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MULTIPLE PLANET FLYBY MISSIONS TO VENUS AND MARS IN 1975 TO 1980 TIME PERIOD

By Archie C. Young
Aero-Astrodynamics Laboratory

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Huntsville, Alabama

ABSTRACT

A detailed analysis of multi-planet flyby missions to Venus and Mars during 1975 to 1980 time period is presented. Results for multi-planet flyby mission opportunities in 1975, 1977, and 1978 are given. Data are presented for earth departure, planet encounter, and earth return phases of the mission.

A comparison of the desirable and undesirable features of a single-planet (Mars) flyby mission and a multi-planet flyby mission is made. A timeline for all of the flyby missions studied is given in terms of earth departure date, planet encounter date, and earth return date.

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Archie C. Young

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RESEARCH AND DEVELOPMENT OPERATIONS

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DEFINITION OF SYMBOLS

Symbol	Definition
AU	astronomical unit
CD	calendar date
EMOS	earth mean orbital speed
I_{sp}	specific impulse
JD	Julian date
R_{cp}	radius of closest approach
V	velocity magnitude
VE	reentry velocity magnitude
ΔV	impulse velocity increment
ζ	communication angle - see Figure 14
ξ	comminication angle - see Figure 14
ρ	communication distance - see Figure 14
κ	total required bend angle between approach and departure asymptotes
α	angular change of velocity vector - see Figure C2
β	angle between incoming asymptotes - see Figure C1
ν	true anomaly - see Figure C1
θ	path angle - see Figure C1
ψ	complement of half angle of hyperbola - see Figure C1

SUBSCRIPTS

1	incoming hyperbola
2	outgoing hyperbola
∞	infinity relative to planet (sphere of influence)

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MULTIPLE PLANET FLYBY MISSIONS TO VENUS AND MARS IN 1975 TO 1980 TIME PERIOD

SUMMARY

A detailed analysis of all possible low energy opportunities for multiple planet flyby missions to Venus and Mars during 1975 to 1980 time period was made. Trajectory profiles passing Venus first and then continuing to Mars and returning to earth were considered for a dual-planet flyby mission. Triple-planet flyby missions passing Venus, then Mars, then passing Venus the second time and then returning to earth were investigated. Powered maneuvers at Mars and Venus were utilized when required to match the approach hyperbola with the departure hyperbola and to constrain the minimum passage distance at the respective planet.

Pertinent trajectory parameters and the weight required in earth orbit to perform the missions are presented graphically.

SECTION I. INTRODUCTION

Over the past few years, a great volume of data has been obtained for free flight single-planet flyby missions to Mars and Venus, but very little data have been available up to this time for multi-planet flyby missions to Mars and Venus. This report presents the results of a detailed analysis for multi-planet flyby mission during the 1975 to 1980 time period. The relative geometry of Earth, Venus and Mars is approximately repetitive every 6.4 years; therefore, opportunities for similar free flight mission profile occur every 6.4 years. Opportunities exist for some attractive multi-planet flyby missions during the 1975 - 1980 time period. These missions can be accomplished either by passing Mars enroute to Venus or passing Venus enroute to Mars. A powered maneuver is usually required while passing one of the planets.

Data are given for the multi-planet mission such that comparison can be made between single-planet and multi-planet flyby missions.

SECTION II. DISCUSSION OF PROBLEM

Multiple planet flyby missions were investigated to determine if they offer more attractive features over a single-planet Mars flyby mission. One attractive feature is apparent immediately in that two planets can be explored as compared to one for a Mars or Venus single-planet flyby mission. Other desired features are as follows:

1. Shorter mission time.

2. Shorter time interval between planet encounter.

3. Lower encounter velocity.

4. Reduced aphelion distance.

A. General Solution for Free Flight Planet Passage

For a dual-planet trajectory, there are three individual transfer segments which must be merged to obtain one complete dual-planet trajectory. The first segment is determined by the position of the departure and first passage planet and the transfer time between the two planets; the second segment is determined by the position of the first and second passage planets and the transfer time between them; the third segment is determined by the position of the second-passage planet and the terminal planet and the flight time between the two planets. From two-body theory, a free flight solution via a passage planet exists if the approach and departure hyperbolic excess speeds are of equal magnitude since there is no energy change relative to the passage planet. The radius of closest approach must be equal to or greater than the planet radius. To have a complete free flight dual-planet trajectory, the second-passage planet can consider only merging approach hyperbolas which are derived from segments (determined by first-passage and second-passage planets) that have free-flight characteristics at the first-passage planet. When an approach hyperbola and a departure hyperbola have been merged at the second-passage planet, the complete dual-planet trajectory is determined.

For a triple-planet flyby mission, four individual transfer segments have to be merged at the three-passage planets in the same manner as in the dual-planet mission.

B. Execution of a Powered Maneuver at Passage Planet to Obtain Multiple Planet Flyby Missions

For a maneuver with unlimited power available, a complete dual- or triple-planet flyby trajectory can be obtained for any three or four segments, respectively, provided that at the passage planet the approach segment and depart segment have common dates at the passage planet. The velocity increment required can be determined by the approach hyperbolic excess velocity vector ($\bar{V}_{\infty 1}$), the depart hyperbolic excess velocity vector ($\bar{V}_{\infty 2}$) and the closest passage distance. However, to keep the powered maneuver requirement within some reasonable range, the scalar magnitude of $\bar{V}_{\infty 1}$ and $\bar{V}_{\infty 2}$ should not differ by more than 0.10 EMOS (3.0 km/sec), and the angle between the two vectors $\bar{V}_{\infty 1}$ and $\bar{V}_{\infty 2}$ should not differ by more than approximately 50 degrees from the natural turning capability of the passage planet due to its gravitational attraction.

C. Admissible Solution

Since mission objectives and spacecraft propulsion system capabilities dictate permissible trajectory profiles, it is necessary to constrain some of the pertinent trajectory parameters to stay within some specified range in order to expect a high probability of mission success or even to attempt to perform the mission. Constraints considered in this report were (1) departure and reentry speed at earth, (2) perihelion and aphelion distance, (3) the closest approach distance and speed at the passage planet, and (4) the total flight time of the mission.

SECTION III. APPROACH TO THE PROBLEM

For the multi-planet flyby mission, existing or improved orbit launch vehicles were assumed to inject the spacecraft onto heliocentric trajectories. Considering the above assumption, the following constraints were made: the hyperbolic excess speed at earth departure must be equal to or less than 0.30 EMOS, the hyperbolic excess speed at Mars arrival and departure must be equal to or less than 0.30 EMOS, and the hyperbolic excess speed at Venus arrival and departure must be equal to or less than 0.50 EMOS, total time of mission must not exceed 750 days, and the radius of closest approach must be equal to or greater than 1.0 planet radii at planet encounter.

All possible earth launch dates were considered wherein the mission could depart from earth with hyperbolic excess speeds of less than 0.30 EMOS, and wherein the approach speed at passage of the first planet was within the imposed constraint. This approach gave all admissible first segment transfers. The second step involved merging the second segment with the first. If this merging could be done without requiring unreasonable values of impulsive velocity ($\Delta V < 3.0$ km/sec) at the first passage planet, the first and second admissible segments of the trajectory are now determined. For a dual-planet mission, the final step is to match the third segment with an admissible second segment without requiring a velocity maneuver greater than 3.0 km/sec at the second passage planet. Merging the three segments at the two passage planets yields the complete dual-planet flyby mission. The same procedure is used for a triple-planet mission; however, in this case, four individual segments are involved. If at the first or second passage planet, the power maneuver requirement was greater than 3.0 km/sec, the earth launch window opportunity was no longer considered, and the next earth launch date opportunity was investigated.

SECTION IV. LAUNCH OPPORTUNITY FOR MULTIPLE PLANET MISSIONS DURING 1975 TO 1980 TIME PERIOD

A detailed analysis of multiple-planet missions was conducted on all possible launch year opportunities during the time period of 1975 to 1980. During this time period, there are three earth launch window opportunities for earth to Venus transfers occurring in 1975, 1977 and 1978. For multiple-planet missions, the 1975 opportunity passing Venus first exceeds the constraint of $\Delta V \leqq 3.0$ km/sec. The 1977 opportunity yields a triple-planet flyby mission and the 1978 opportunity is a dual-planet mission which can be flown on either a free return profile or a powered maneuver during the Martian encounter. There are three earth launch windows for the Earth-to-Mars transfer during the 1975 to 1980 time period. Due to large power maneuver requirements, only one of the Earth-to-Mars launch opportunities was considered attractive for multiple-planet missions. The multiple-planet mission considered was a 1975 dual-planet mission which required a powered maneuver at Mars to execute the required bend angle and energy change relative to Mars.

SECTION V. ANALYSIS OF 1975 DUAL-PLANET POWERED FLYBY

All pertinent trajectory parameters for the 1975 opportunity were generated and are presented in Figures 1 through 16. Figure 1 illustrates a typical heliocentric trajectory profile, giving data for Earth departure, Mars passage, Venus passage, and Earth arrival. This trajectory requires a velocity increment of 5.92 km/sec for departing from a 485 km altitude circular geocentric orbit. Mars passage occurs 226 days after Earth departure. A powered maneuver at Mars passage is executed to transfer from an approach hyperbola having a 0.1594 EMOS excess speed to a departing hyperbola with a 0.1726 EMOS excess speed. An impulsive velocity of 0.558 km/sec is required. The angle between the two hyperbolic excess velocity vectors is 44.3 degrees; the gravitational attraction of Mars is capable of bending the trajectory the required 44.3 degrees by passing relatively close (Rcp = 1.1) to Mars and applying the impulse velocity increment after the incoming hyperbolic has passed through periapsis. The trajectory continues on to Venus and makes a free flight passage at Venus on September 26, 1976, 232 days after Mars encounter, with a closest approach distance of 1.25 planet radii and hyperbolic excess speed of .3972 EMOS. Flight time from Venus to Earth is 135 days, arriving at Earth February 8, 1977, with a reentry speed of 13.0 km/sec.

Figure 2 presents the earth departure and Mars passage impulsive velocity requirement for the earth departure window. The earth departure window for the 1975 dual-planet flyby mission occurs about two months before the low energy Mars flyby mission. Due to the rapidly increasing high impulsive velocity requirement at Mars passage, the earth departure cannot be delayed for the dual-planet mission to take advantage of the lower impulsive velocity requirement at earth departure. Figures 3 and 4 indicate the initial weight in earth orbit and propellant required for earth departure and Mars passage. Figure 3 contains data for assumed chemical propulsion system and Figure 4 pertains to an assumed nuclear configuration.

Figure 5 shows the total flight time of the mission and the Mars passage window. Total mission time varies from 560 to 640 days, and for a thirty-day departure window at earth, there is a sixty-day passage window at Mars. The passage window at Venus is approximately eight days. Figure 6 gives the direction of the hyperbolic excess velocity vector for earth departure. Since the absolute value of the declination is less than ten degrees, launch azimuth would not be a problem.

A representative trajectory profile for Mars passage is shown in Figure 7. The flyby spacecraft would approach Mars on the sunlit side and exit Mars on the dark side. The closest approach point of 1.1 planet radii is slightly on the dark side. After periapsis passage, a propulsive maneuver is executed at 9.7 planet radii. The spacecraft stays within the Martian sphere of influence about sixty-five hours. Given in Figure 8 are the approach and depart hyperbolic excess velocity and the required bend angle of the hyperbolic excess velocity vector. From this figure, the Mars impulsive velocity curve given in Figure 2 can be explained; at the beginning of the Mars passage window, the approach and depart excess velocity differ by 0.025 to 0.030 EMOS with a resultant impulsive velocity of 0.65 to 0.75 km/sec. The required bend angle can be obtained from the gravity field of Mars by executing the maneuver at the optimum point. Approximately ten days into the earth-depart window the corresponding approach and depart hyperbolic excess velocities at Mars differ the least amount. This results in a minimum point on the impulsive velocity curve in Figure 2. At the end of the passage window, the difference between the approach and depart hyperbolic excess velocity is increasing and the bend angle requirement is greater than that which the gravity field of Mars can provide. The combined effect of the velocity difference and the necessary extra bend angle requires a large impulsive velocity as shown in Figure 2.

Shown in Figure 9 is a typical hyperbolic trajectory profile at Venus encounter. Most of the projected trajectory on the surface of Venus would be on the sunlit side. The radius of closest approach is 1.25 planet radii with an encounter velocity of 11.83 km/sec. The spacecraft stays within the sphere influence of Venus 28 hours. Figures 10 and 11 present the hyperbolic bend angle, hyperbolic excess speed, and the radius and closest approach at Venus encounter.

Reentry speed at earth arrival ranges from 12.4 to 14.5 km/sec as shown in Figure 12. Figure 13 gives the orientation of the hyperbolic excess velocity vector at earth arrival.

Communication distances and angles to the spacecraft relative to Earth, Mars, and Venus are given in Figures 14, 15 and 16.

SECTION VI. 1977 TRIPLE-PLANET FLYBY

The Earth, Venus, and Mars relative positions are such that, with an earth departure date during February 1977, a triple-planet flyby mission is possible. The triple-planet trajectory encounters Venus first, then Mars, and then Venus for the second time. Except for a slight maneuver requirement at Venus first passage, the trajectory profile is free-flight by the passage planets. The earth departure date for the triple-planet mission occurs one and one-half months after the opportunity for a single-planet Venus flyby mission, and the Venus passage window is about one month later. The triple-planet mission requires the Earth-Venus transfer to be almost a 180-degree transfer arc. Therefore, the earth departure date is near an area where the velocity requirements would be rapidly increasing. When the transfer arc approaches 180 degrees, the heliocentric transfer plane inclination is large relative to the ecliptic plane, resulting in high velocities relative to Earth and Venus.

A typical heliocentric trajectory profile is shown in Figure 17. Earth departure date occurs on February 14, 1977, requiring an impulsive velocity of 4.400 km/sec from earth parking orbit. The spacecraft encounters Venus 118 days later. Mars encounter takes place 172 days after the first Venus passage. Flight time from Mars to Venus second passage is 259 days; Venus-to-Earth transfer duration is 127 days, arriving at Earth on December 22, 1978. The total mission time required 674 days.

Shown in Figures 18 through 20 are data pertinent to earth departure. Given in Figure 18 is hyperbolic excess velocity and impulse velocity increment at earth departure. Figure 19 gives the initial weight in earth orbit and the required propellant departing from orbit for assumed chemical and nuclear orbit launch vehicles. Assuming a 20-day earth departure window, the assumed chemical vehicle required 1 x 10^6 pounds in earth orbit of which .7 x 10^6 pounds is propellant; the assumed nuclear vehicle required .54 x 10^6 pounds in earth orbit and .25 x 10^6 pounds of propellant. Eleven thousand pounds of storable propellant (Isp = 310) is required for the power maneuver at Venus first passage. The net injected payload into heliocentric transfer orbit is 191,000 pounds (180,000-pound spacecraft and 11,000 pounds of propellant for power maneuver at Venus first passage). Figure 20 indicates the orientation of the hyperbolic excess velocity vector at earth departure.

A typical hyperbolic trajectory profile at the first Venus passage is presented in Figure 12. The trajectory passes on the light side of Venus with a closest approach distance of 1.1 planet radii. A powered maneuver is executed at 1.6 planet radii to transfer to a higher energy hyperbola. Time within the sphere of influence is 52 hours. Figure 22 depicts the magnitude of the hyperbolic excess speed of the approach and depart hyperbola at Venus. The bend angle between approach and depart hyperbolic excess velocity vectors is also shown.

Figures 23 and 24 indicate the trajectory profile and other pertinent parameters at Mars encounter. The spacecraft stays within Martian sphere of influence for approximately 60 hours. Similar data are presented for Venus second passage in Figures 25 and 26. The spacecraft stays within Venus' sphere of influence for 40 hours.

Earth reentry speed and the mission's total flight time are determined from Figure 27. Reentry speed ranges from 12.9 km/sec to 13.8 km/sec. Total flight time varies from 674 days to 679 days. Figure 28 shows the angular orientation of the hyperbolic excess velocity vector at earth return.

Figures 29, 30, and 31 present the communication parameters for the spacecraft relative to Earth, Venus, and Mars.

VII. 1978 FREE-RETURN DUAL PLANET FLYBY

The alignment of Earth, Venus, and Mars positions is such that by departing earth in December 1978 a free-return dual-planet mission can be achieved. The trajectory encounters Venus 160 days after earth departure; Mars encounter occurs 240 days after Venus passage. Mars-to-Earth flight requires 250 days. Earth return date occurs in September 1980, with the total mission time being 650 days. The spacecraft would encounter Mars just after passing through aphelion. Mars would be near the Martian aphelion position also. To rendezvous with Earth, the spacecraft must pass inside Earth's orbit on the Mars-to-Earth transfer. Figure 32 gives a typical heliocentric trajectory profile for 1978 mission.

Earth departure data are presented in Figure 33 through 35. Figure 36 shows the total mission time corresponding to the minimum velocity requirement envelope departing the earth.

Data for Venus and Mars encounter are given in Figures 37 through 42. Venus passage is a twilight passage, as shown in Figure 38, having a closest approach distance of 1.17 planet radii. The spacecraft stays within the Venusian sphere of influence for 32 hours. Mars approach is made on the dark side; the closest approach radius of 1.14 planet radii is slightly in the dark. The spacecraft departure is on the sunlit side of Mars. Time within Mars sphere of influence is 56 hours. The Venus passage window is approximately 8 days, and the passage window at Mars is on the order of 50 days. Hyperbolic excess speed and orientation is given in Figures 43 through 45.

Communication angles and distance relative to Earth, Venus, and Mars are shown in Figures 46 through 48.

VIII. 1978 DUAL-PLANET POWERED FLYBY

The 1978 dual-planet powered flyby mission is obtained by adjusting the arrival date at Mars to be earlier than for the 1978 dual-planet free return trajectory such that the spacecraft's heliocentric trajectory will encounter Mars before or at aphelion. By encountering Mars at an earlier date and executing a power maneuver at Mars, the Mars-to-Earth trajectory rendezvous with earth the first time it intersects the earth's orbit. Therefore, the Mars-Earth segment of this mission does not dip inside the Earth's orbit as was the situation for the 1978 free return mission shown in Figure 32. The powered flyby offers a reduction in total flight time of approximately 175 days over the free flight mission; however, the reentry velocity is higher, 16.74 km/sec compared to 14.46 km/sec.

The powered flyby earth launch window occurs 18 days before the free flight window. Venus passage window is about ten days earlier; Mars encounter occurs about 100 days earlier, and earth return date occurs about 195 days before the free return date.

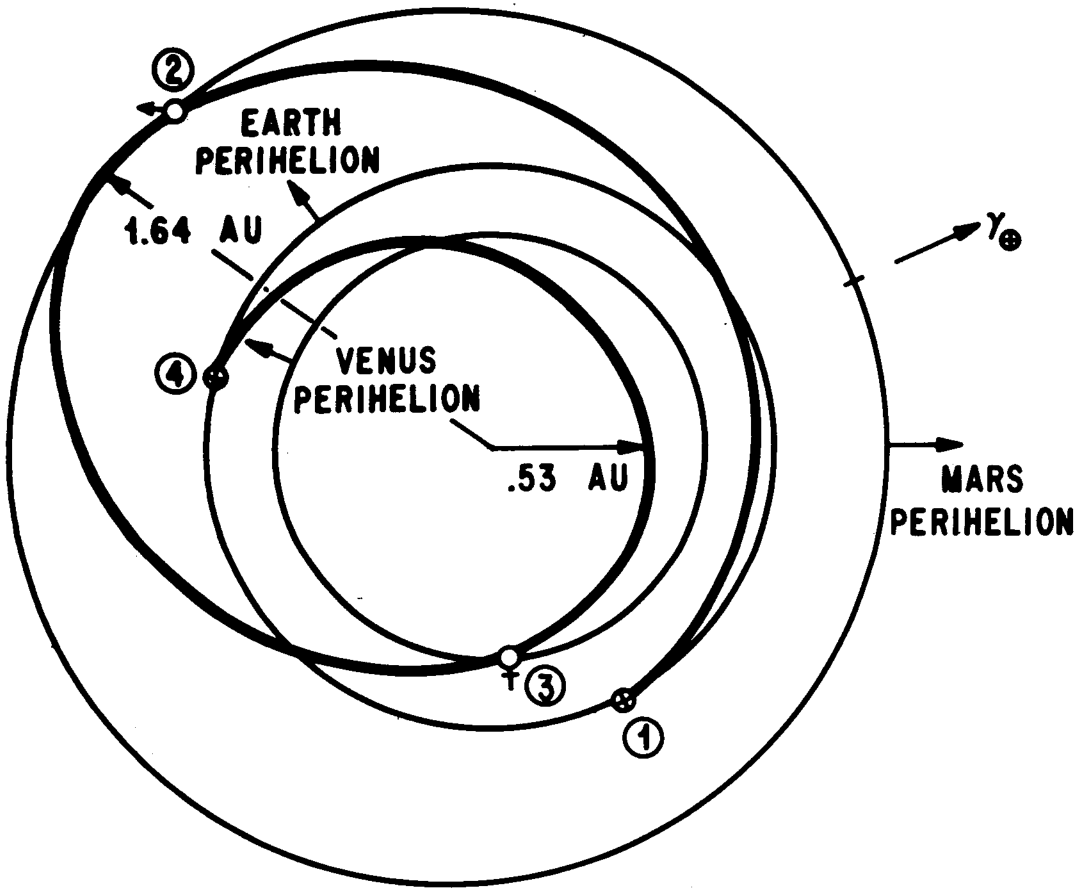
Data for the powered flyby mission are given in the same manner as the free flight data in Figures 49 through 63.

