Earth and Venus occur near Earth-Venus conjunction; those between Venus and Mars occur near Venus-Mars alignment; and those between Earth and Mars near Earth-Mars opposition.

Thus, it would not seem unreasonable that a vehicle could depart from Earth on a low energy trip toward Venus and, in a manner quite analogous to the round trip flybys, have its trajectory perturbed by Venus so that it would arrive at Mars at a moderate speed. Of more importance, since the mean angular rate of both the Earth-Venus and Venus-Mars legs of the outbound trajectory would be greater than that of a low energy Earth-Mars trajectory, it might thus be possible to arrive at Mars in time to permit a low energy inbound leg to Earth. Conversely, it would seem possible to travel directly to Mars on a low energy outbound leg and employ the Venus swingby technique during the inbound leg to overtake Earth.

2. Swingby Mission Characteristics

The remainder of this paper presents basic trajectory data which delineates the characteristics of several such Venus swingby missions. To illustrate the potential advantage these missions have over the standard Mars stopover missions, initial mass on Earth Orbit (MEO) requirements are presented and compared with those associated with the standard round trips.

To determine those years, without recourse to a lengthy trajectory analysis, for which either outbound or inbound swingbys might yield lower energy requirements than those needed for the standard trips and yet might not require excessive mission durations, an

artifice which has proven useful is a continuous plot of the dates of the conjunctions, alignments and oppositions. Such a plot is shown in Figure 2. Considering first the outbound swingbys we search for the regions in which an Earth-Venus conjunction is followed, not too quickly (say at least 200 days later), by a Venus-Mars alignment which, in turn, is followed about 200 days later by an Earth-Mars opposition. Scanning the data we can infer that an outbound swingby with return to Earth near the 1980 opposition, for example, would probably prove beneficial. On the other hand, a similar mission based on the 1982 opposition would likely be unattractive since the three events occur almost simultaneously. By considering the sequence of opposition-alignment-conjunction useful years for the inbound swingbys can be inferred. Thus, a mission begun near the 1975 opposition should be promising, whereas an inbound swingby initiated near the 1980 opposition would prove unattractive. During a few of the opposition years (1971, 1978, 1984), the time phasing between the appropriate planetary positions is almost equal for the outbound and inbound swingbys but successive events are separated by something less than 200 days. The availability of useful swingby missions during these years must be determined by detailed trajectory analysis.*

Based on the analysis of the planetary positions, the swingbys should be available as shown in Table 1.

Table 1

AVAILABILITY OF SWINGBYS

Mission	Year of Earth - Mars Opposition 1971	73	75	78	80	82	84	86
Outbound Swingby	Maybe	Yes	No	Maybe	Yes	No	Maybe	Yes
Inbound Swingby	Maybe	No	Yes	Maybe	No	Yes	Maybe	No

*A plot such as Figure 2 may also be helpful to determine the years during which nonstop multiplanet flybys can occur. For instance, a nonstop Earth-Venus-Mars-Venus-Earth mission can be considered as the composite of an outbound swingby and an inbound swingby with equal hyperbolic excess speeds at Mars.

It would appear that swingbys will be useful for at least two-thirds of the mission opportunities. The data is cyclic with a period of about six years. This is because in 2336 days, four Earth-Venus conjunction periods occur while three Earth-Mars opposition cycles span 2340 days. On the average, then, the three planets will repeat their approximate positions every 2338 days, or 6.4 years.

Detailed trajectory analyses of the 1978 and 1980 outbound swingbys and of the 1975 inbound swingby have been conducted. The data were obtained using the digital computer programs that were used to develop the round trip planetary flyby data contained in Ref. 2. The results tend to bear out quantitatively what the results of Table 1 indicate qualitatively.

Figures 3 and 4 illustrate mission profiles for a typical 1980 standard round trip and a 1980 outbound swingby, respectively. Both missions are ten-day stopovers. Notice that the heliocentric transit angle of the outbound leg of the standard trip is less than 180 degrees, yet Earth is far ahead of Mars at arrival. This necessitates a large transfer angle on the inbound leg with perihelion occurring inside Venus' orbit in order to attain a sufficiently large angular rate. The heliocentric velocity vectors at departure and arrival intersect, respectively, the orbital velocity vectors of Mars and Earth at rather high angles. This causes large hyperbolic excess speeds at each planet, resulting in large velocity additions at Mars and high entry speeds at Earth.

The swingby (Figure 4) is characterized by heliocentric transfer angles between Earth and Venus of over 180 degrees; transfer angles between Venus and Mars of less than 180 degrees. The total angle, however, is about 360 degrees. That the transit angles on the Earth-Venus and Venus-Mars legs are greater than 180 degrees and less than 180 degrees, respectively, is of no particular significance; during other years that are favorable for outbound swingbys, the relative magnitudes of these transit angles may well be reversed.

Of paramount importance is the fact that the average angular rate of the outbound trajectory is much greater than that of Earth in its orbit. Thus, in contrast to the standard missions, Earth is far behind Mars at arrival, i.e., arrival occurs much sooner

than opposition. This situation permits, as shown, a near-Hohmann Mars-Earth trajectory to be employed on the inbound leg.