IX. CONCLUSIONS

The results presented in this report indicate that, in the time period of 1975 through 1980, a multi-planet flyby mission opportunity occurs in 1975, 1977, and 1978. The 1975 mission is a dual-planet flyby which passes Mars first and then Venus; a power maneuver is required at Mars to perform this mission. A triple-planet opportunity occurs in 1977, the trajectory passes Venus, then Mars, and then Venus the second time; a slight power maneuver is required at Venus first passage. In 1978, there exists a dual-planet free return opportunity, passing Venus first and then Mars; there also exists a dual-planet powered flyby (powered maneuver at Mars) in 1978 which has a total mission time of 175 days less than the 1978 free return opportunity.

Figure 64 depicts the single and multi-planet flyby characteristics for the 1975 to 1980 time period. Figure 65 shows the time events for the flyby missions.

The multi-planet flyby missions offer advantages over a single-planet Mars flyby mission in the following areas: shorter trip time; aphelion distance less than 1.7 A.U. compared to 2.2 for a Mars flyby mission; lower velocities at Mars encounter (longer stay time within the sphere of influence of Mars); shorter period of time of possible inactivity for the crew; 270 days the longest flight time between any two planets compared to 530-day flight time for return trip from Mars to Earth on a Mars flyby mission.



① EARTH DEPARTURE
JD 2590: CD JUNE 26, 1975
$\Delta V = 5.92$ km/sec;
FROM 485 km ORBIT

② MARS PASSAGE
JD 2816: CD FEB 6, 1976
$\Delta V = 0.558$ km/sec; $R_{CP} = 1.1$

③ VENUS PASSAGE
JD 3048: CD SEPT 26, 1976
$V_{\infty} = .3972$ EMOS; $R_{CP} = 1.25$

④ EARTH ARRIVAL
JD 3183: CD FEB 8, 1977
$V_E = 13.0$ km/sec

FIG. 1. 1975 DUAL PLANET POWERED FLYBY TYPICAL TRAJECTORY PROFILE

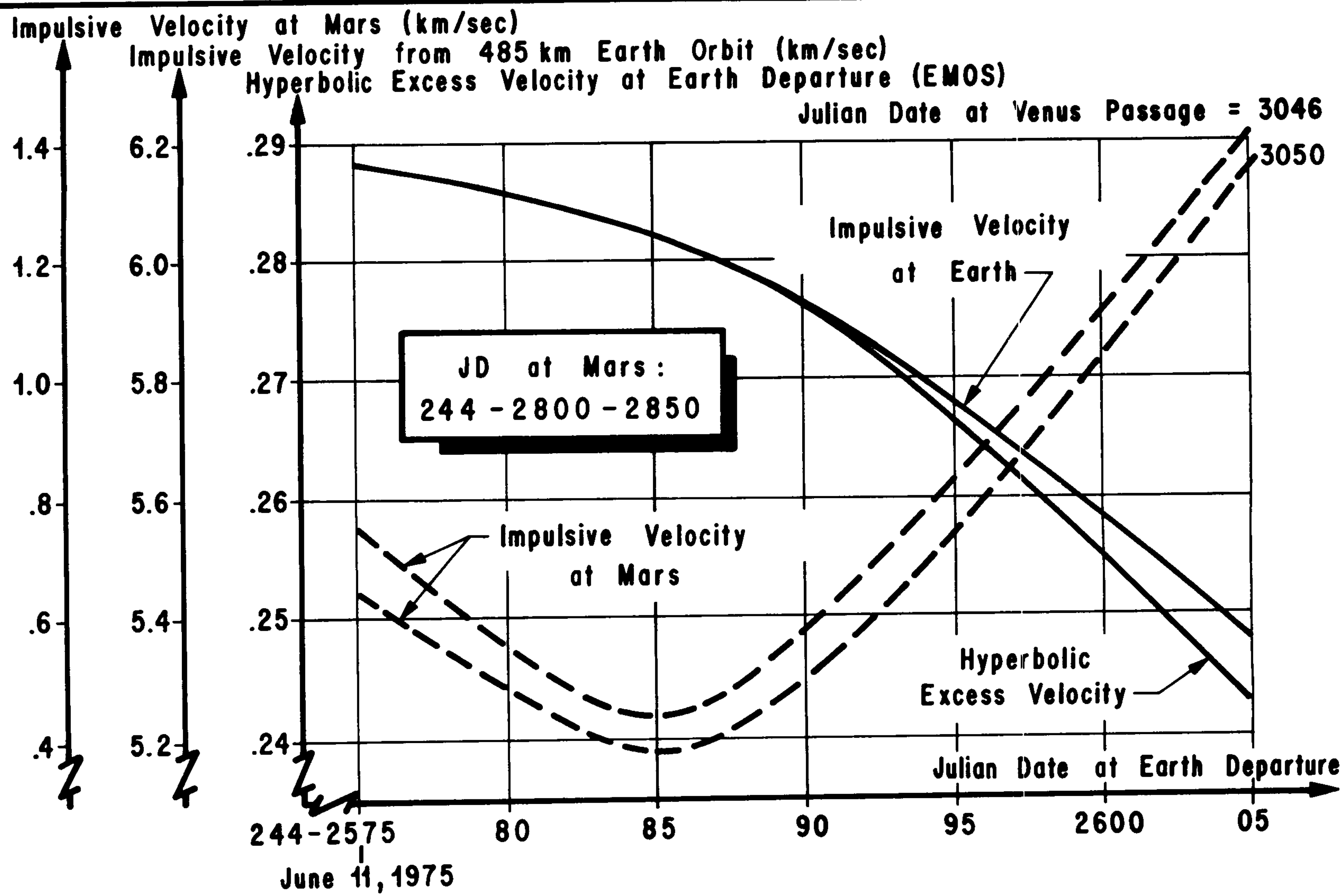


FIG. 2. 1975 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

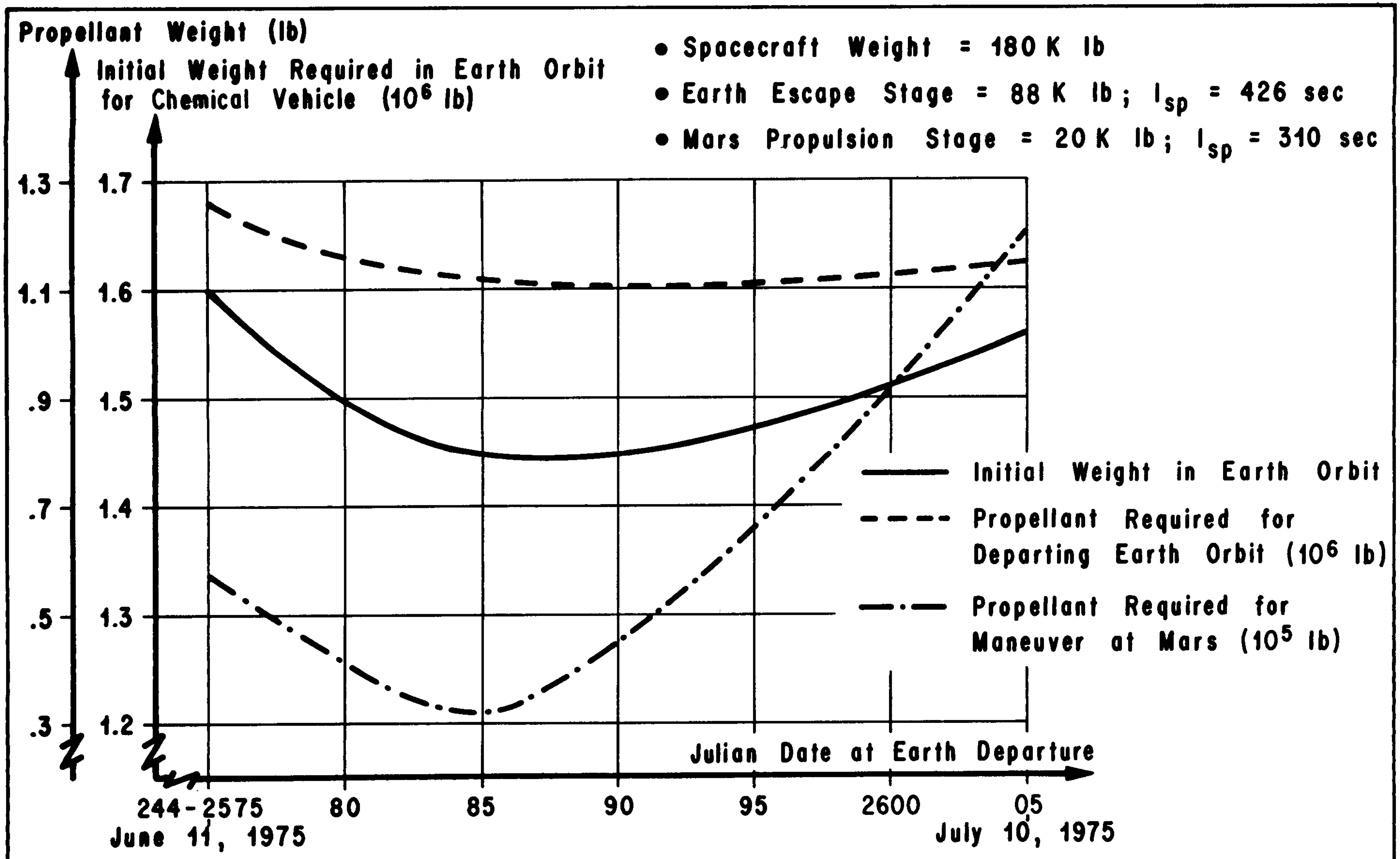


FIG. 3. 1975 DUAL PLANET FLYBY
POWER MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

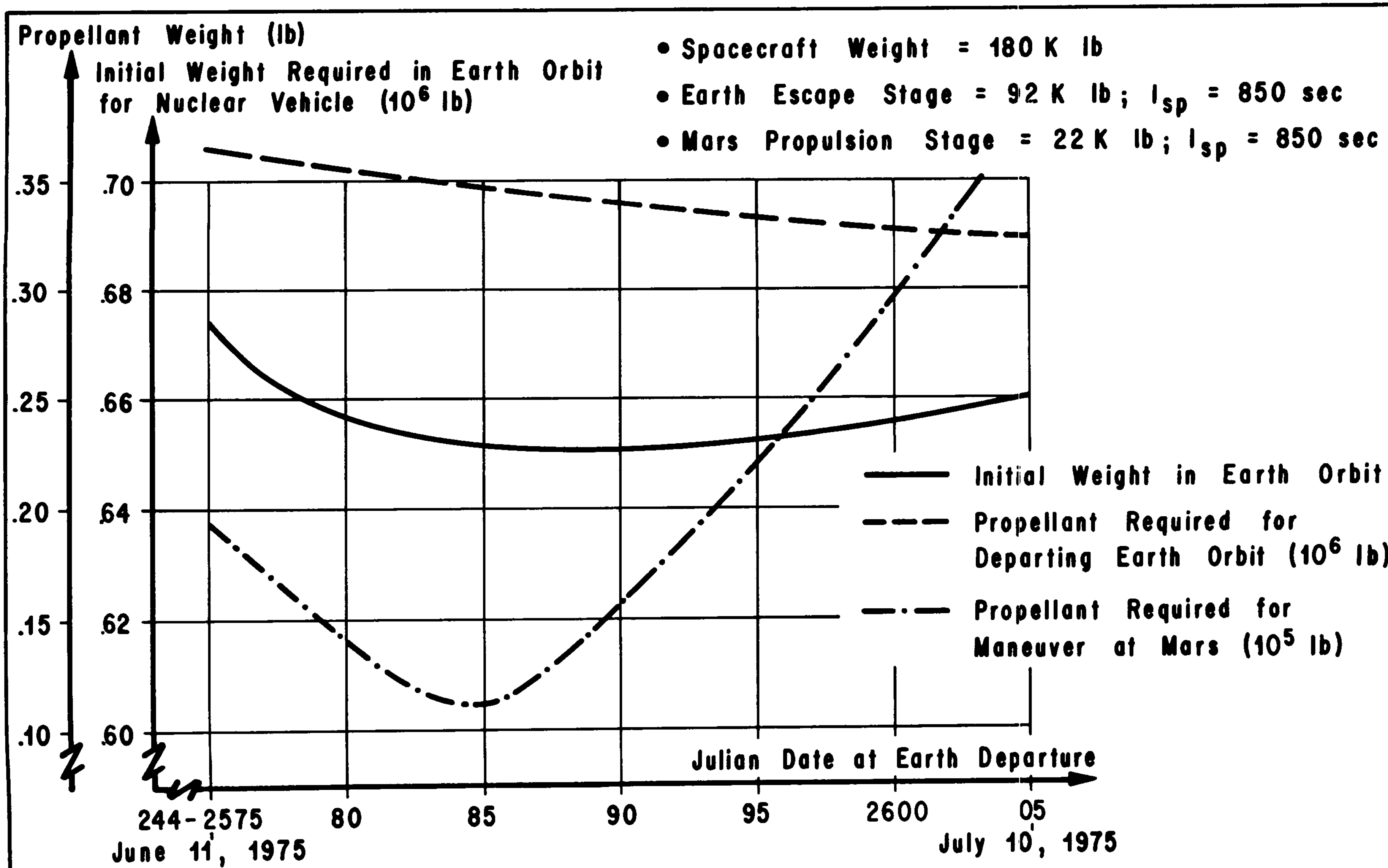


FIG. 4. 1975 DUAL PLANET FLYBY
POWER MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