Similar profiles are shown in Figures 5 and 6 for a 1978 outbound swingby and a 1975 inbound swingby. Even before directly comparing the speeds, it can be inferred that the 1978 outbound swingby is not as advantageous as the 1980 swingby. Notice in 1978 that the heliocentric speed at Earth departure is directed noticeably outward. This gives rise to a somewhat higher departure hyperbolic excess speed than during 1980. In addition, the outbound leg flight time is greater than one year, compared to about nine months in 1980. Moreover, since much of the Earth-Venus leg lies beyond Earth's orbit, the average angular rate of the outbound leg is somewhat lower than in 1980 so that the longitude difference between Earth and Mars at arrival is less. To employ a low speed departure from Mars, this smaller longitude difference necessitates a rather long inbound leg, resulting in a total mission time of almost two years.

The reason for these unattractive features lies in the not-altogether favorable positions of the planets, as was indicated by Figure 2. The result is that, while low speed departures to Venus are possible, the corresponding hyperbolic excess approach speeds at Venus are lower than the hyperbolic excess departure speeds needed at Venus to arrive at Mars in time to employ low energy-short duration inbound legs from Mars to Earth. Based on the results of the trajectory computations, these characteristics manifest themselves into Earth launch windows of less than one month duration. It is tentatively concluded, therefore, that during those years indicated in Table 1 by "maybe" swingbys are possible but not particularly desirable.

The 1975 inbound swingbys, on the other hand, typified by Figure 5, have essentially the same desirable characteristics as the more favorable outbound swingbys. Notice that, after following a typical standard outbound leg, arrival at Mars naturally occurs long after opposition. The swingby of Venus on the inbound leg permits a trajectory with the high angular rate needed to overtake Earth and yet permits near-tangential departures from Mars and arrivals at Earth.

Figure 7 is the hyperbolic excess speed contour chart associated with 1980 outbound swingbys. The left-hand portion of the chart is the outbound (swingby) leg. The right-hand portion shows the standard speed contours for single leg Mars-Earth inbound legs. For a given set of arrival and departure dates at Earth and Mars, one can estimate from the figure the departure and arrival speeds at Earth and Mars, and the passage distance and date of passage at Venus. (Passage speeds at Venus are of secondary importance and are omitted for clarity; typical values are between 0.25 and 0.45 EMOS.)

As an aid to understanding the chart the "path" followed to ascertain the data for the typical profile shown in Figure 4 will be traced.

Point 1:

	Julian Date	Excess Speed (EMOS)	Passage Distance (Venusian Radii)
Leave Earth	2443840	0.167	
Pass Venus	2443996		1.12
Arrive Mars	2444120	0.258	

Point 2:

Leave Mars	2444130	0.100	
Arrive Earth	2444380	0.148	

The advantages of such swingbys are apparent. Whereas the Mars departure speeds for optimum 1980 standard round trips are greater than 0.20 EMOS, it is seen that the swingbys can permit Mars departure speeds below 0.10 EMOS and yet permit Earth departure speeds of less than 0.20 EMOS.* Furthermore, the excess speeds at Earth return can be less than 0.15 EMOS. Associated entry speeds would be about 40,000 ft/sec compared to about 65,000 ft/sec for the 1980 standard trips. The only apparent disadvantage is that total mission durations are at least 500 days long compared to slightly over 400 days for the standard short stopover missions. It is also apparent from Figure 7 that increases in Mars departure velocity, hence increases in MEO, associated with longer stopover times are much less than required during standard missions. By employing a longer inbound leg having a heliocentric transit angle greater than 180 degrees, a sixty day stopover, for example, can be achieved with a Mars departure velocity of only 0.166 EMOS.

*A decrease in the Mars departure excess speed by a given amount at the expense of an increase in Earth departure excess speed by the same amount will result in a net reduction in total mission velocity requirements. Since Mars is less massive than Earth, a given decrease in excess speed represents a larger reduction in the energy of the Mars escape hyperbola than the same speed increase would raise the energy of the Earth escape hyperbola.

Further inspection of the speed contour chart reveals that launch window durations during 1980 (and quite likely during every year favorable for the swingbys) are adequate. Earth departure speeds below 0.20 EMOS, for example, can be attained throughout a period of about one month. Furthermore, since the departure speeds from Mars are low, and since the increase in initial velocity per unit time delay is lowest when departure velocity itself is low, it can be concluded that MEO increases due to departure delays at Mars will be less for the swingbys than for the standard missions.

Figure 8 is a similar speed contour chart for the 1975 inbound swingby. The left-hand portion applies to the direct Earth-Mars outbound leg; the right-hand portion to the inbound (swingby) leg. Although the speeds are not as low as those of the 1980 swingby, there are, nonetheless, compatible regions within which departure from Earth and Mars can occur for less than 0.20 EMOS and which also permit Earth return speeds of less than 0.20 EMOS.

3. Mass on Earth Orbit Comparisons

The effects of these various characteristics can be combined and a valid comparison made to the standard round trips by determining the MEO requirements. It must be emphasized that our primary interest at this time is a comparison of MEO requirements between standard missions and swingby missions. Until future systems studies are carried out, a more precise definition of requirements is impossible.

Several missions have been considered. Their dates and excess speeds are presented in Table 2. Also shown for comparison is the standard round trip data for the 1971 favorable opposition. The dates for the standard trips were obtained from Ref. 3.

Table 2

MISSION DEFINITION

Mission Mode	Lv Earth (J.D.-2440000) (EMOS)	Pass Venus	Ar Mars	Lv Mars	Pass Venus	Ar Earth
1971 Standard	1080 (.125)	--	1220 (.196)	1230 (.193)	--	1500 (.334)
1980 Standard	4190 (.140)	--	4380 (.230)	4390 (.215)	--	4620 (.539)
1980 Outbound Swingby	3840 (.167)	3996 (.330)	4120 (.258)	4130 (.100)	--	4380 (.148)
1978 Standard	3440 (.152)	--	3620 (.211)	3630 (.228)	--	3870 (.599)
1978 Outbound Swingby	3081 (.241)	3319 (.259)	3458 (.233)	3468 (.138)	--	3780 (.361)
1975 Standard	2670 (.158)	--	2840 (.190)	2850 (.227)	--	3100 (.577)
1975 Inbound Swingby	2670 (.178)		2820 (.241)	2830 (.166)	3050 (.390)	3188 (.219)

Table 3 compares the MEO requirements, Earth entry speeds and mission durations for these trips. The assumptions used for the basic calculations are listed below.

- Ten day orbital stopover at Mars
- O_2/H_2 Earth departure system and storable Mars departure system (all single stage)
- Atmospheric capture at Mars, direct aerodynamic entry at Earth
- Earth departure from 200 s.m. orbit, Mars departure from 500 s.m. orbit
- Command module weight after Earth entry of 15,000 lb - three-man crew
- Solar radiation storm cellar weighing 5400 lb for standard missions and 7000 lb for swingby missions
- Mars atmospheric capture system mass per Ref. 4

- Earth entry system mass per Ref. 5
- All other parametric structural and subsystem weight data per Ref. 6
- Life support system weight of 3500 lb plus 22.7 lb per day of mission duration

Table 3

MISSION SUMMARY

TEN DAY ORBITAL STOPOVERS AT MARS

Mission	Mass on Earth Orbit (million lbs)	Earth Entry Velocity (ft/sec)	Mission Duration (days)	Passage Distance (Venusian radii)
1971 Standard	1.42	48,900	420	--
1980 Standard	2.08	64,000	430	--
1980 Outbound Swingby	0.85	39,100	540	1.12
1978 Standard	2.52	68,900	430	--
1978 Outbound Swingby	1.60	50,600	700	1.48
1975 Standard	2.49	67,100	430	--
1975 Inbound Swingby	1.46	42,200	520	1.28

Notice that during every opposition year considered the swingbys reduce the initial MEO requirements between thirty to sixty percent and reduce the Earth entry speeds by over 18,000 ft/sec. These low entry speeds are in substantial agreement with those presented in Ref. 1.

Other, more advanced, missions were also considered. Typical of these is a thirty-day landing mission (with a 60,000 lb Mars Excursion Module) using nuclear propulsion at Earth and Mars departure and at Mars arrival. The MEO requirements during 1980 are 1,613,000 lb for the standard mission and are only 989,000 lb for the outbound swingby.

4. Conclusions

Several conclusions are clear, each of which can have strong implications in future manned Mars mission planning. It may be possible to employ either outbound or inbound Venus swingbys during each Earth-Mars opposition period. In the years that are most favorable for the swingbys, i.e., during two-thirds of the opposition periods, the required initial mass on Earth orbit can be less than one-half of that needed for standard round trips. In some years these requirements are lower than would have been needed if standard missions were used during the most favorable opposition periods. It appears that these benefits accrue regardless of the propulsion systems used. Moreover, Earth entry speeds are at least 15,000 ft/sec lower than the comparable standard missions and during the most favorable years are only slightly higher than Apollo entry speeds. In addition, since arrival at Mars during the opposition years considered in this paper (1975, 1978, 1980) occurs not farther than eighty degrees from Mars' aphelion, it is expected that in many other favorable swingby years the energy (hence MEO) requirements will be even less than shown. Perhaps the most important conclusion is that it may now be possible to realistically consider a spacecraft and boost system of a particular size that could be employed for many manned planetary missions. Admittedly, analyses have been made for only a few years in which swingbys are beneficial. Nevertheless, the results indicate that if one considers an optimal sequence of outbound swingbys, inbound swingbys and standard missions, the average MEO requirement and the variation in MEO requirements between successive launch opportunities will be much less than that associated with standard missions alone.

While these benefits can be accrued at an expense of only about twenty percent in total mission time, the argument can be put forth that the swingbys appear to inordinately increase the guidance problems. To be sure, the dates of Venus passage and the passage distances must be accurately controlled, but this should not be difficult (Ref. 7). It should be remembered that this is also true of the round trip planetary flybys - missions considered by many to represent the earliest manned trips to the planets.