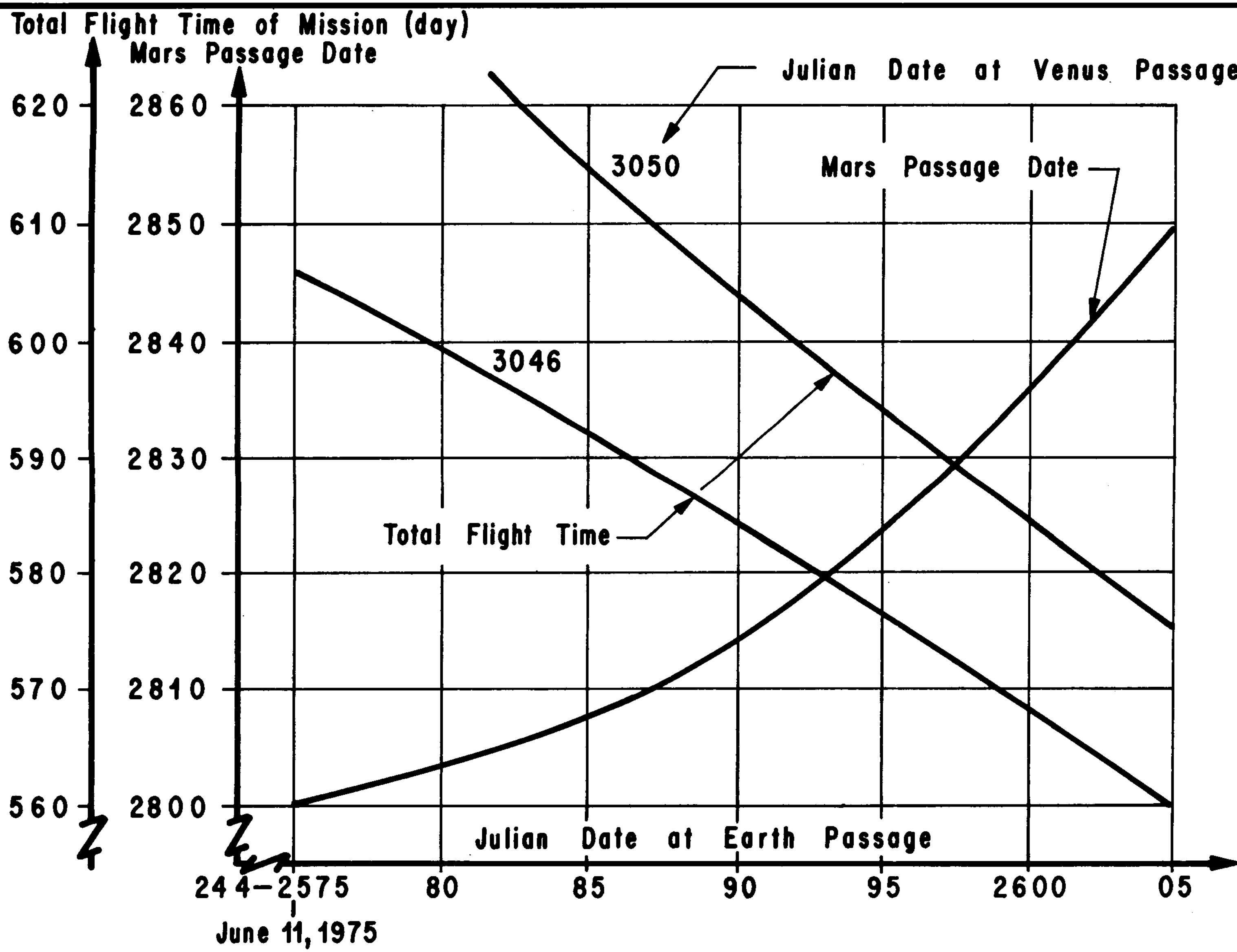


FIG. 5. 1975 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

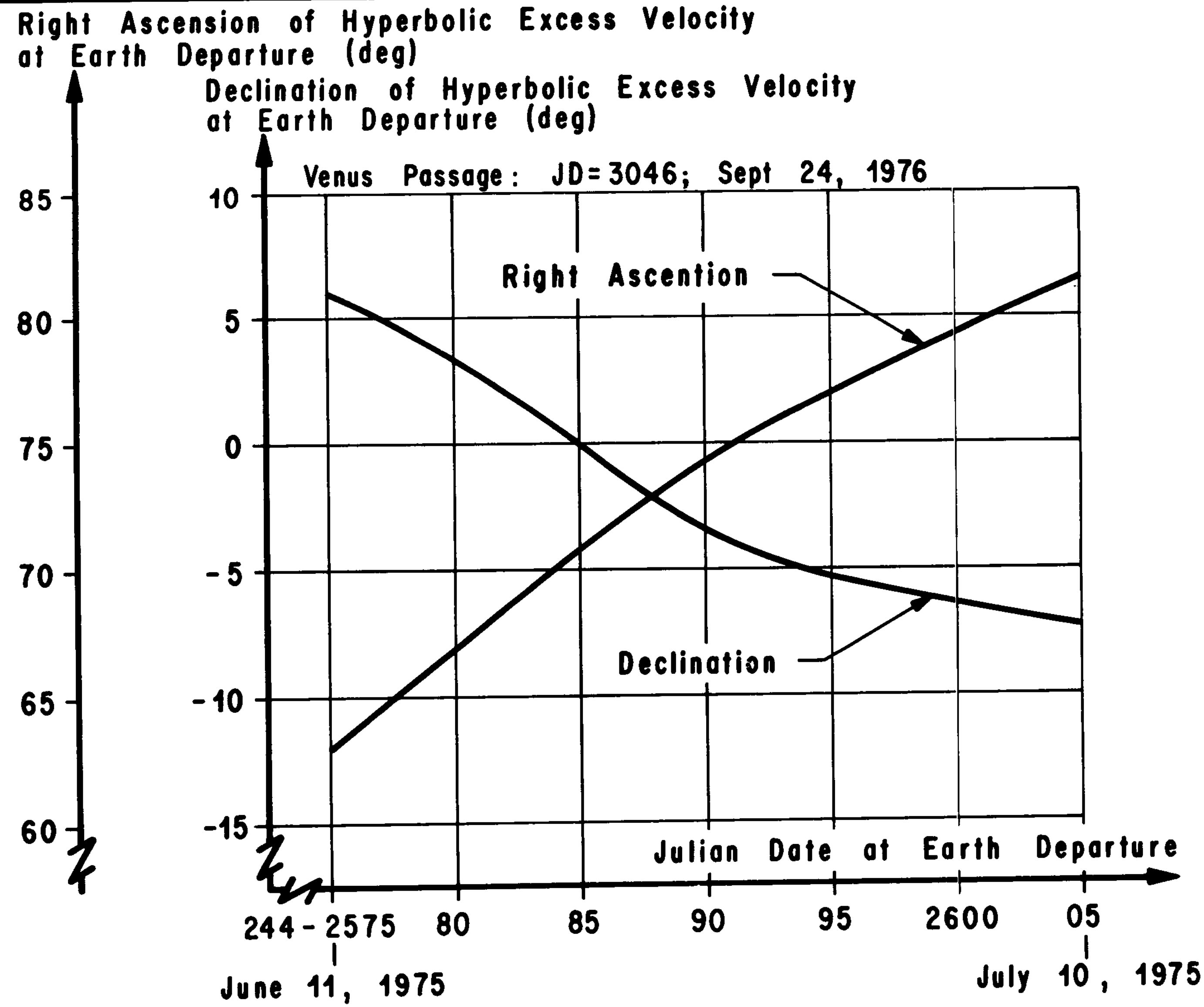
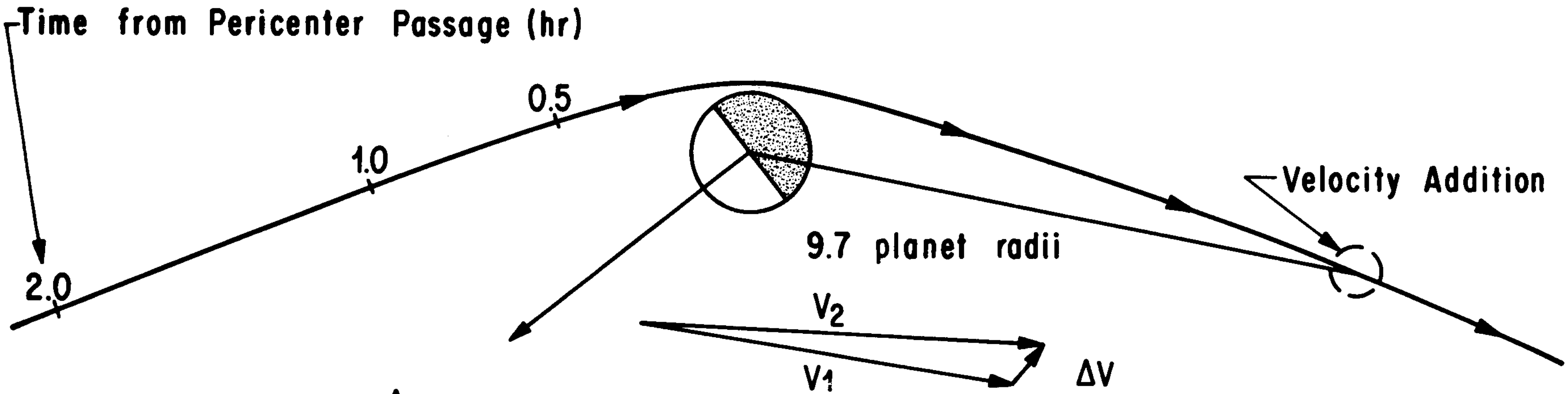


FIG. 6. 1975 DUAL PLANET FLYBY

POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE



$V_1 \triangleq$ Magnitude of Velocity Vector on Incoming Hyperbola at Location of Velocity Addition $= 5.01$ km/sec

$V_2 \triangleq$ Magnitude of Velocity Vector on Outgoing Hyperbola at Location of Velocity Additon $= 5.384$ km/sec