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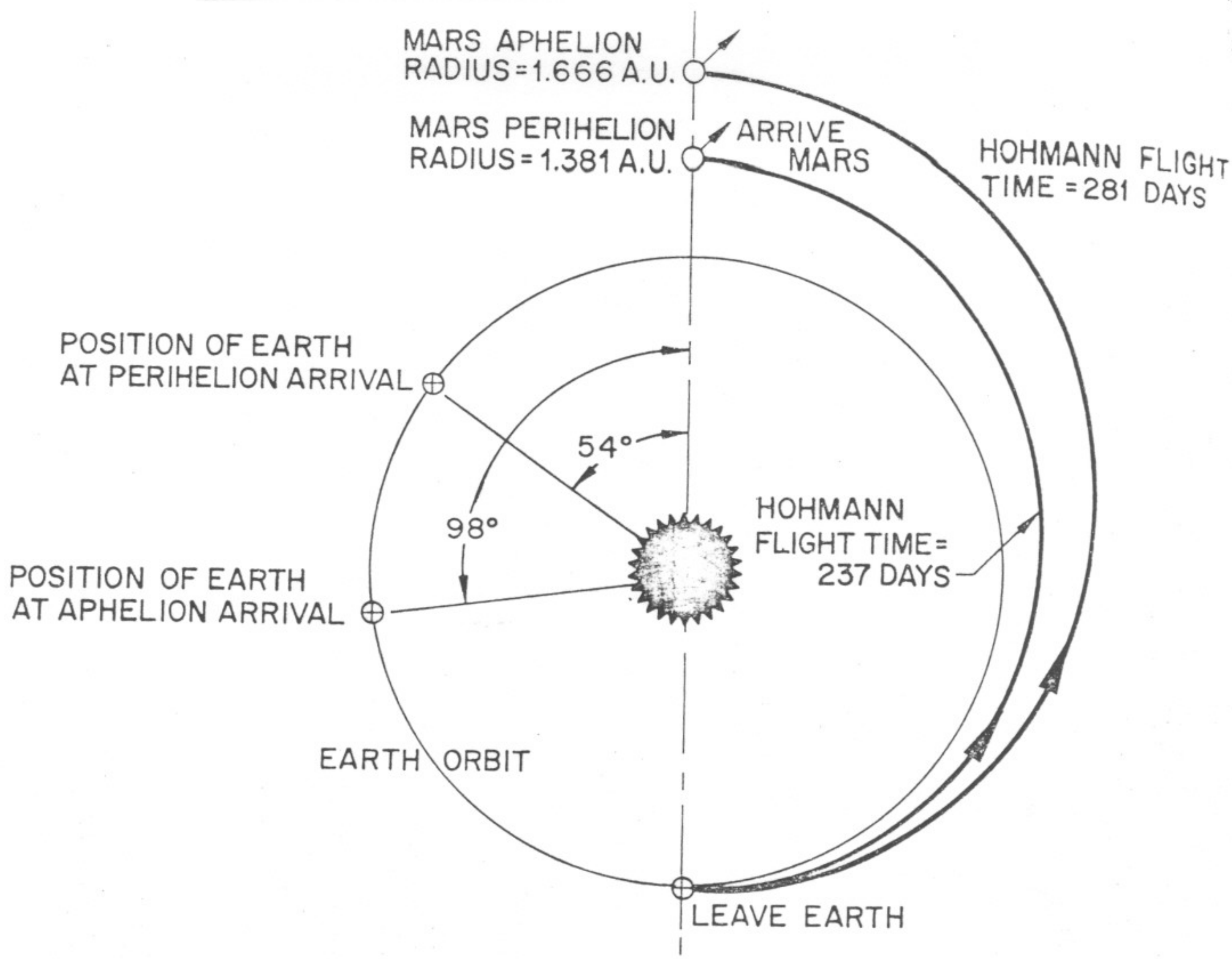

FIG.1 EFFECT OF MARS ARRIVAL POSITION ON INBOUND LEG TRANSIT ANGLE

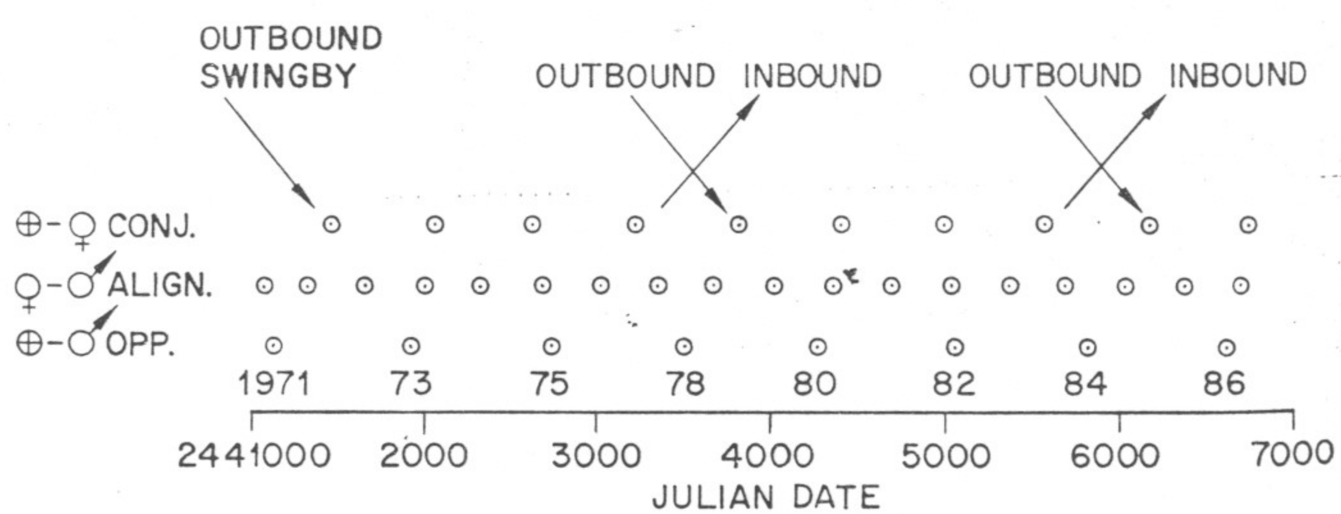

FIG. 2 PLANETARY POSITION DATA

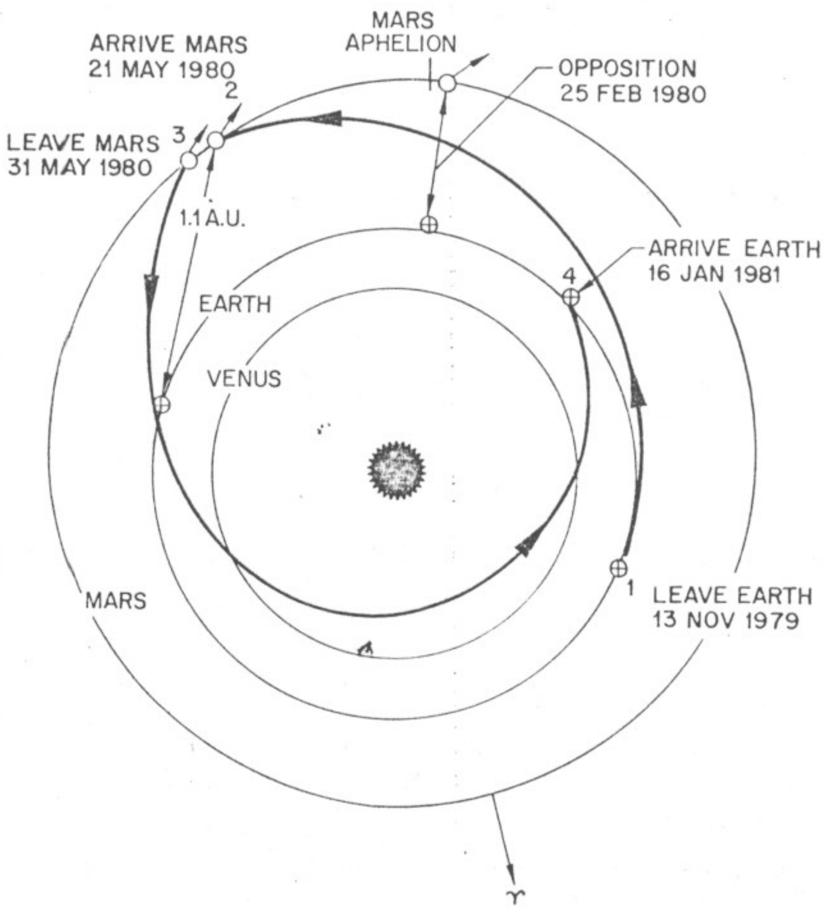