$\Delta V \triangleq$ Magnitude of Velocity Addition $= .558$ km/sec

FIG. 7. 1975 DUAL PLANET FLYBY HYPERBOLIC TRAJECTORY PROFILE RELATIVE TO MARS AT MARS PASSAGE

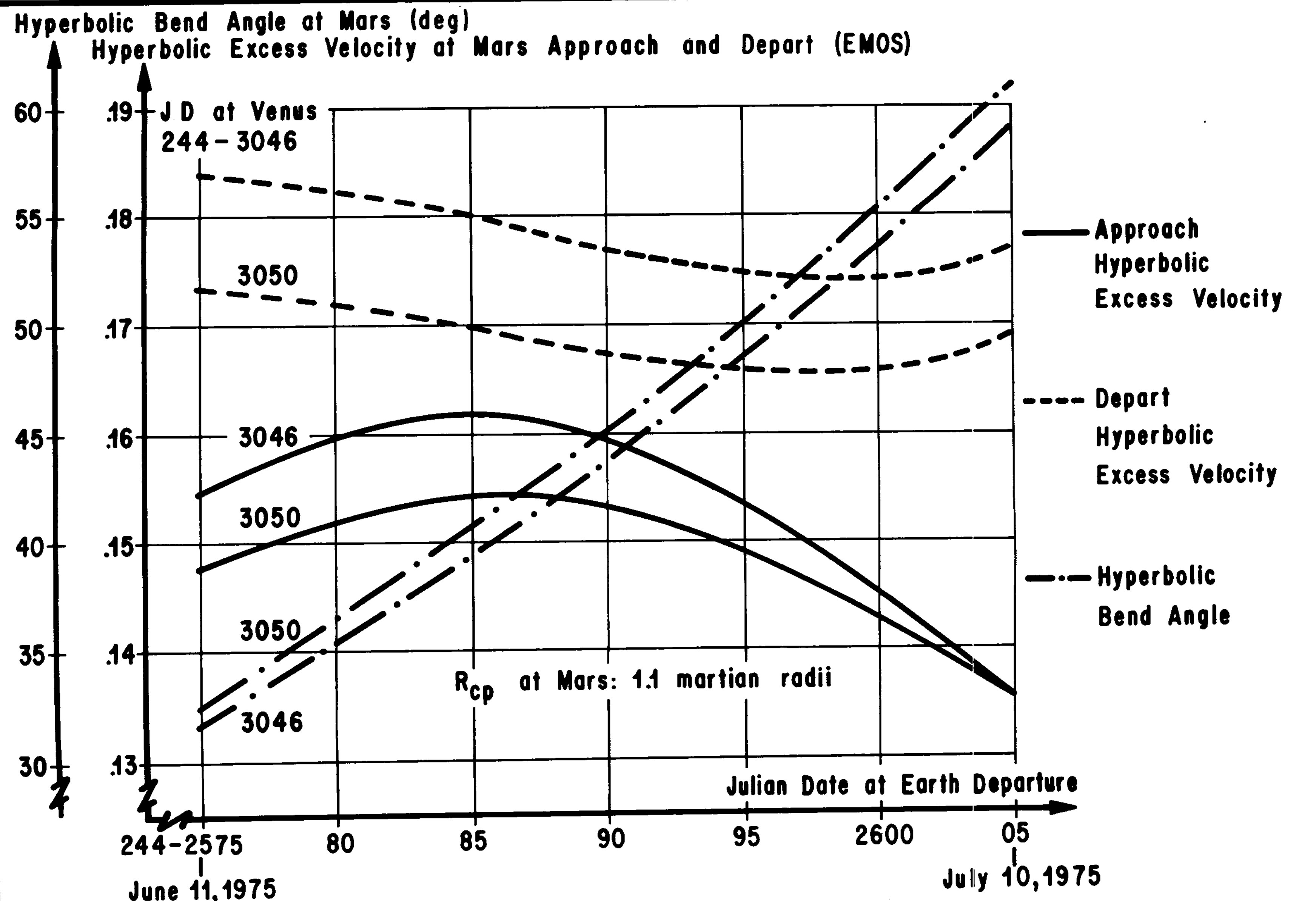


FIG. 8. 1975 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

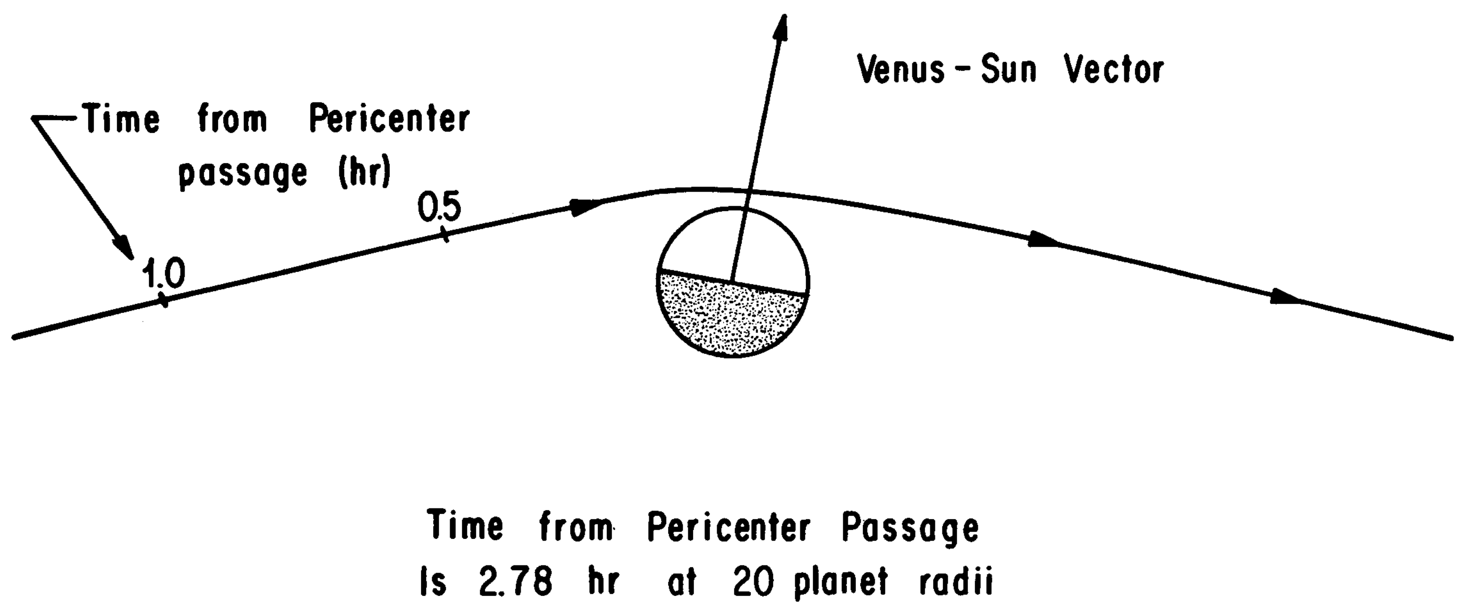


FIG. 9. 1975 DUAL PLANET FLYBY HYPERBOLIC TRAJECTORY PROFILE RELATIVE TO VENUS AT VENUS PASSAGE

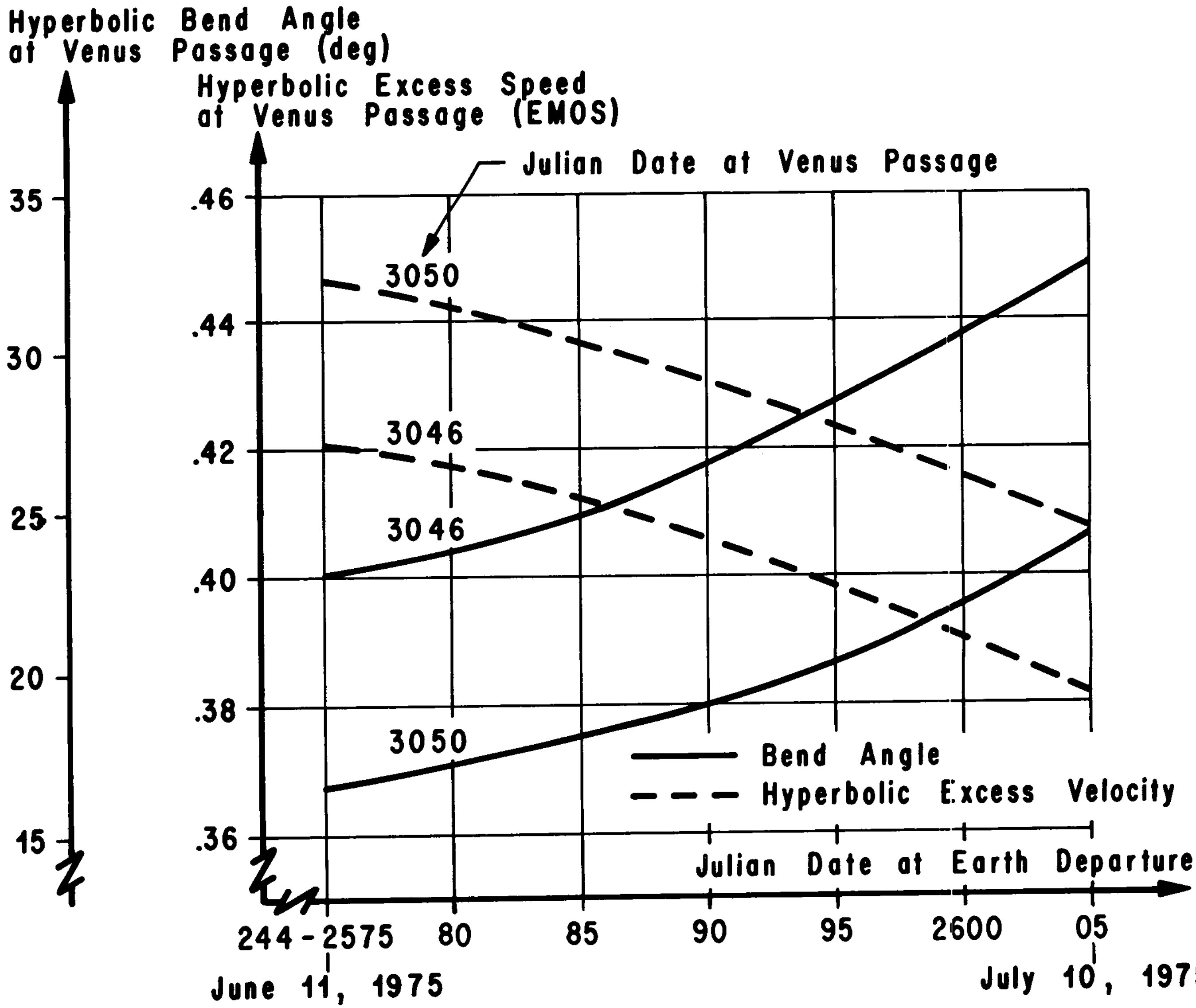


FIG. 10. 1975 DUAL PLANET FLYBY

POWERED MANEUVER AT MARS – FREE FLIGHT AT VENUS PASSAGE

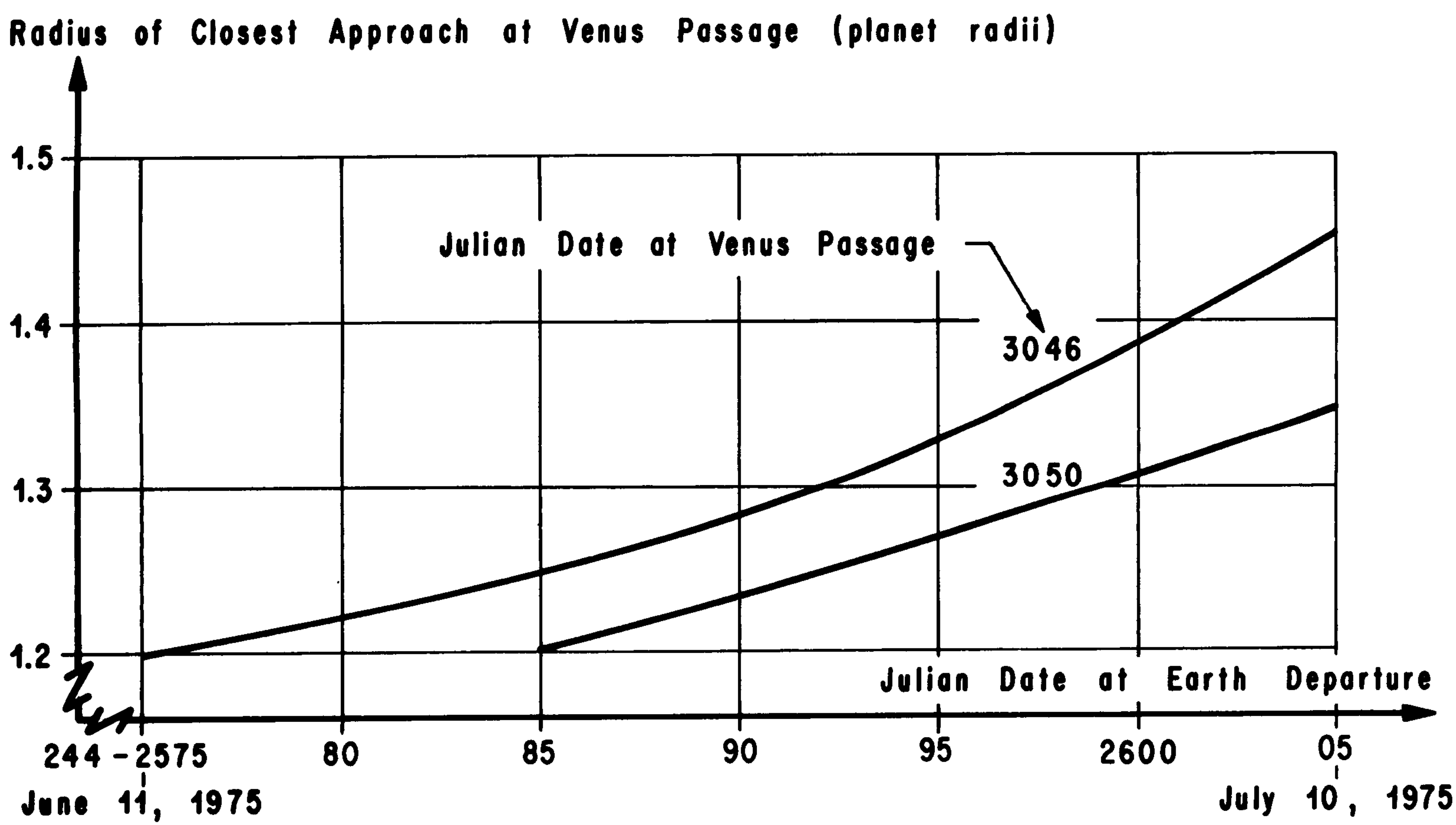


FIG. 11. 1975 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

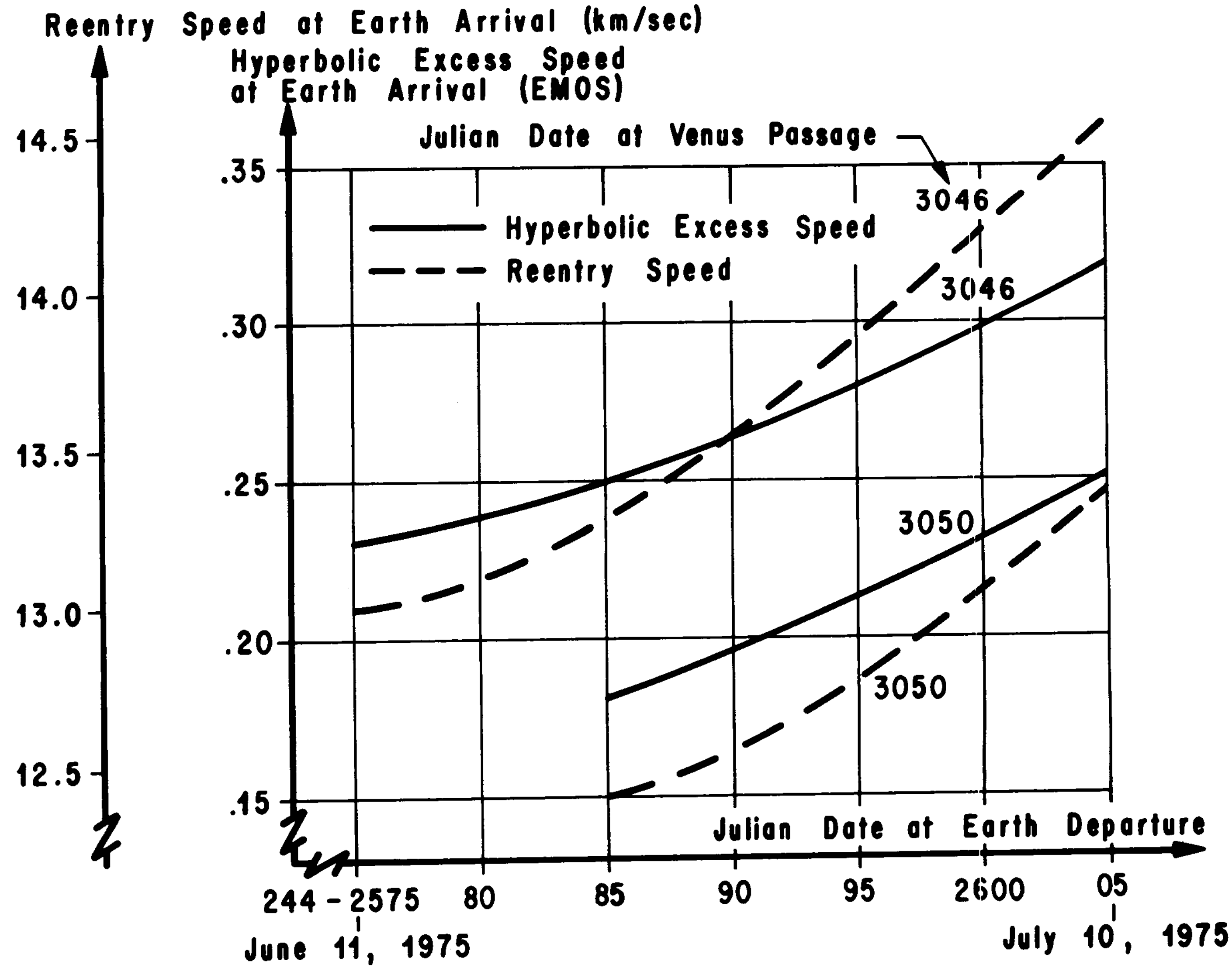


FIG. 12. 1975 DUAL PLANET FLYBY

POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

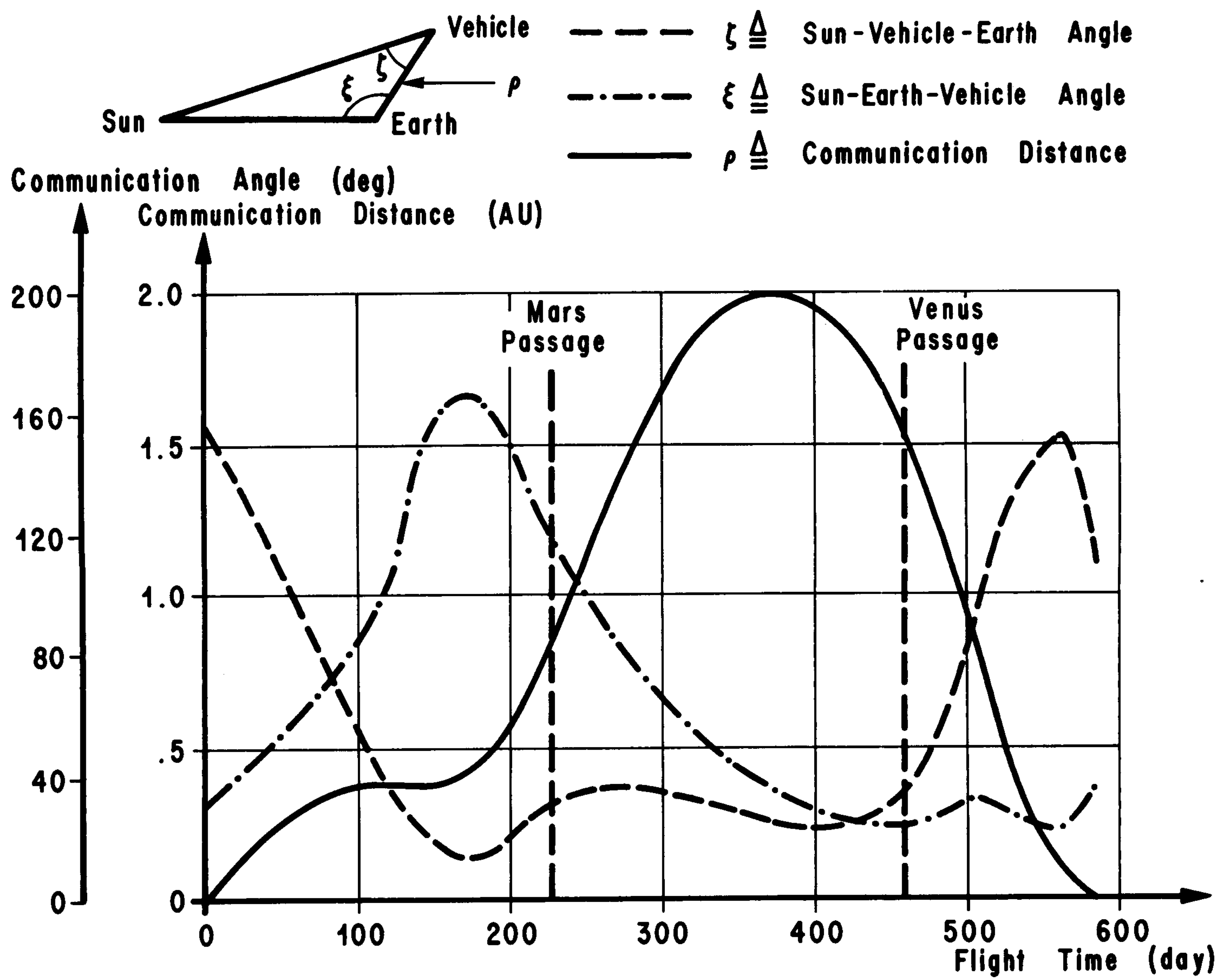


FIG. 14. 1975 DUAL PLANET FLYBY
COMMUNICATION DISTANCE AND ANGLES FOR EARTH

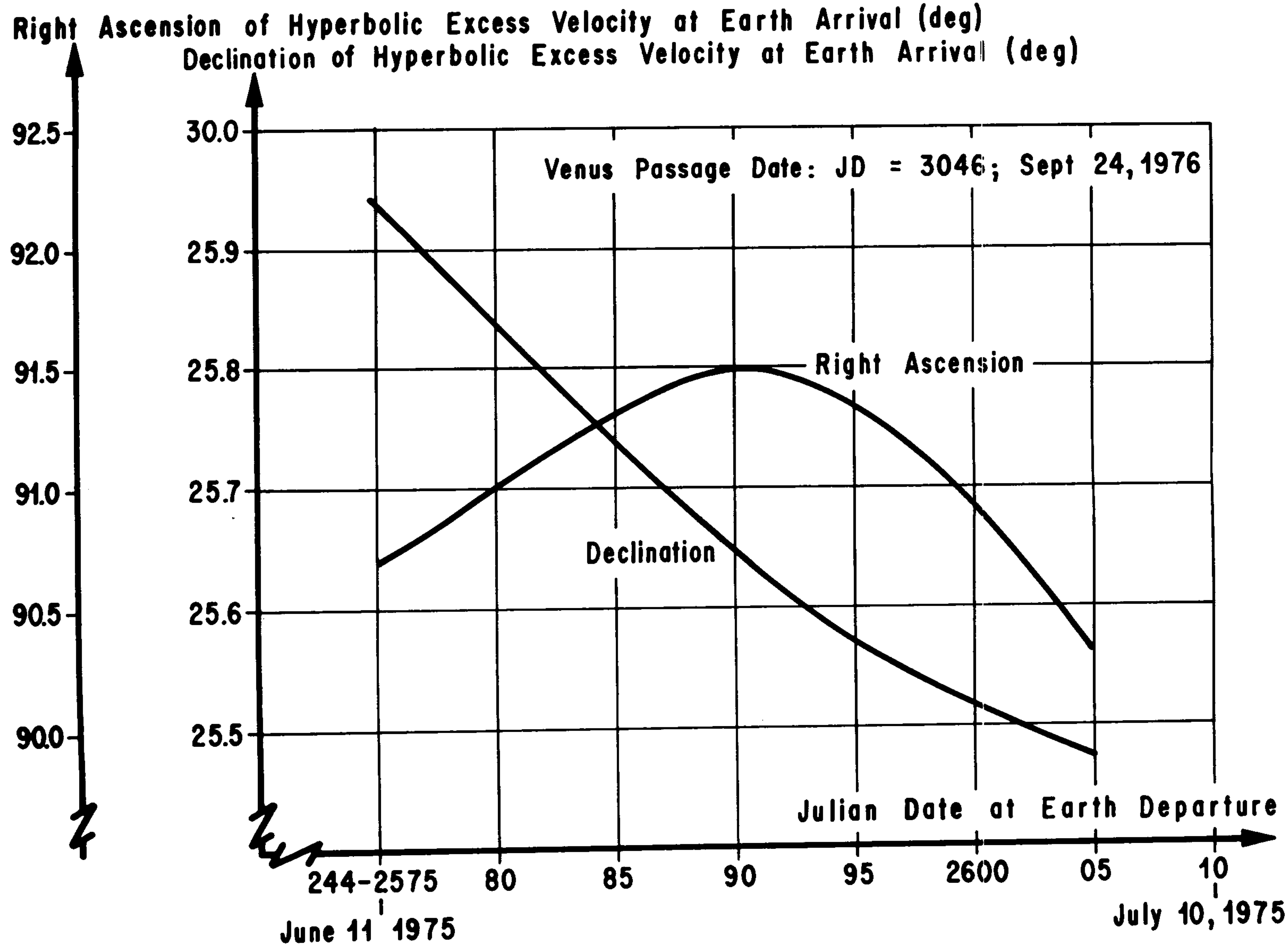


FIG. 13. 1975 DUAL PLANET FLYBY

POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

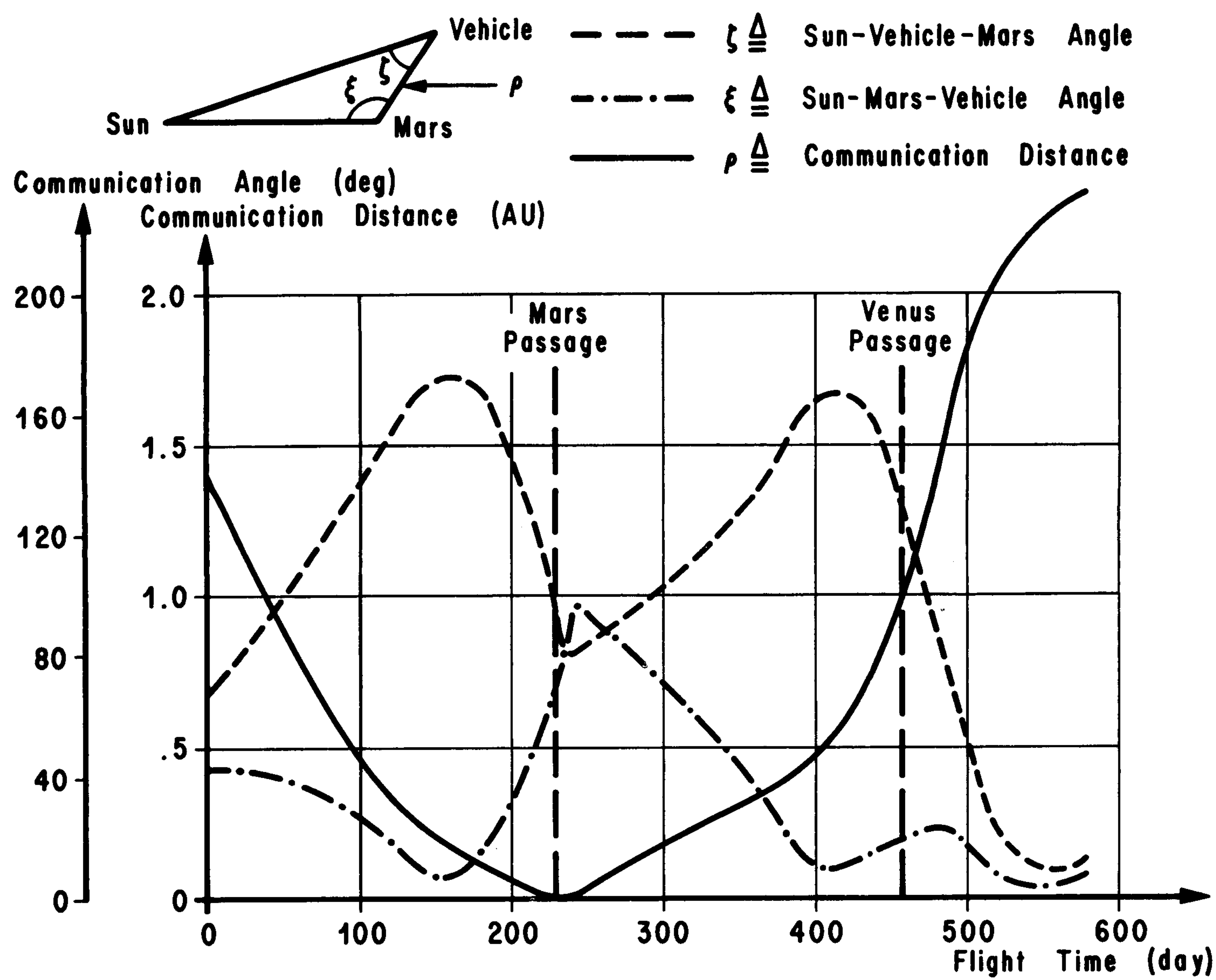


FIG. 15. 1975 DUAL PLANET FLYBY
COMMUNICATION DISTANCE AND ANGLES FOR MARS

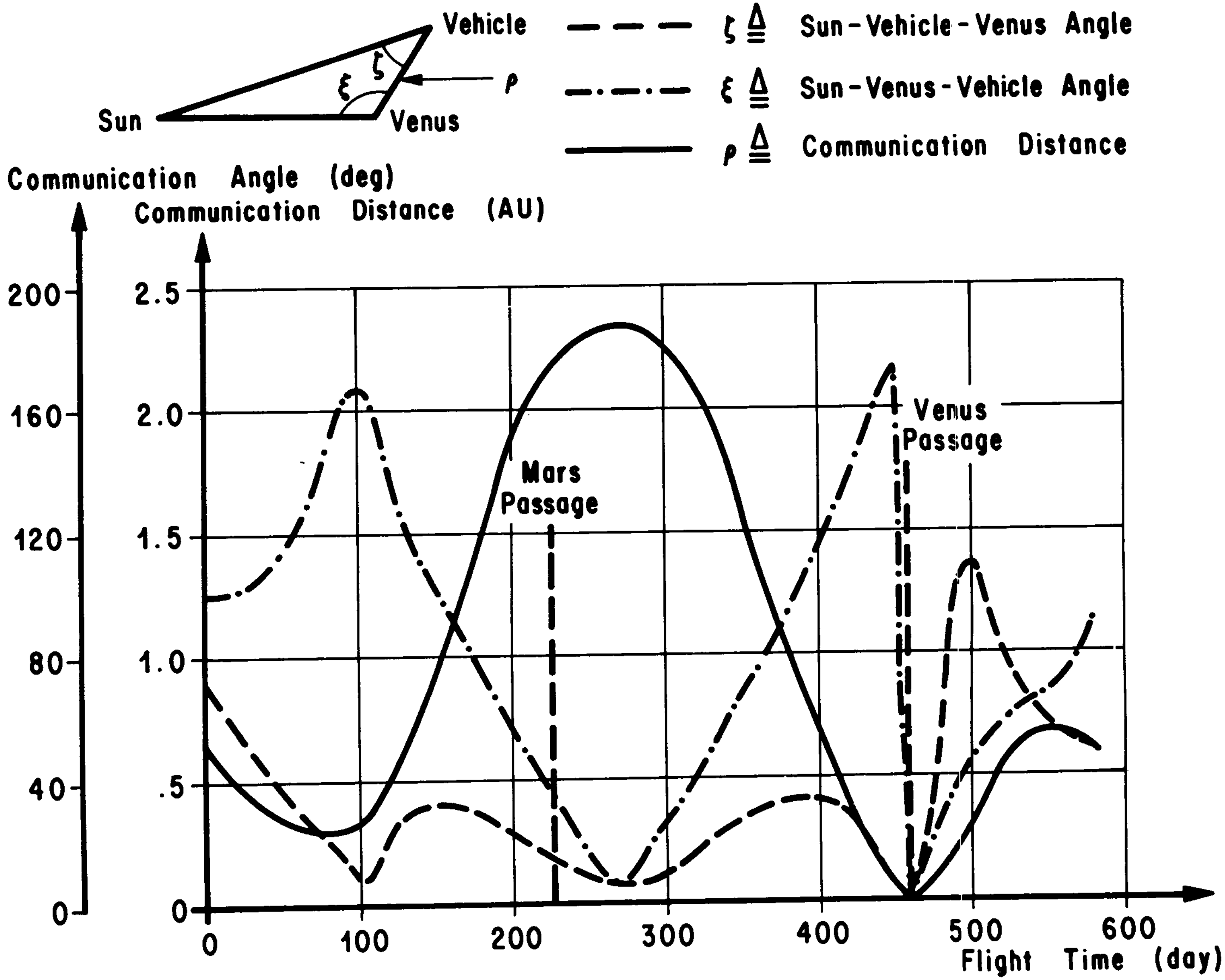


FIG. 16. 1975 DUAL PLANET FLYBY
COMMUNICATION DISTANCE AND ANGLES FOR VENUS

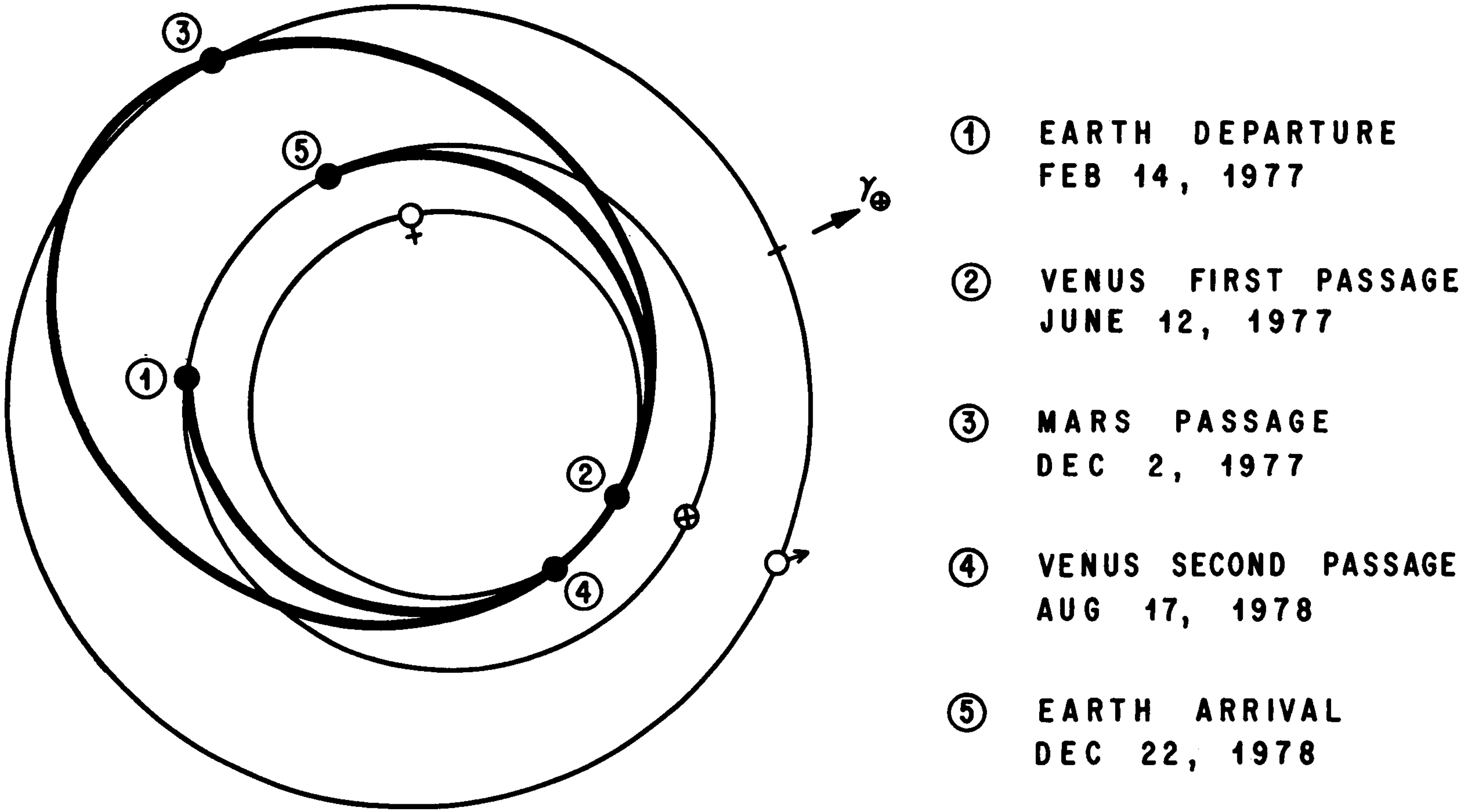


FIG. 17. 1977 TRIPLE PLANET FLYBY
TYPICAL TRAJECTORY PROFILE

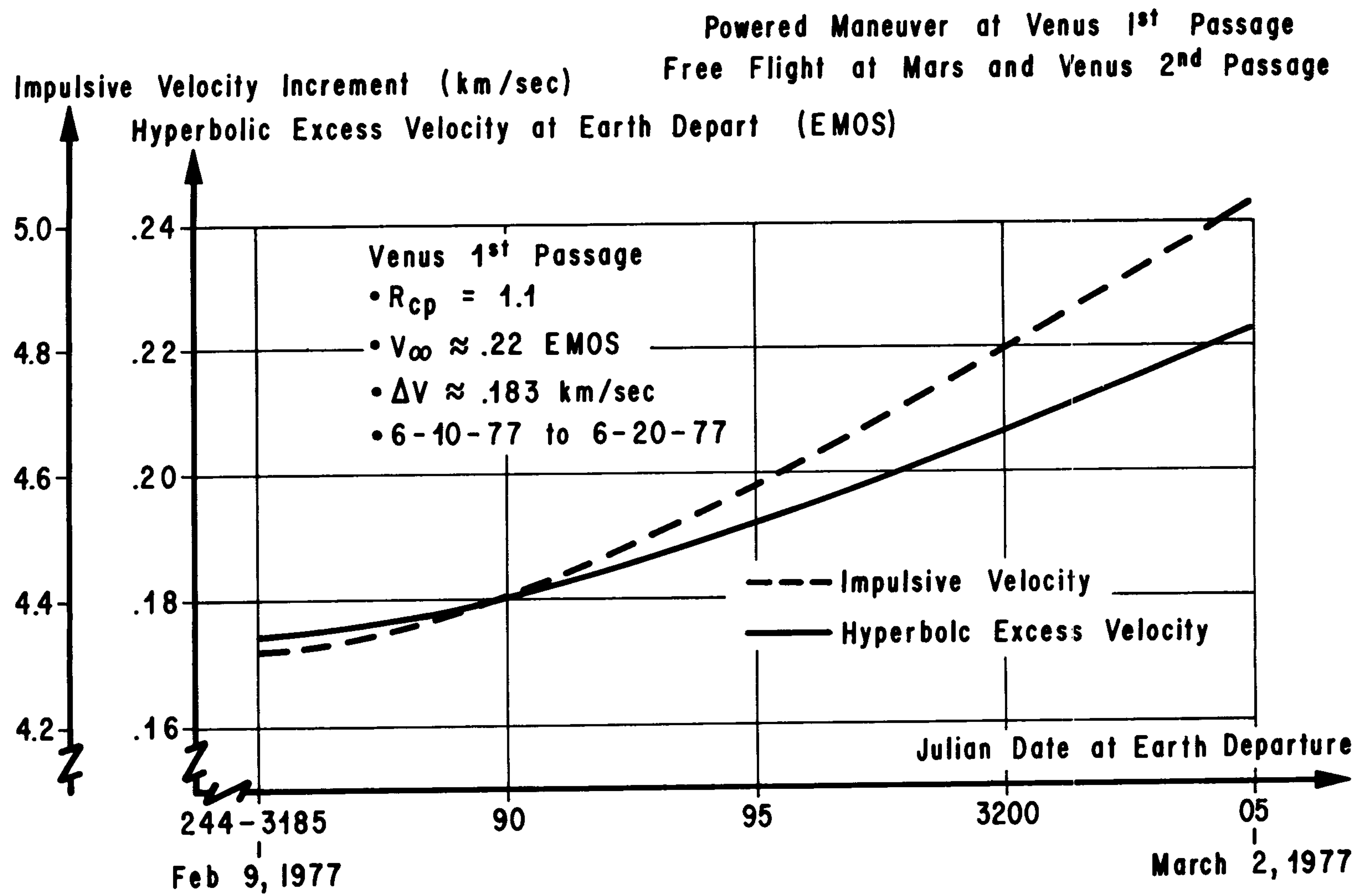


FIG. 18. 1977 TRIPLE PLANET FLYBY

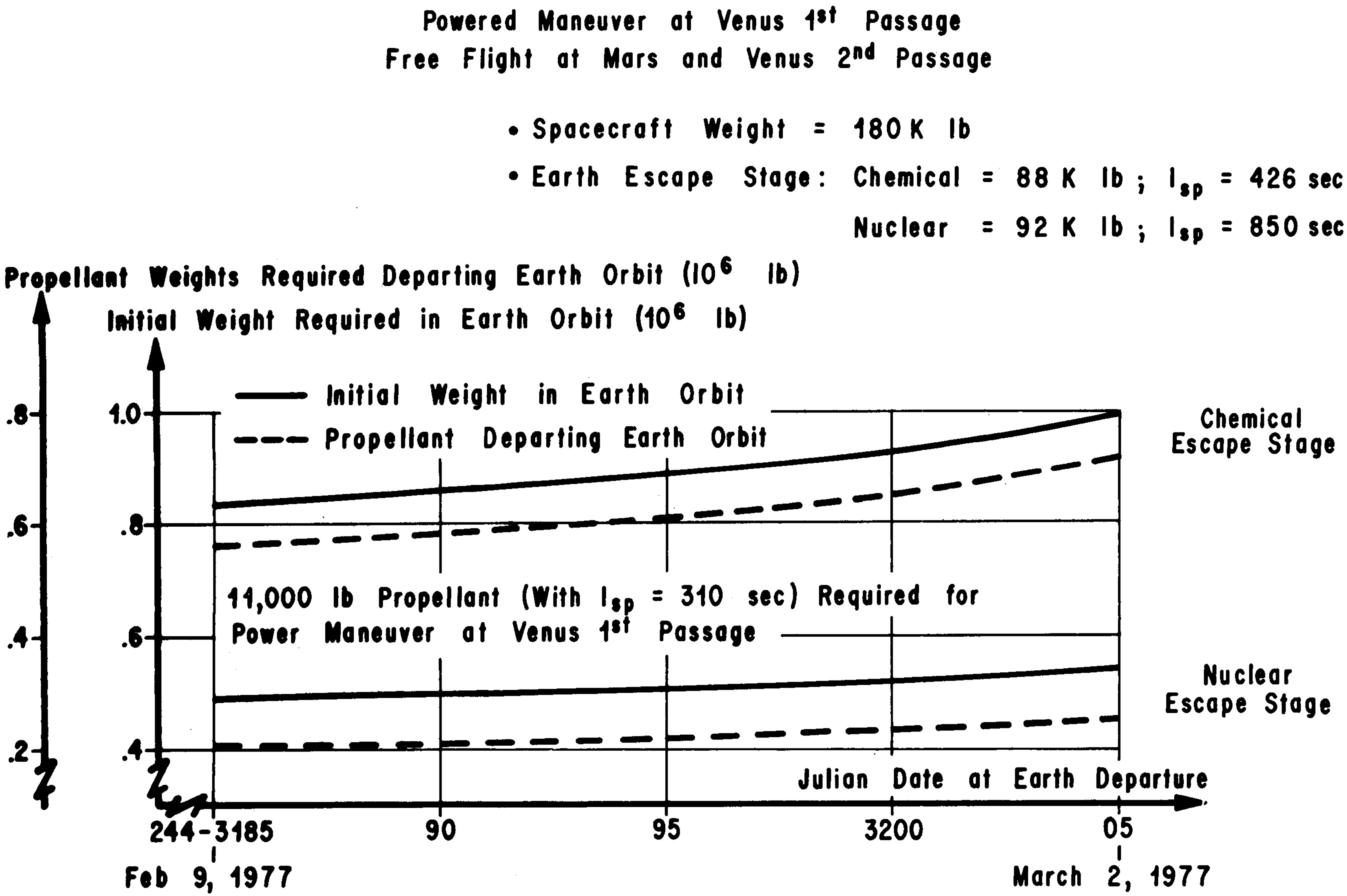


FIG. 19. 1977 TRIPLE PLANET FLYBY

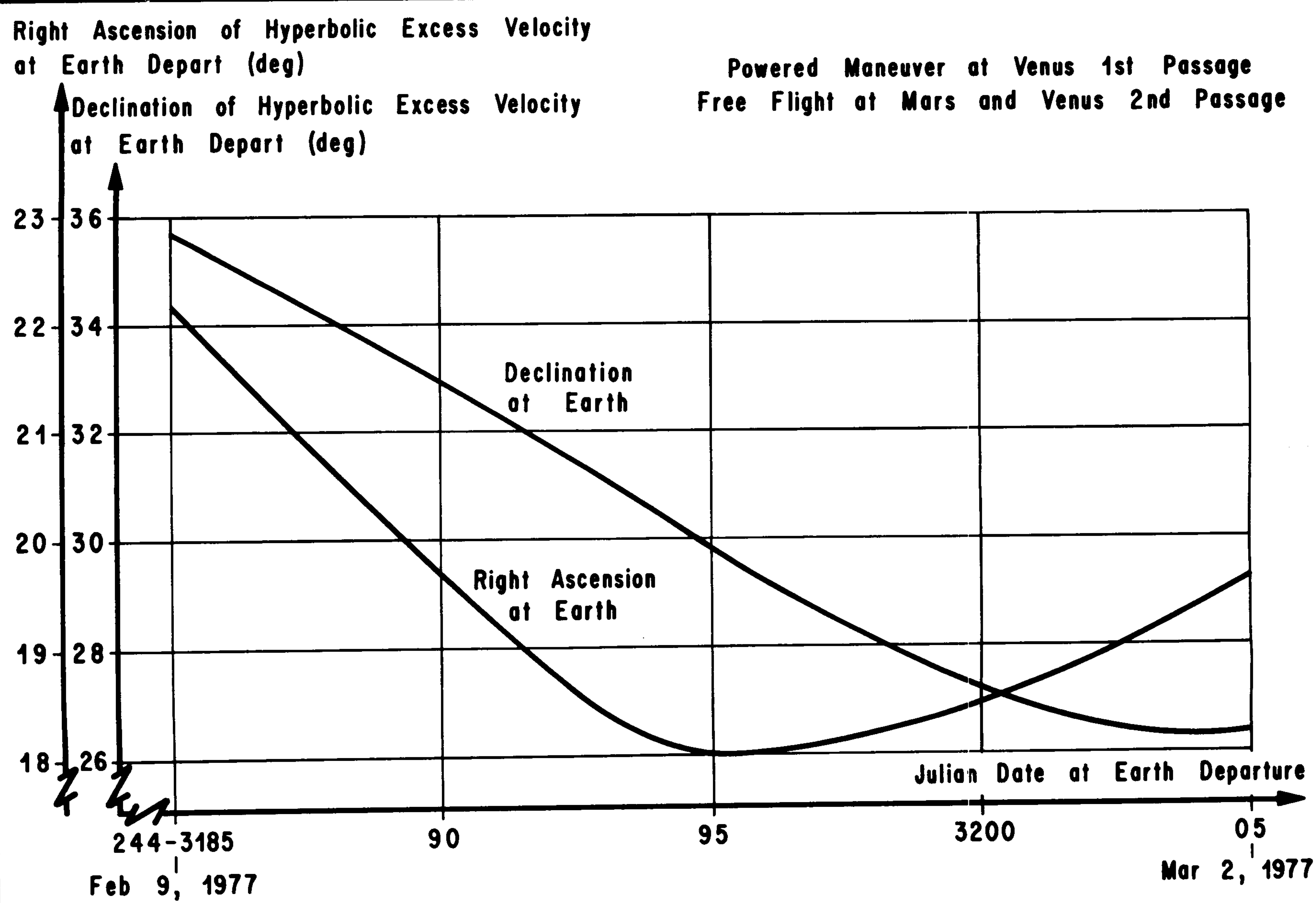
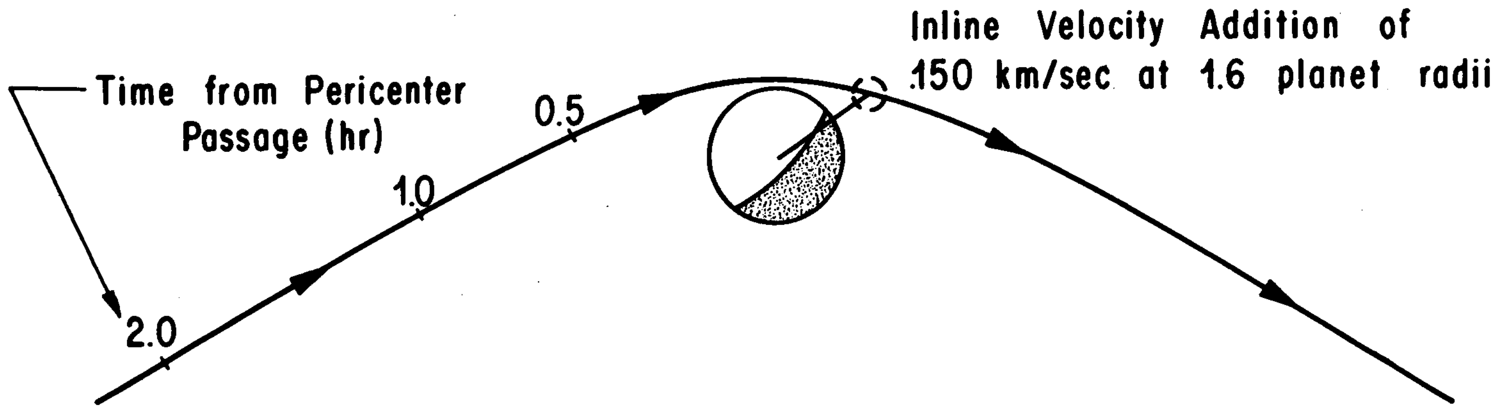


FIG. 20. 1977 TRIPLE PLANET FLYBY AT EARTH DEPARTURE



Radius of Closest Approach = 1.1 planet radii

Velocity at Pericenter Passage = 11.6 km/sec

Time from Pericenter at 20 planet radii = 4.8 hr

FIG. 21. 1977 TRIPLE PLANET FLYBY HYPERBOLIC TRAJECTORY RELATIVE TO VENUS AT VENUS FIRST PASSAGE

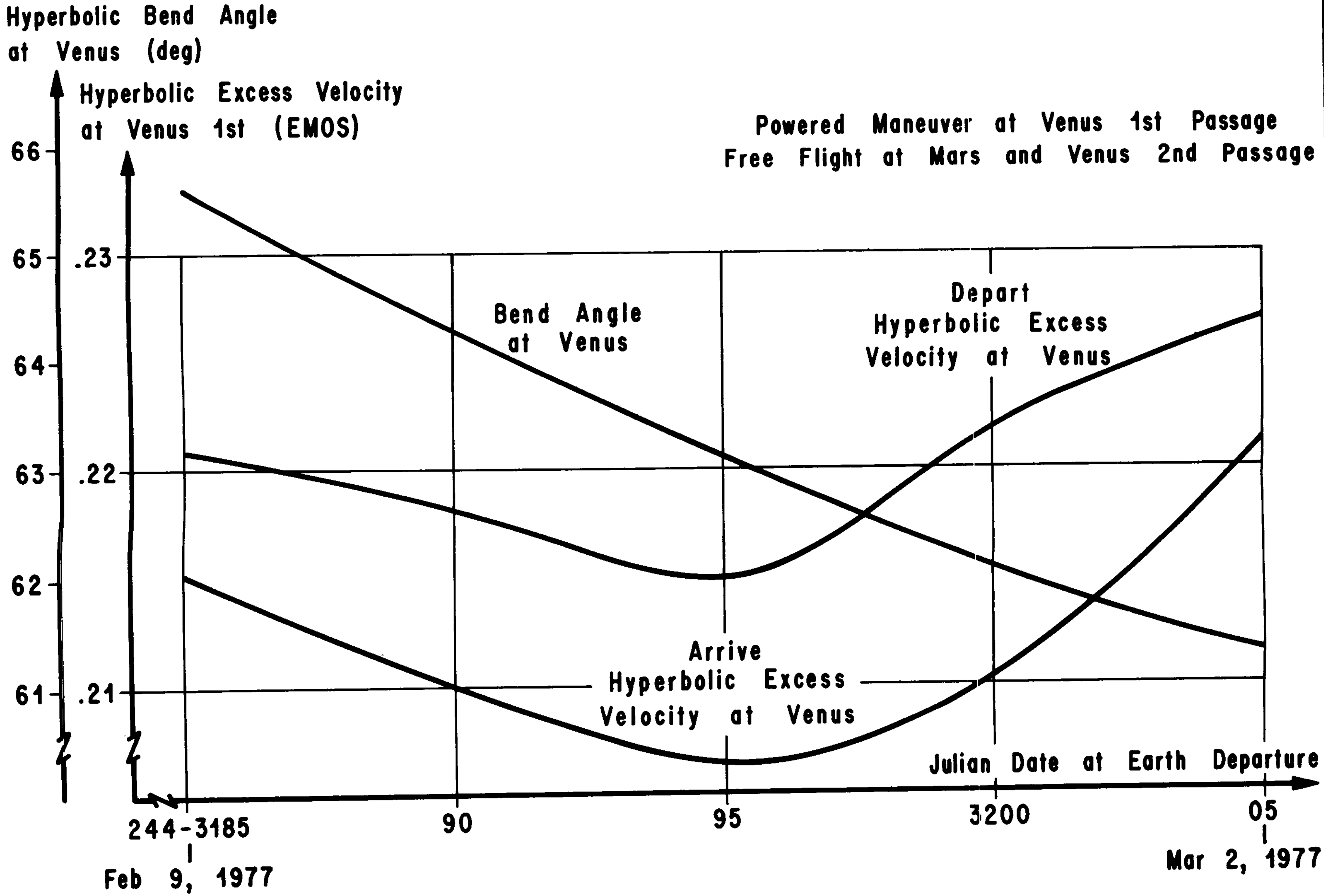
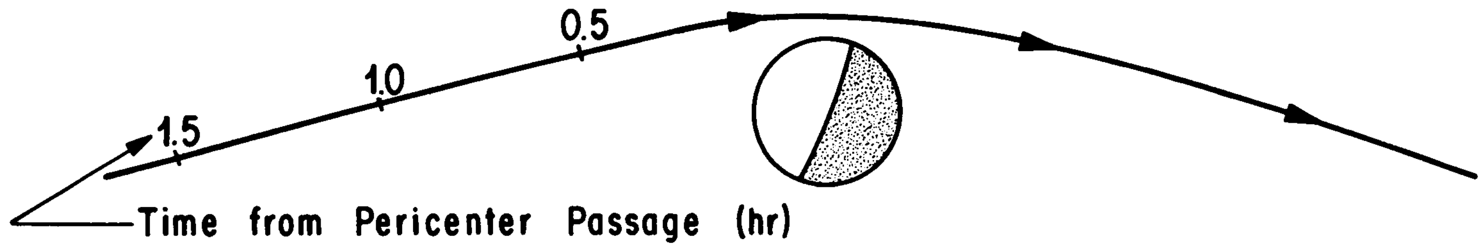