FIG. 3 REPRESENTATIVE STANDARD MISSION-1980

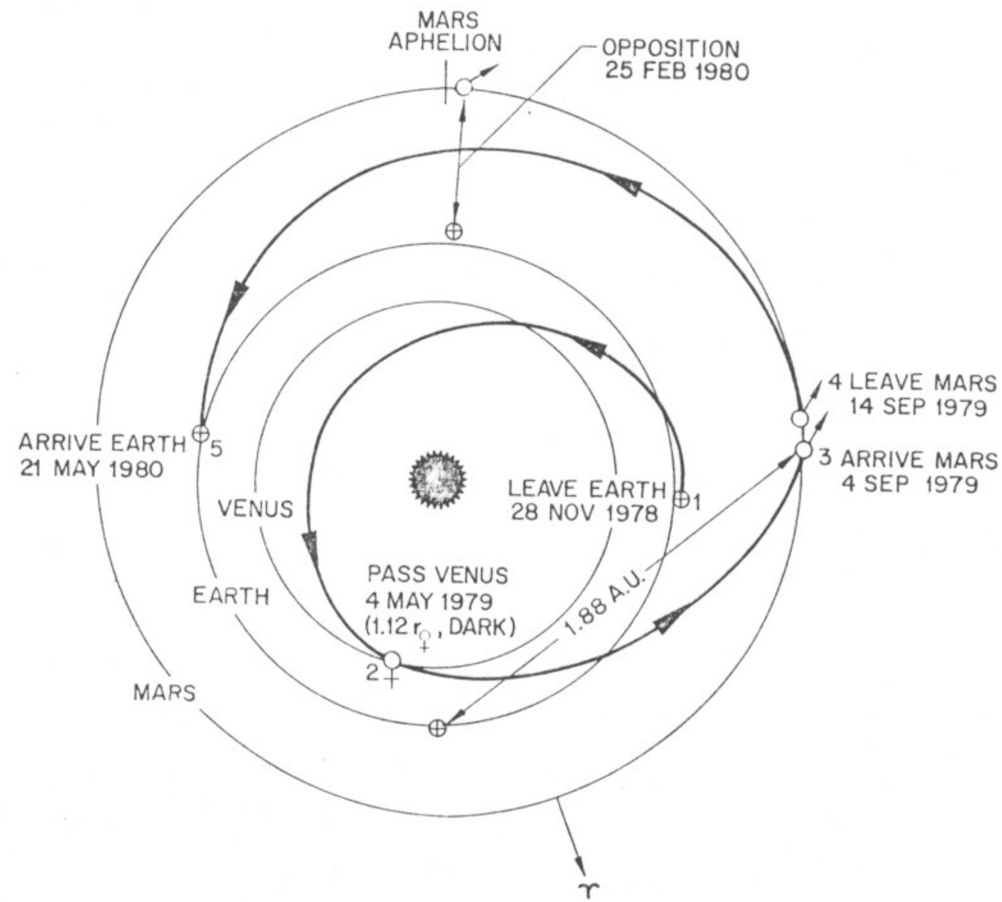

FIG. 4 REPRESENTATIVE OUTBOUND SWINGBY-1980