FIG. 22. 1977 TRIPLE PLANET FLYBY AT VENUS FIRST PASSAGE



Radius of Closest Approach = 1.23 planet radii

Velocity at Pericenter Passage = 6.927 km/sec

Time from Pericenter at 20 planet radii = 3.40 hr

FIG. 23. 1977 TRIPLE PLANET FLYBY HYPERBOLIC TRAJECTORY PROFILE RELATIVE TO MARS AT MARS PASSAGE

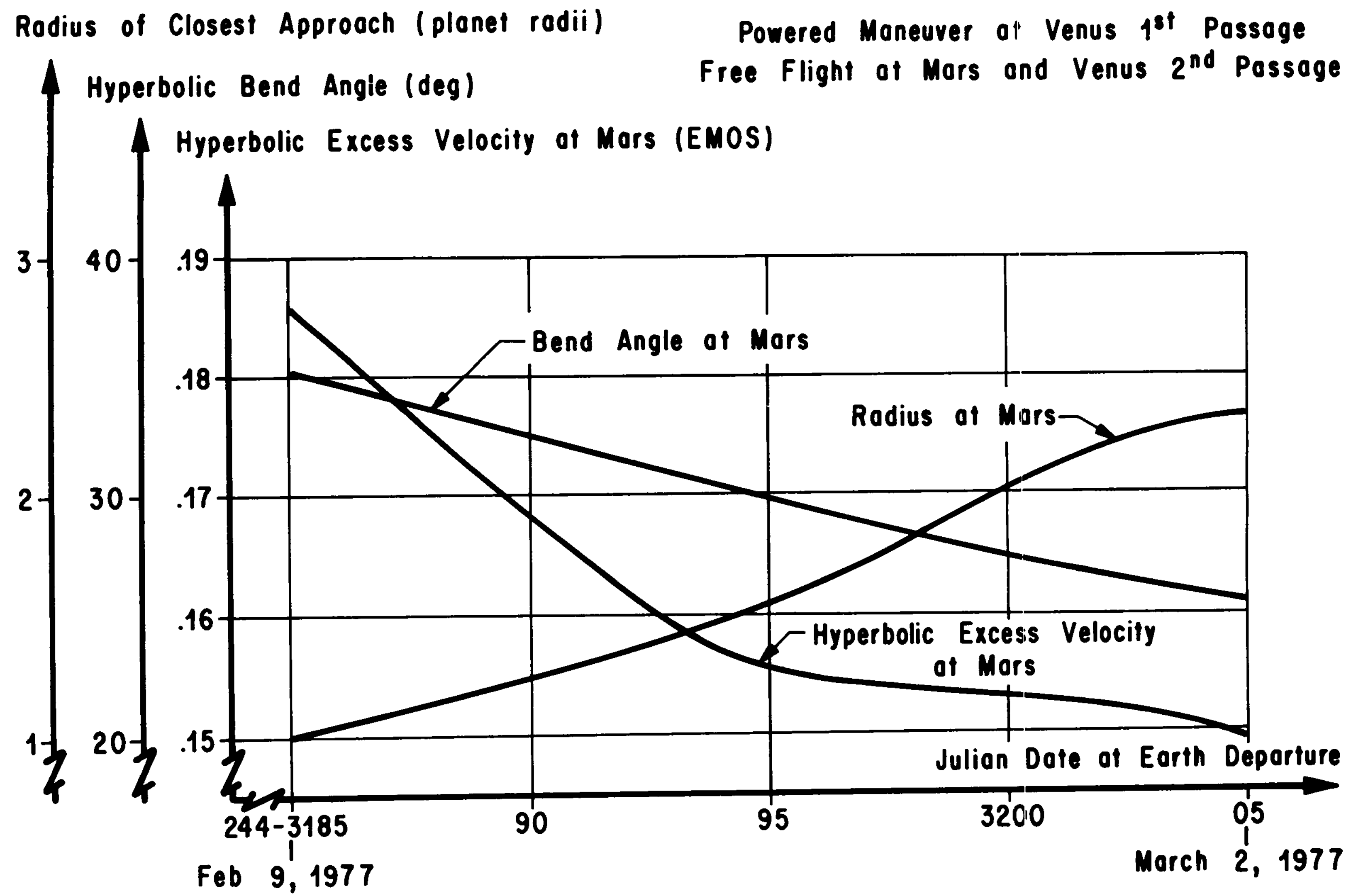
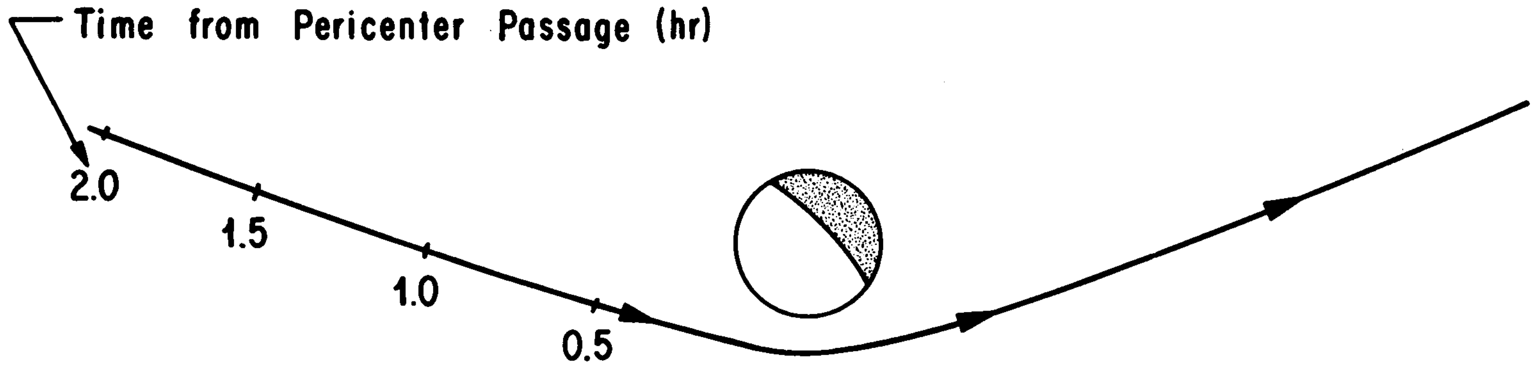


FIG. 24. 1977 TRIPLE PLANET FLYBY AT MARS PASSAGE



Radius of Closest Approach = 1.63 planet radii

Velocity at Pericenter = 10.83 km/sec

Time from Pericenter at 20 planet radii = 4.30 hr

FIG. 25. 1977 TRIPLE PLANET FLYBY
HYPERBOLIC TRAJECTORY PROFILE
RELATIVE TO VENUS AT VENUS SECOND PASSAGE

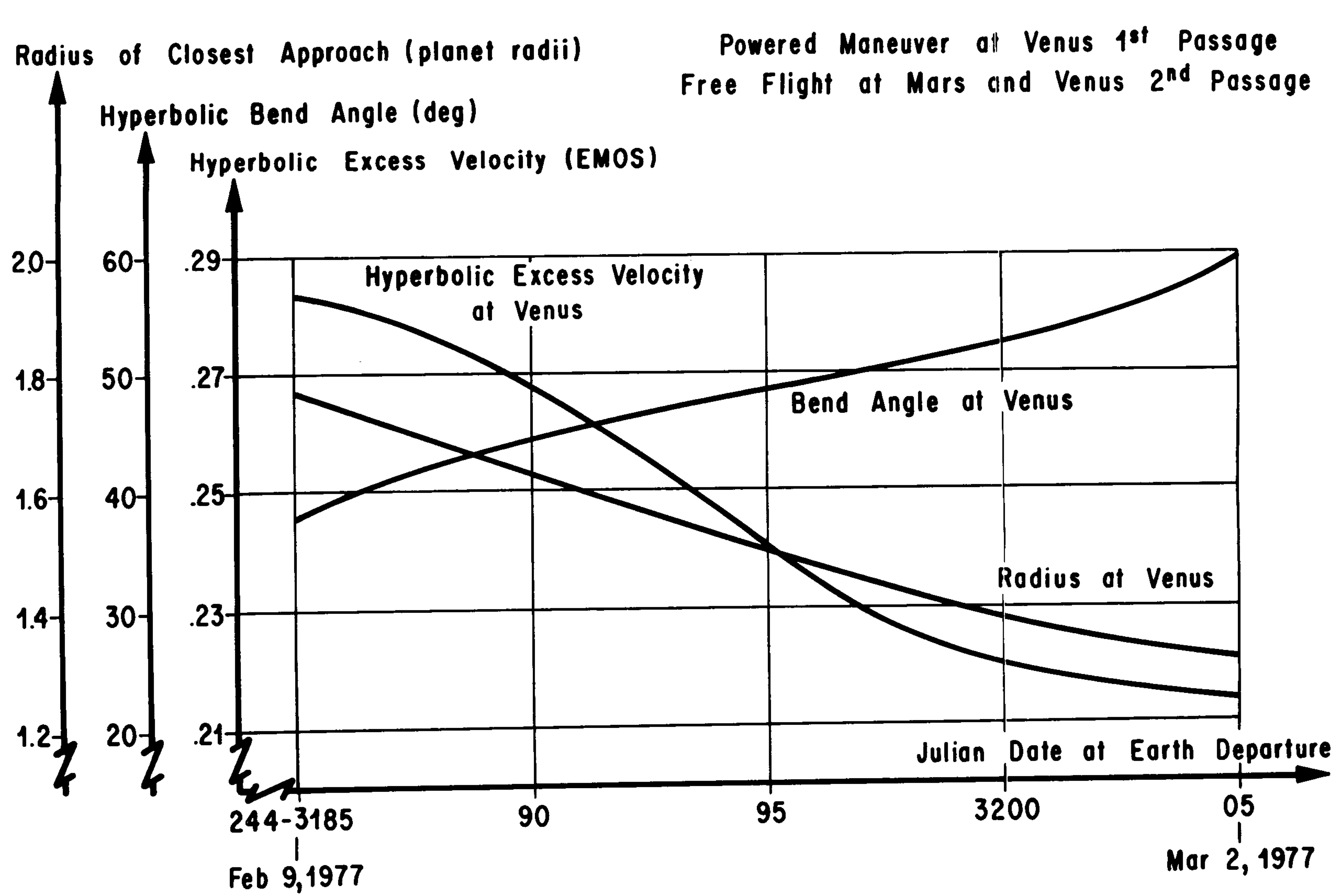


FIG. 26. 1977 TRIPLE PLANET FLYBY AT VENUS SECOND PASSAGE

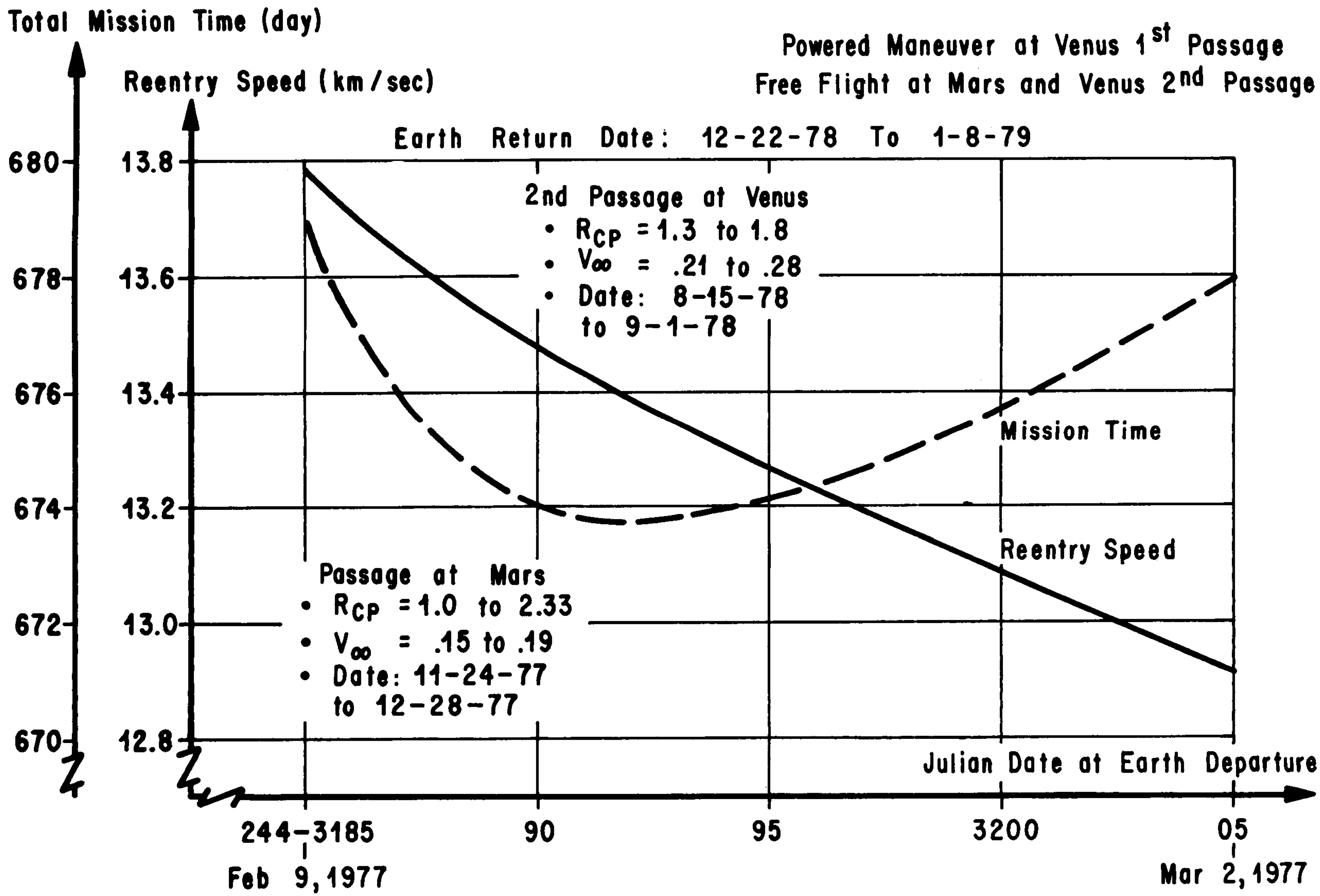


FIG. 27. 1977 TRIPLE PLANET FLYBY

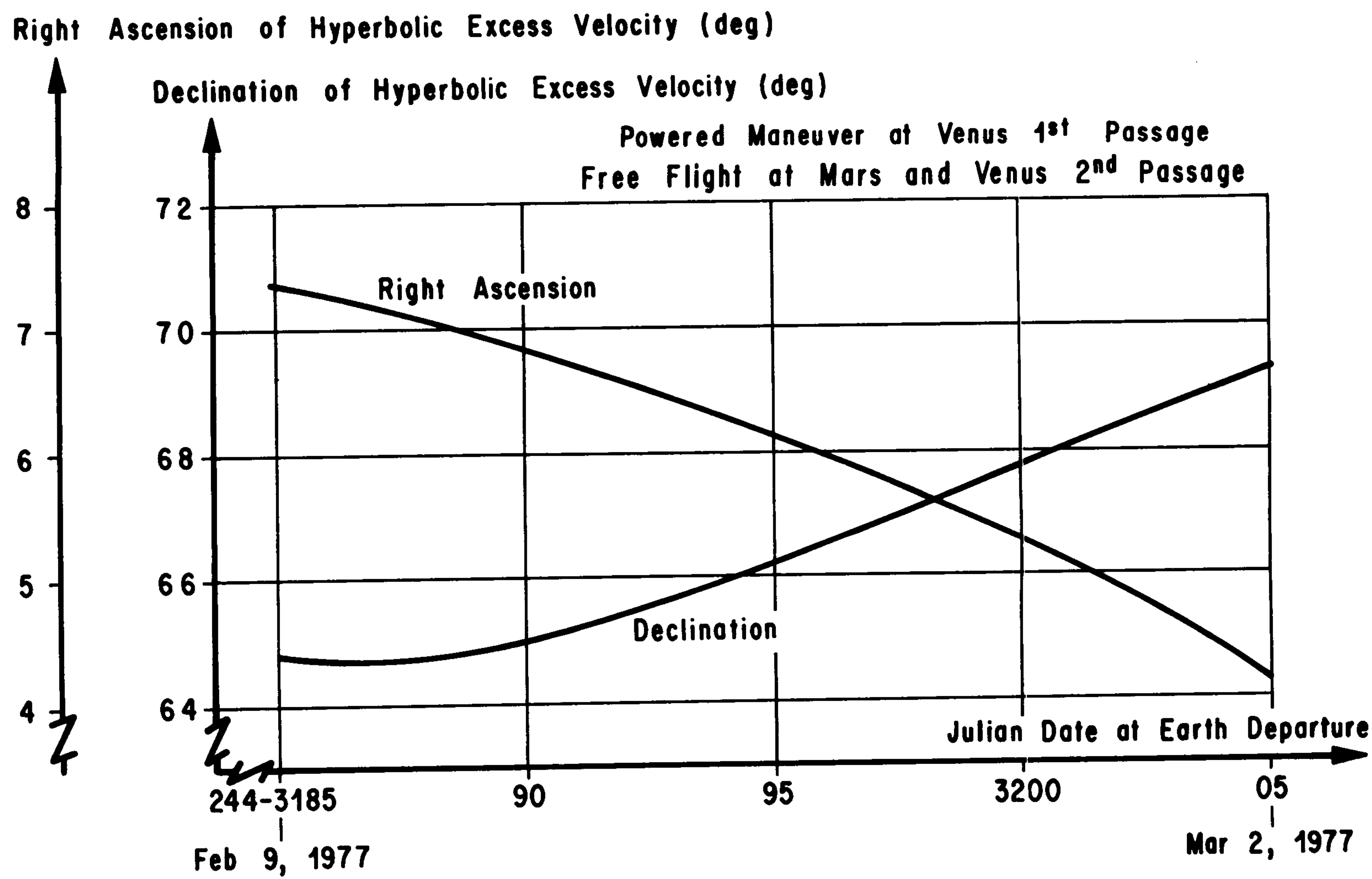


FIG. 28. 1977 TRIPLE PLANET FLYBY AT EARTH ARRIVAL

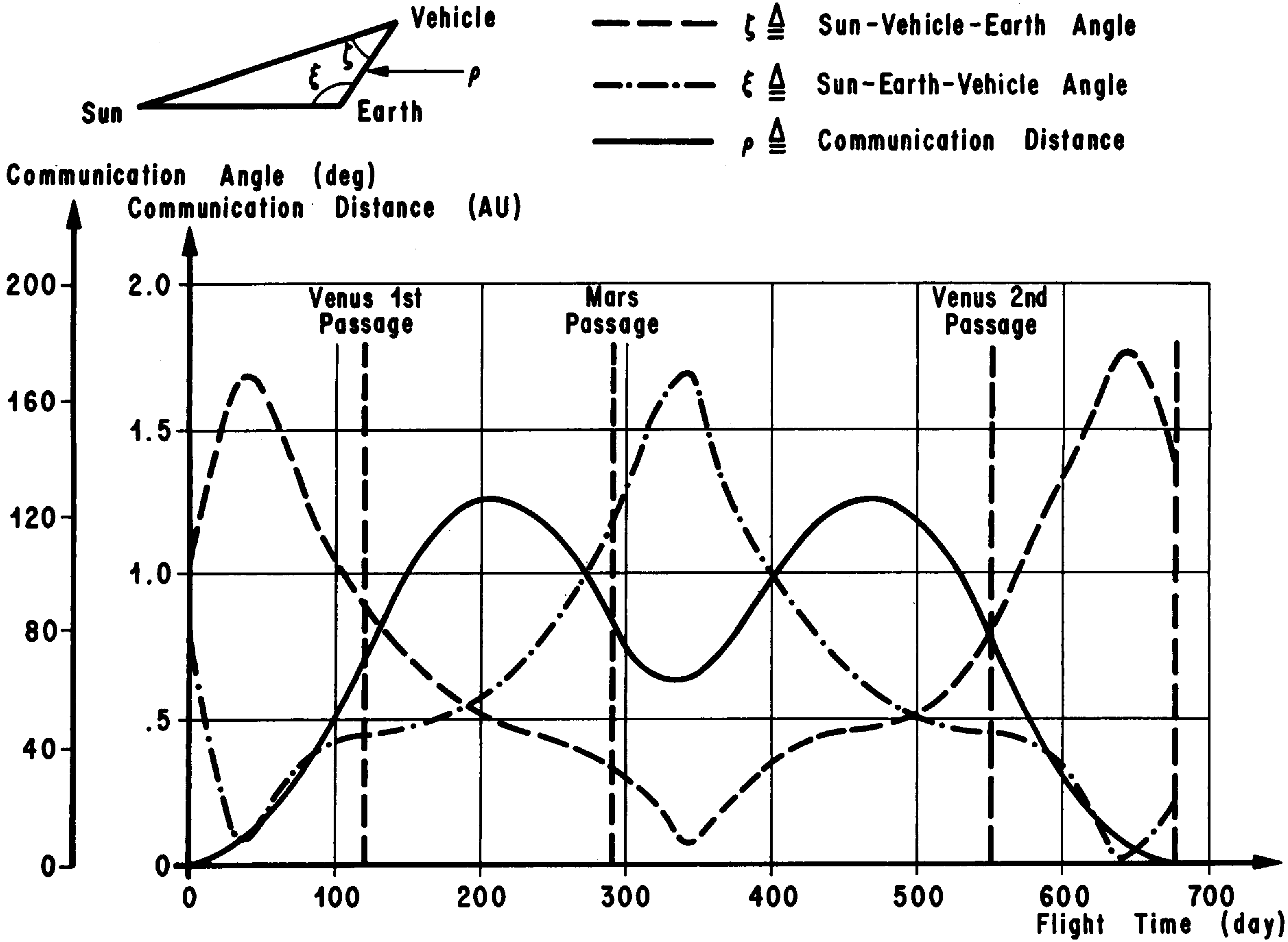


FIG. 29. 1977 TRIPLE PLANET FLYBY COMMUNICATION DISTANCE AND ANGLES FOR EARTH

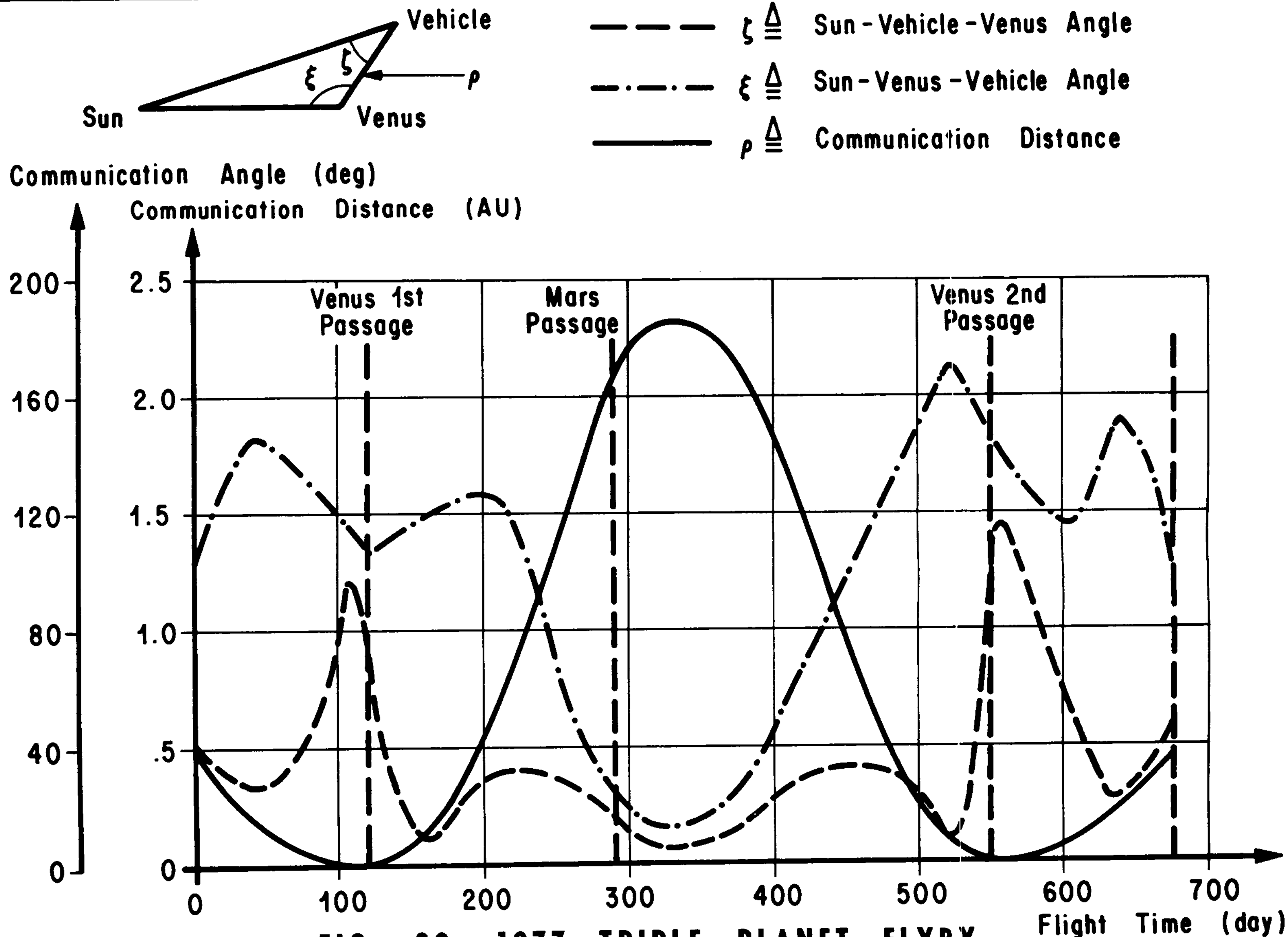


FIG. 30. 1977 TRIPLE PLANET FLYBY COMMUNICATION DISTANCE AND ANGLES FOR VENUS

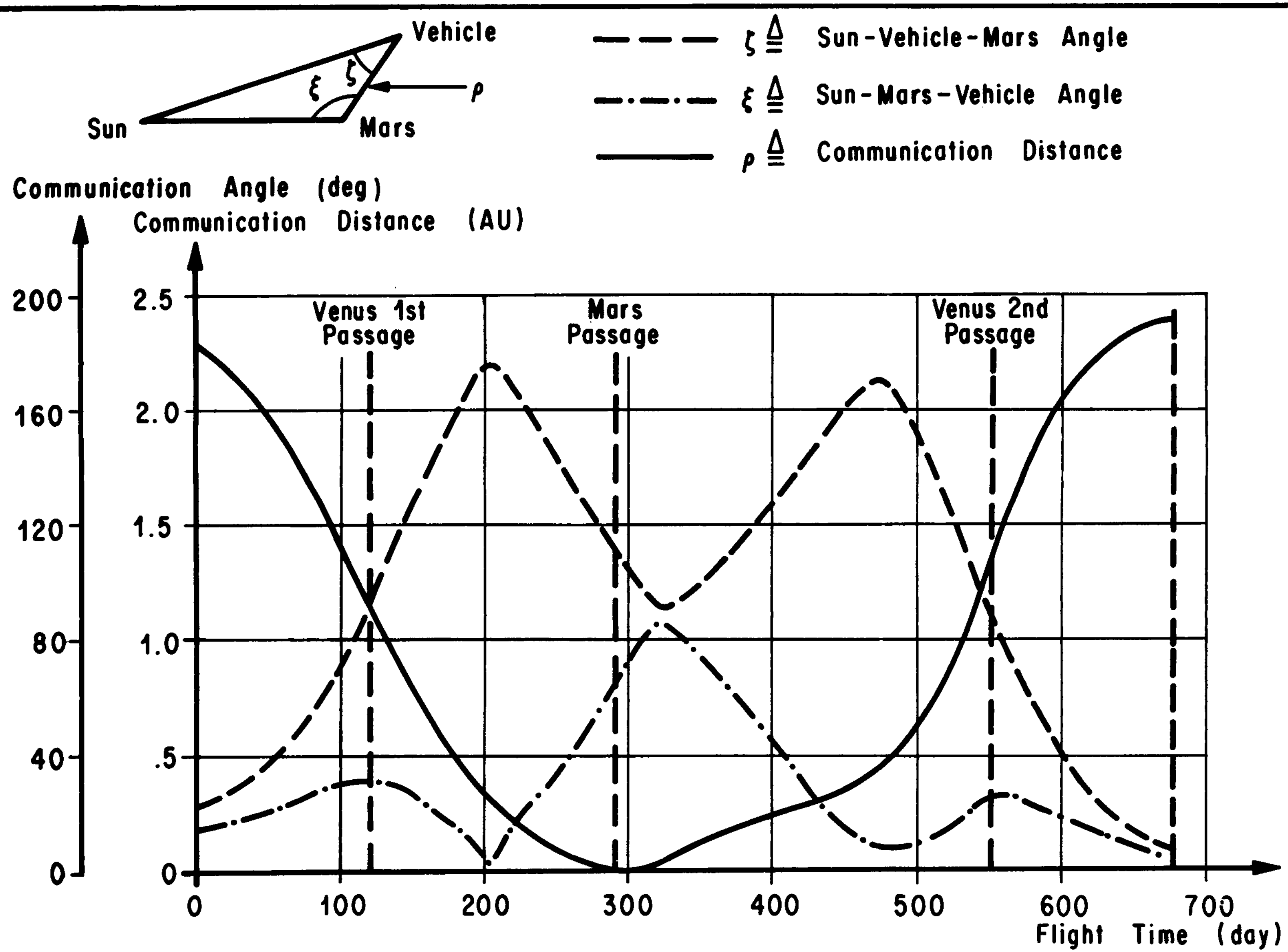


FIG. 31. 1977 TRIPLE PLANET FLYBY COMMUNICATION DISTANCE AND ANGLES FOR MARS

	1 DEPART EARTH	2 ARRIVE VENUS	3 ARRIVE MARS	4 ARRIVE EARTH
JD	3850	4010	4250	4501
CD	12/7/78	5/16/79	1/11/80	9/18/80
V_∞	0.175	0.3551	0.1875	0.313
R_p	1.076	1.17	1.145	1.076
PASSAGE	—	DARK SIDE	LIGHT SIDE	—