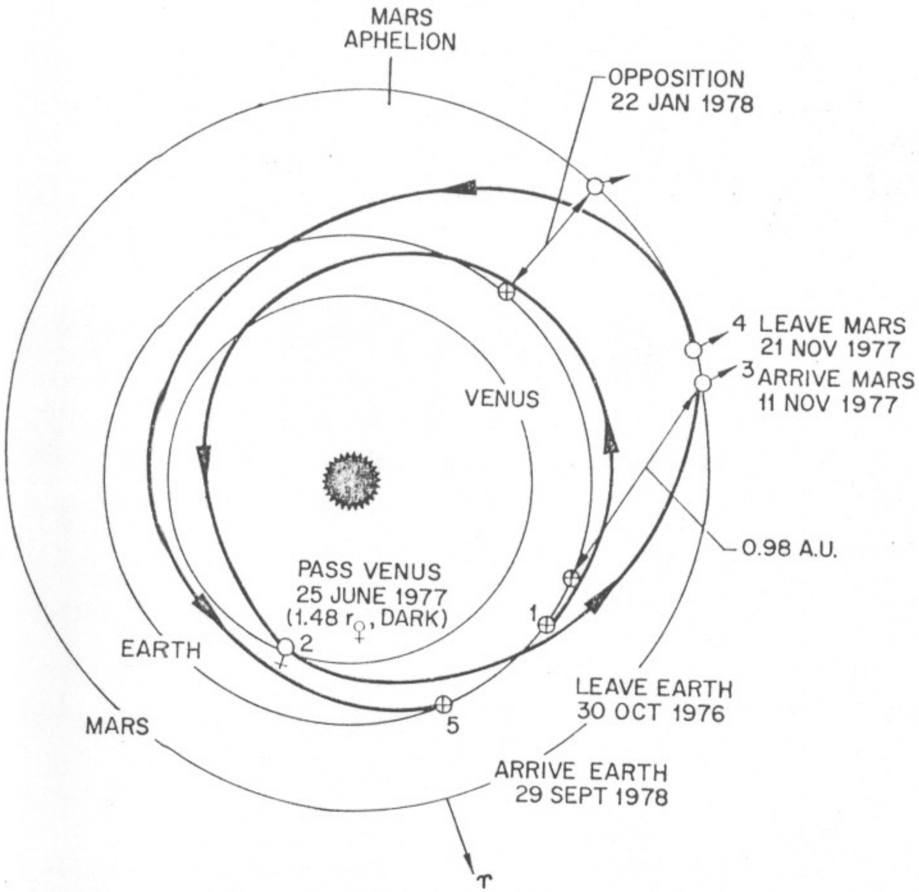

FIG. 5 REPRESENTATIVE OUTBOUND SWINGBY-1978

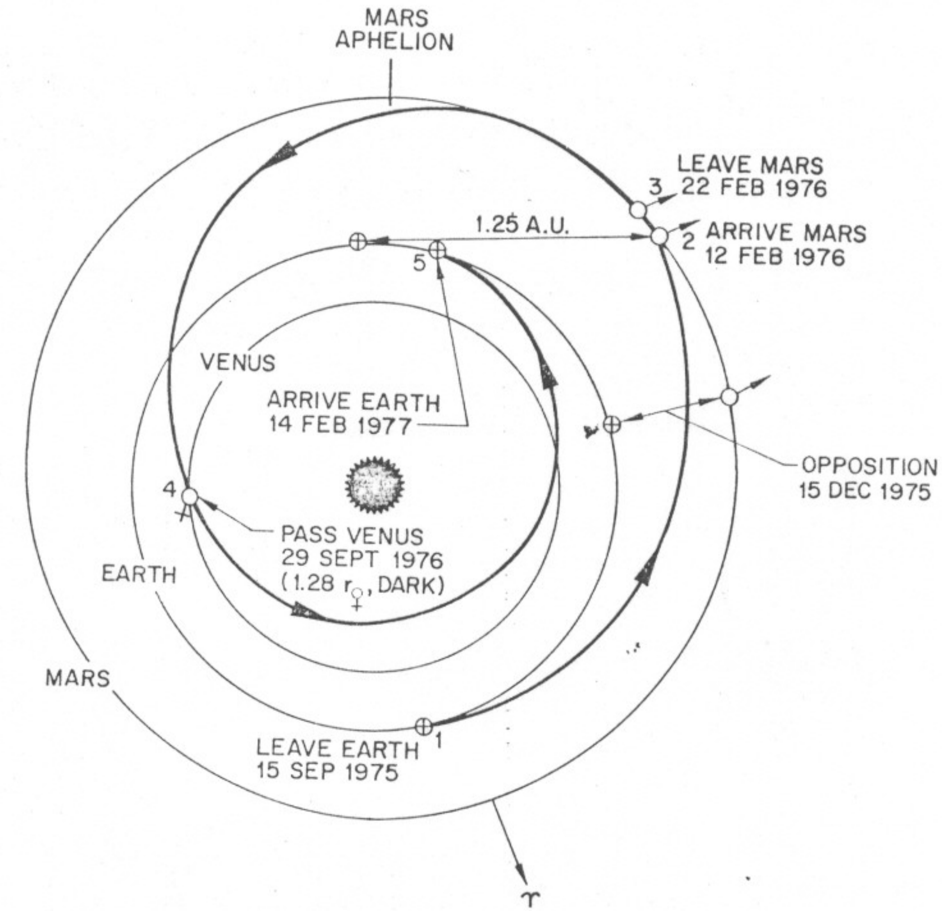

FIG. 6 REPRESENTATIVE INBOUND SWINGBY-1975

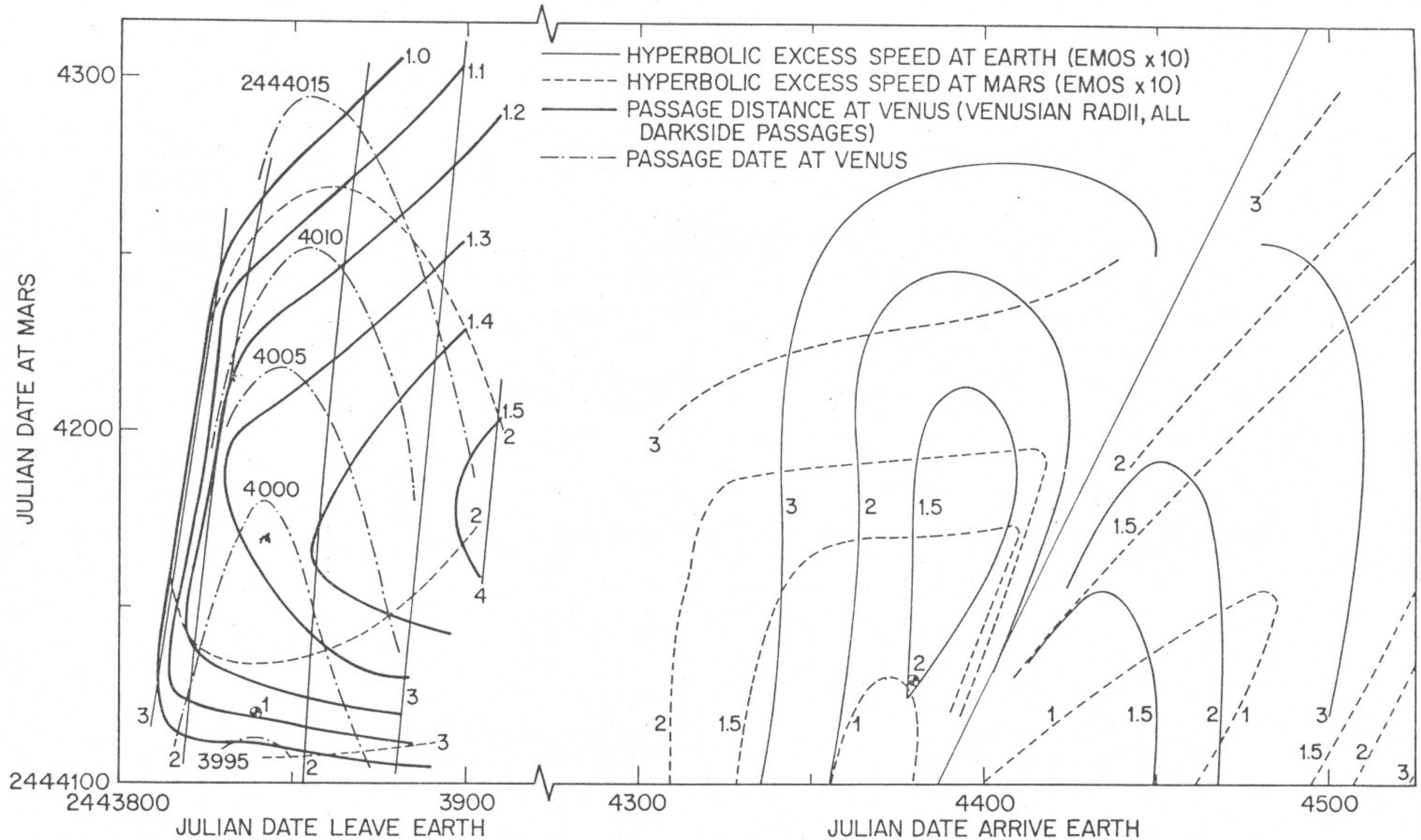

FIG. 7 MARS STOPOVER–1980 OUTBOUND VENUS SWINGBY

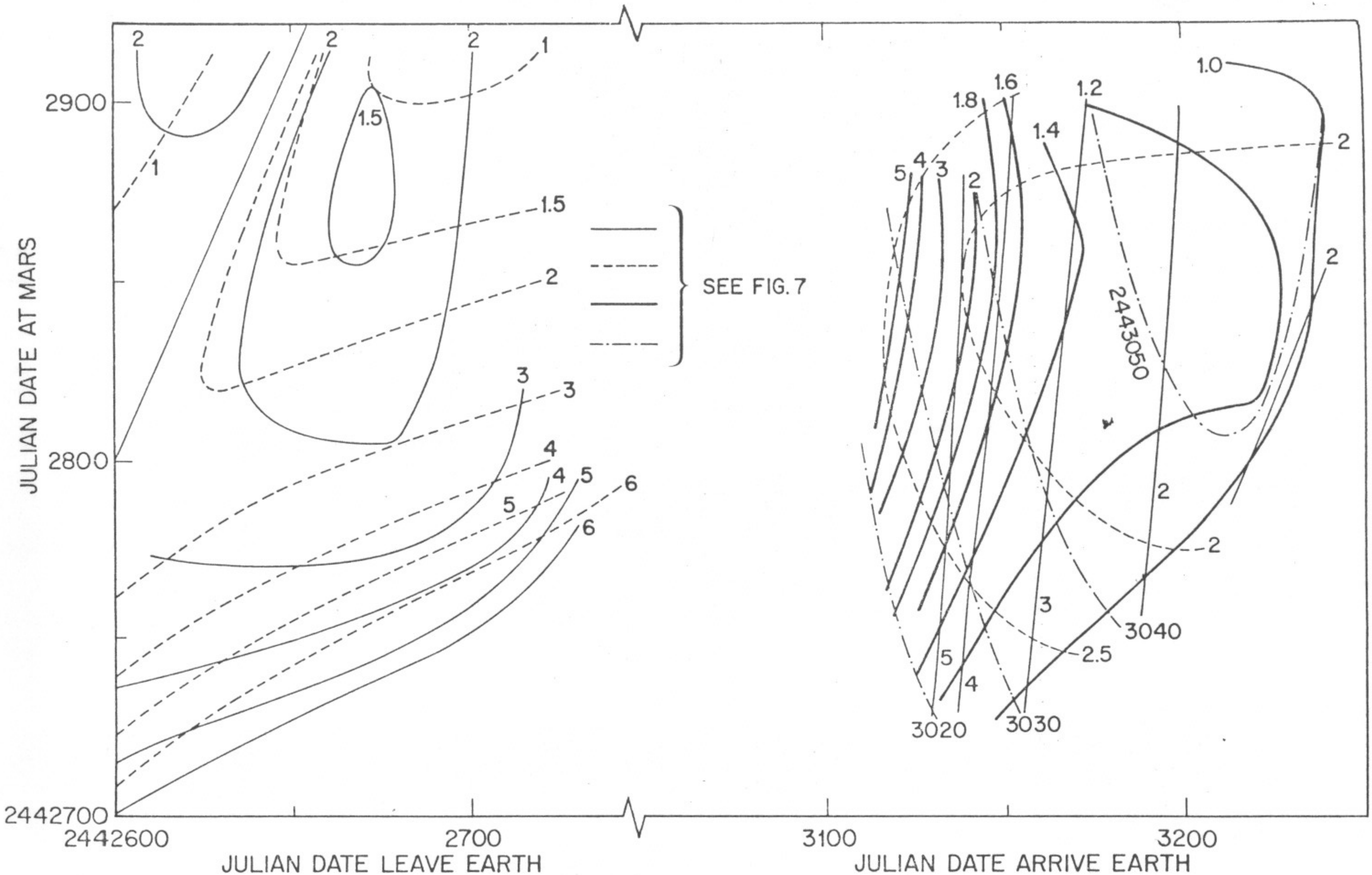

FIG. 8 MARS STOPOVER–1975 INBOUND VENUS SWINGBY