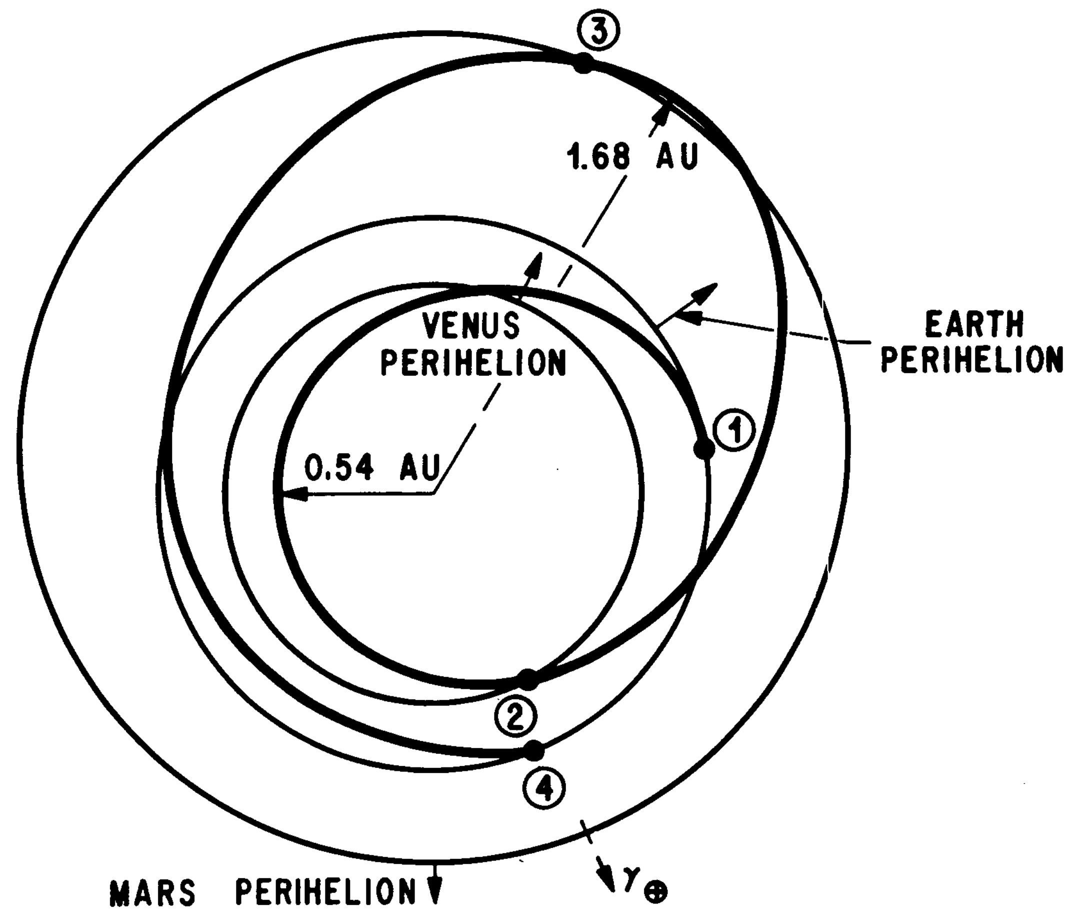


FIG. 32. 1978 FREE-RETURN DUAL PLANET FLYBY

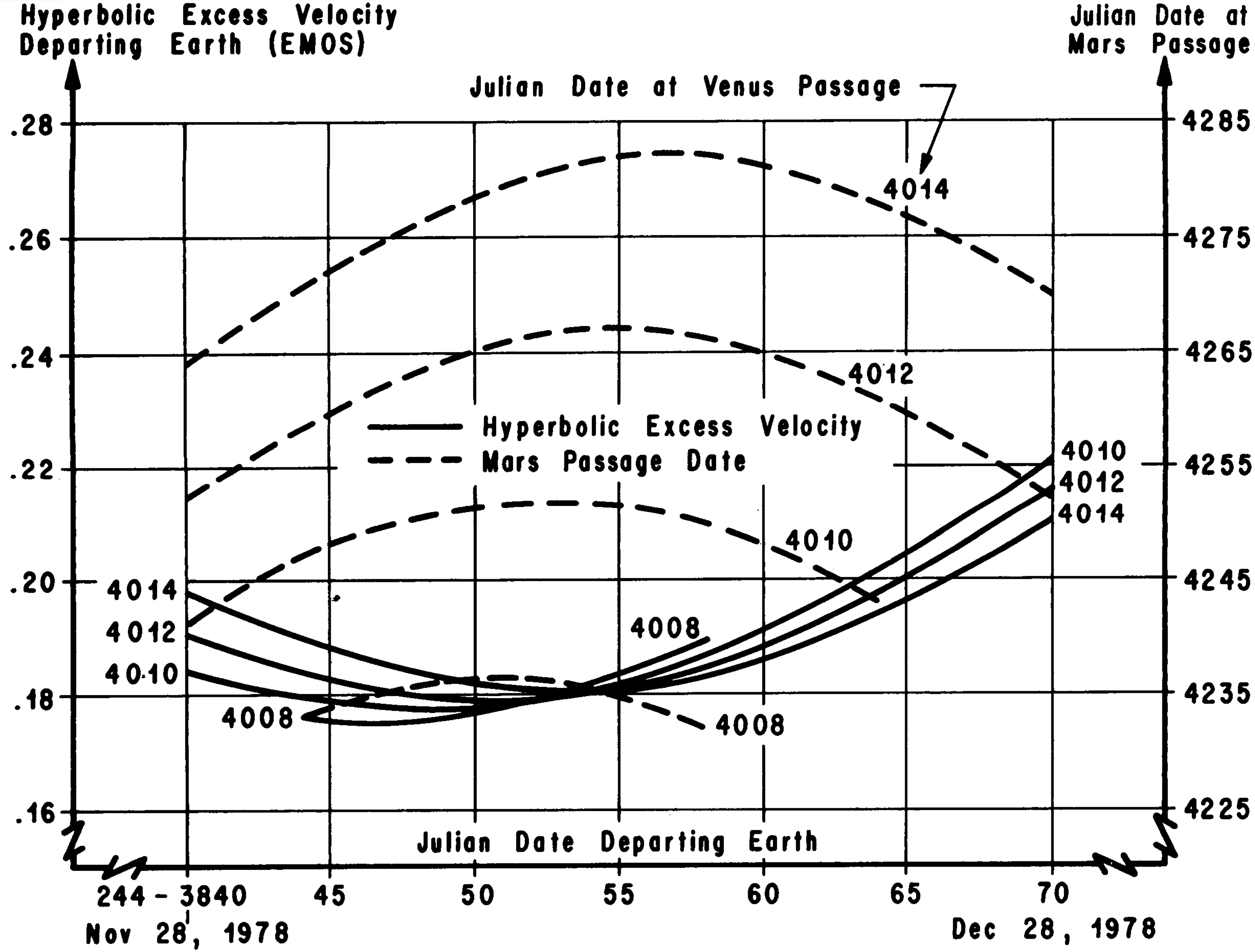


FIG. 33. 1978 FREE-RETURN DUAL PLANET FLYBY

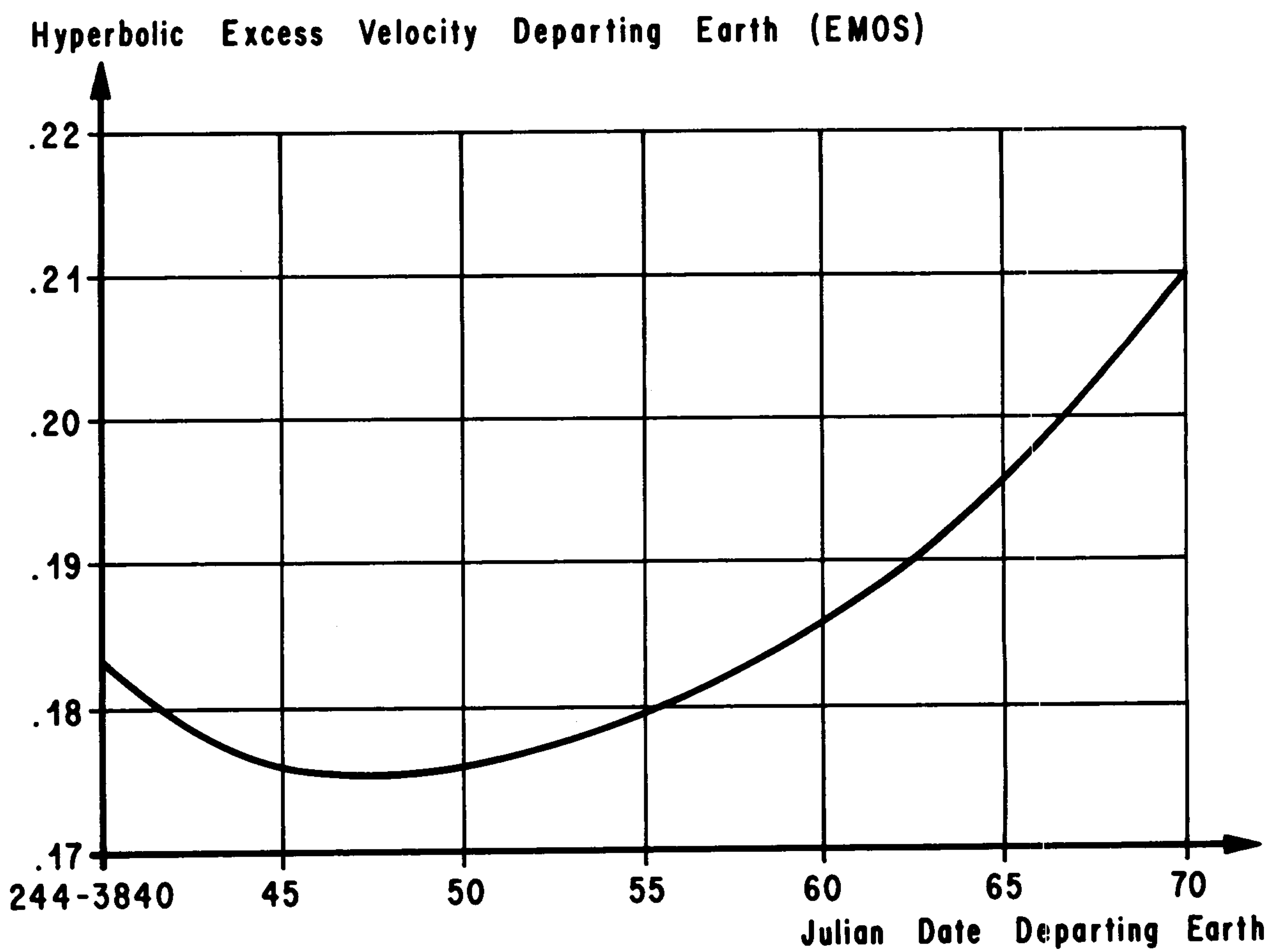


FIG. 34. ENVELOPE OF MINIMUM HYPERBOLIC EXCESS VELOCITY DEPARTING EARTH 1978 FREE-RETURN DUAL PLANET FYBY

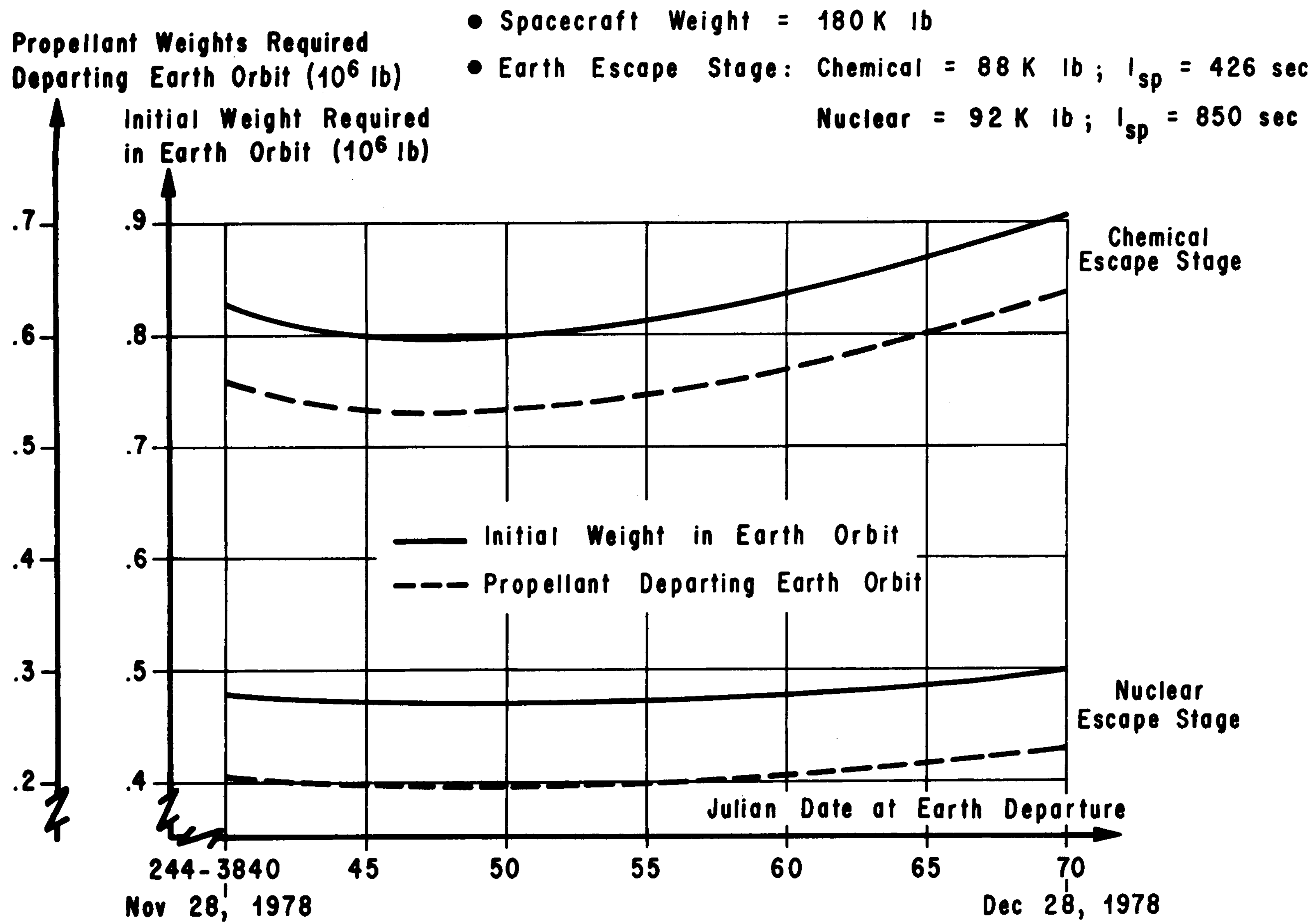


FIG. 35. 1978 FREE-RETURN DUAL PLANET FLYBY

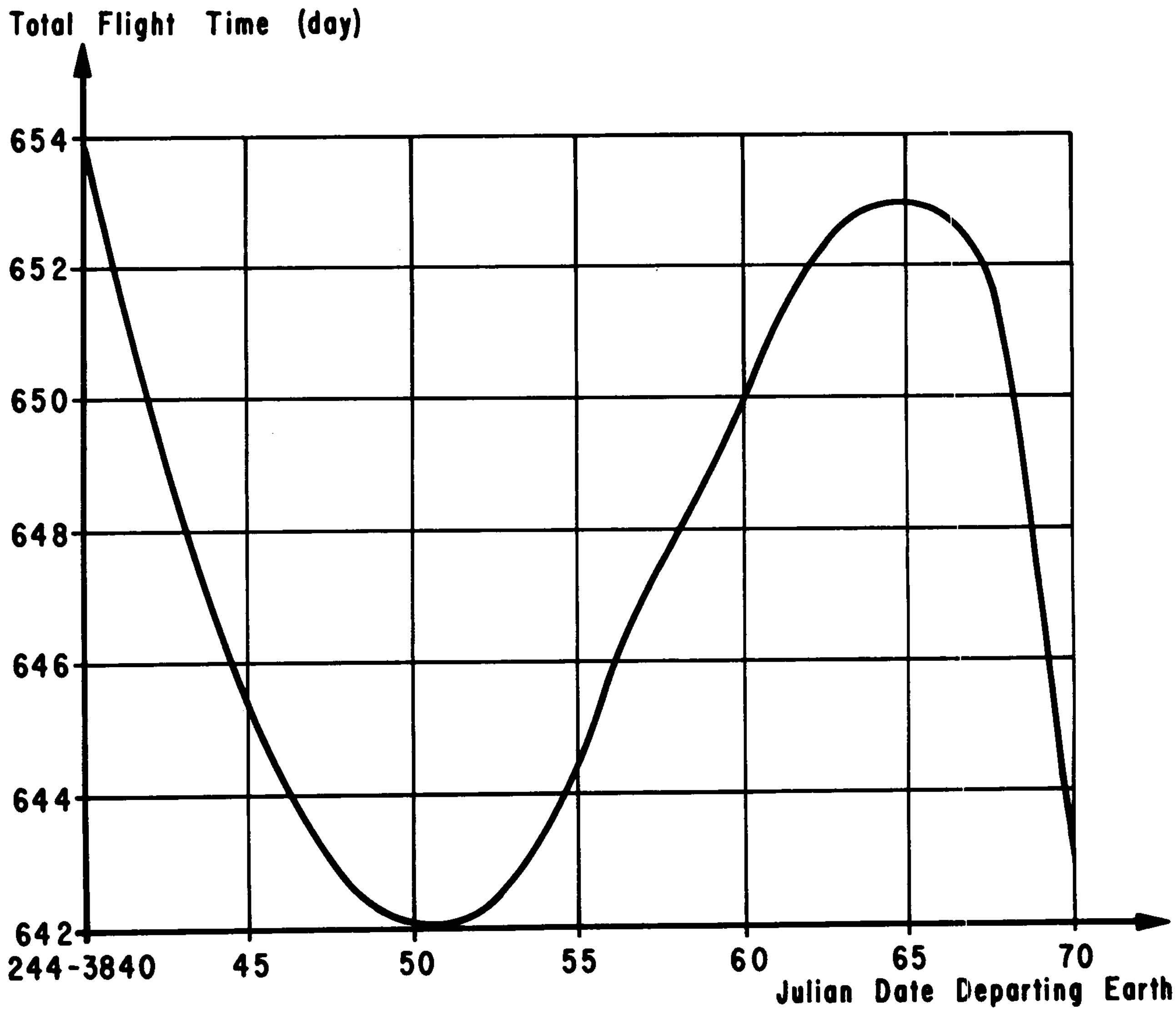


FIG. 36. TOTAL FLIGHT TIME CORRESPONDING TO
THE MINIMUM HYPERBOLIC EXCESS VELOCITY ENVELOPE DEPARTING EARTH
1978 FREE-RETURN DUAL PLANET FLYBY

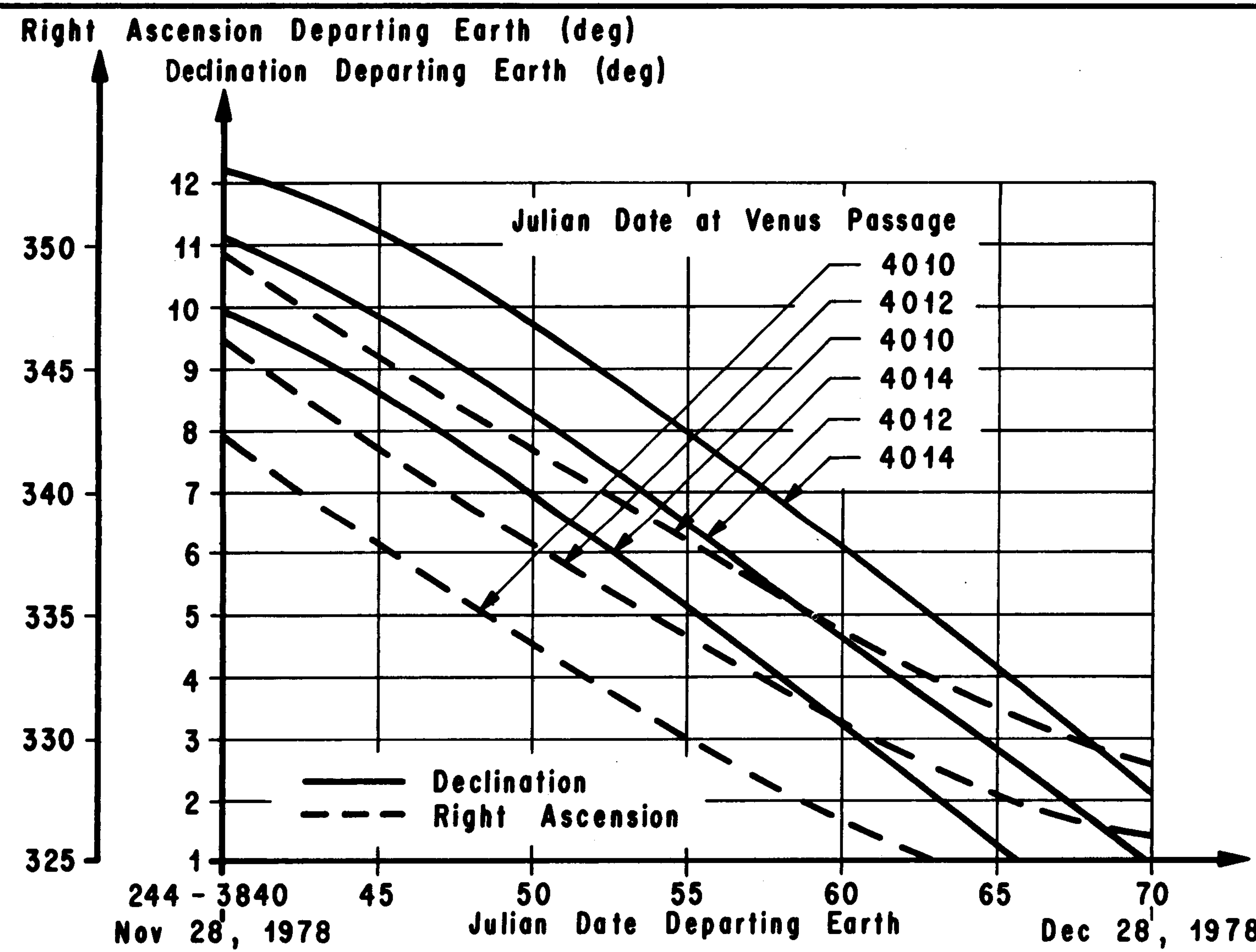


FIG. 37. 1978 FREE-RETURN DUAL PLANET FLYBY

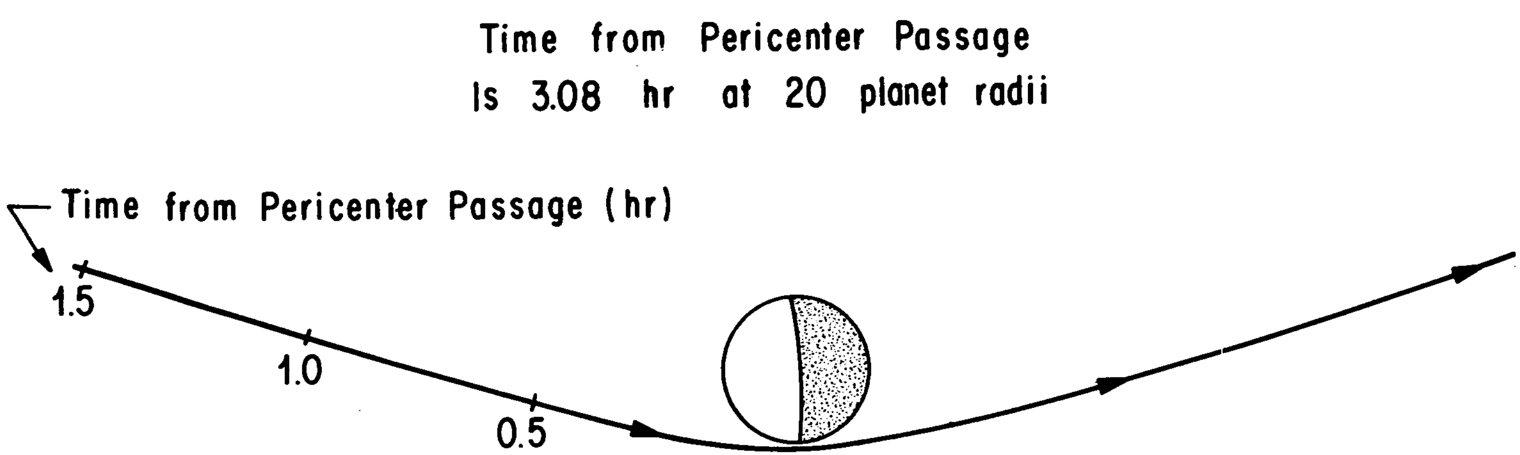


FIG. 38. 1978 FREE-RETURN DUAL PLANET FLYBY HYPERBOLIC TRAJECTORY PROFILE RELATIVE TO VENUS AT VENUS PASSAGE

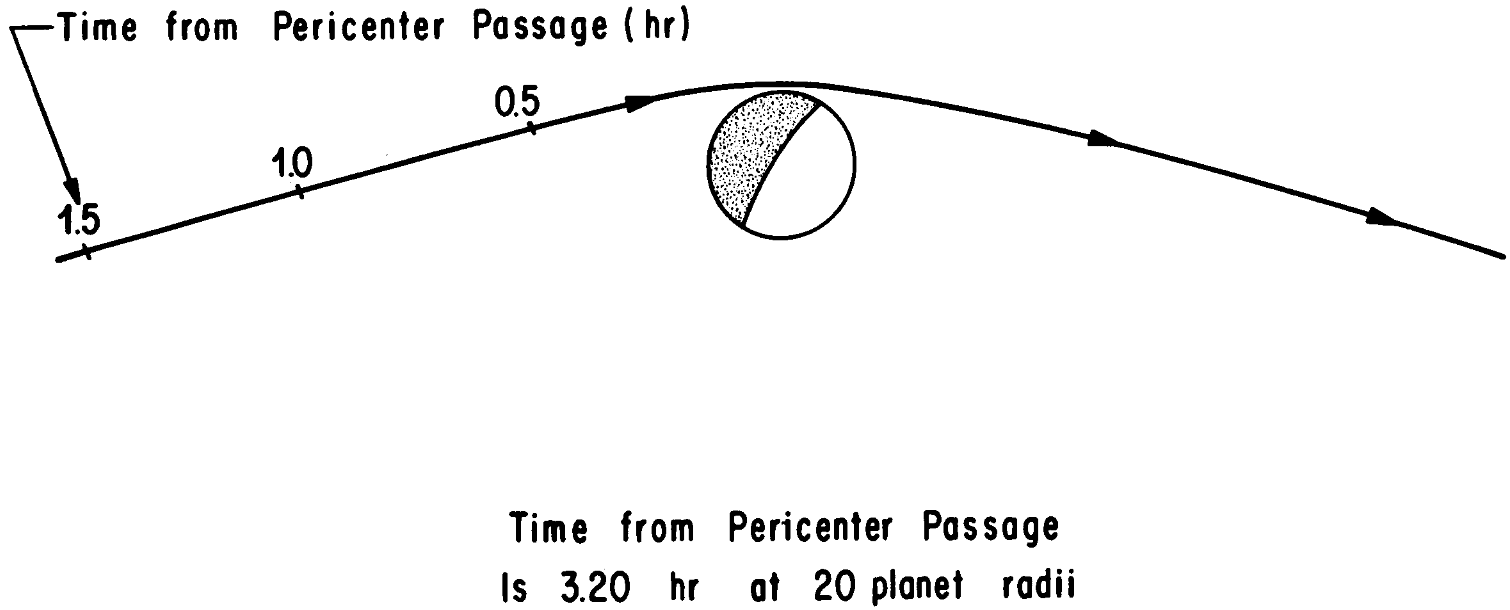


FIG. 39. 1978 FREE-RETURN DUAL PLANET FLYBY HYPERBOLIC TRAJECTORY PROFILE RELATIVE TO MARS AT MARS PASSAGE

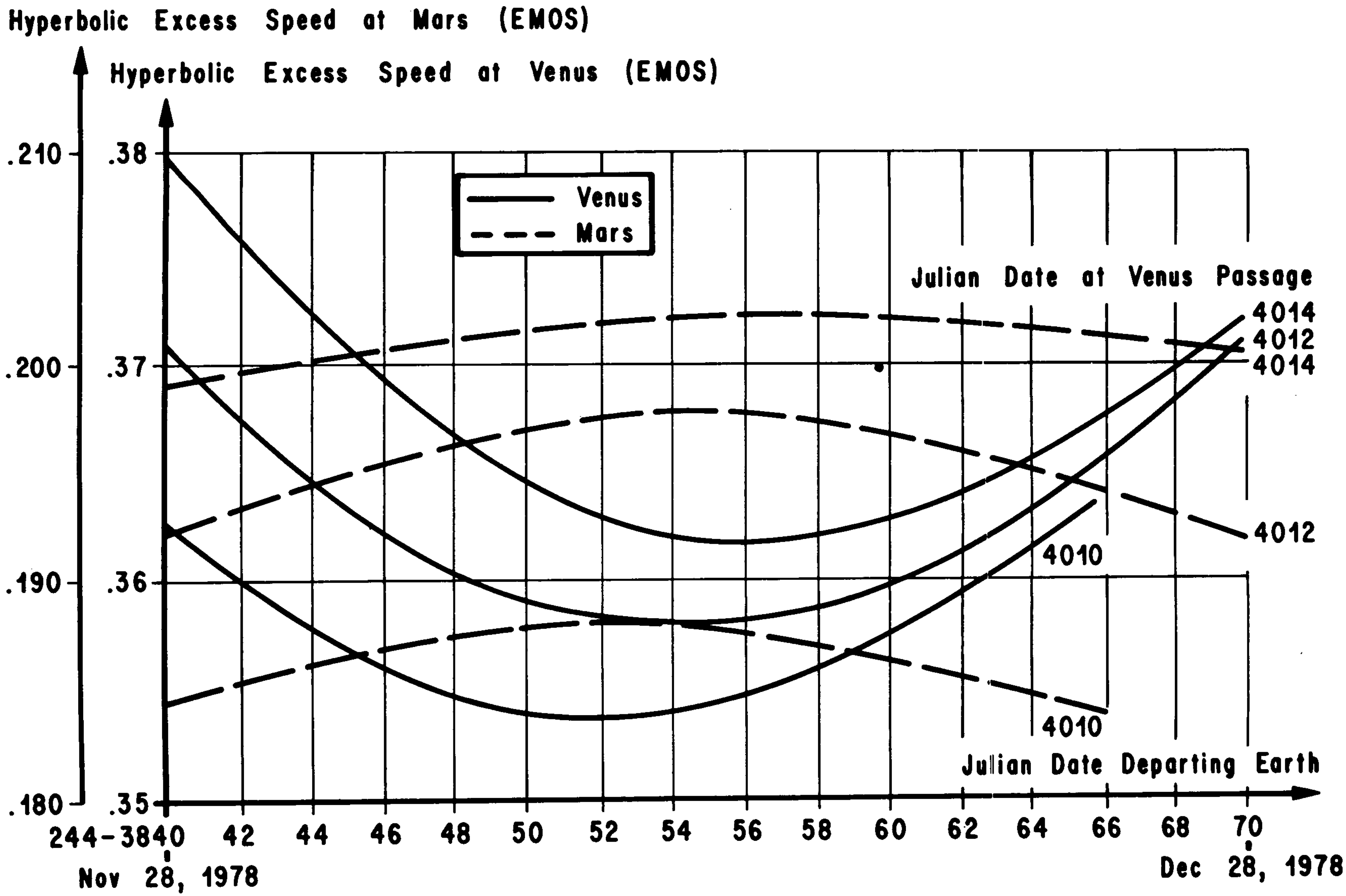


FIG. 40. 1978 FREE-RETURN DUAL PLANET FLYBY

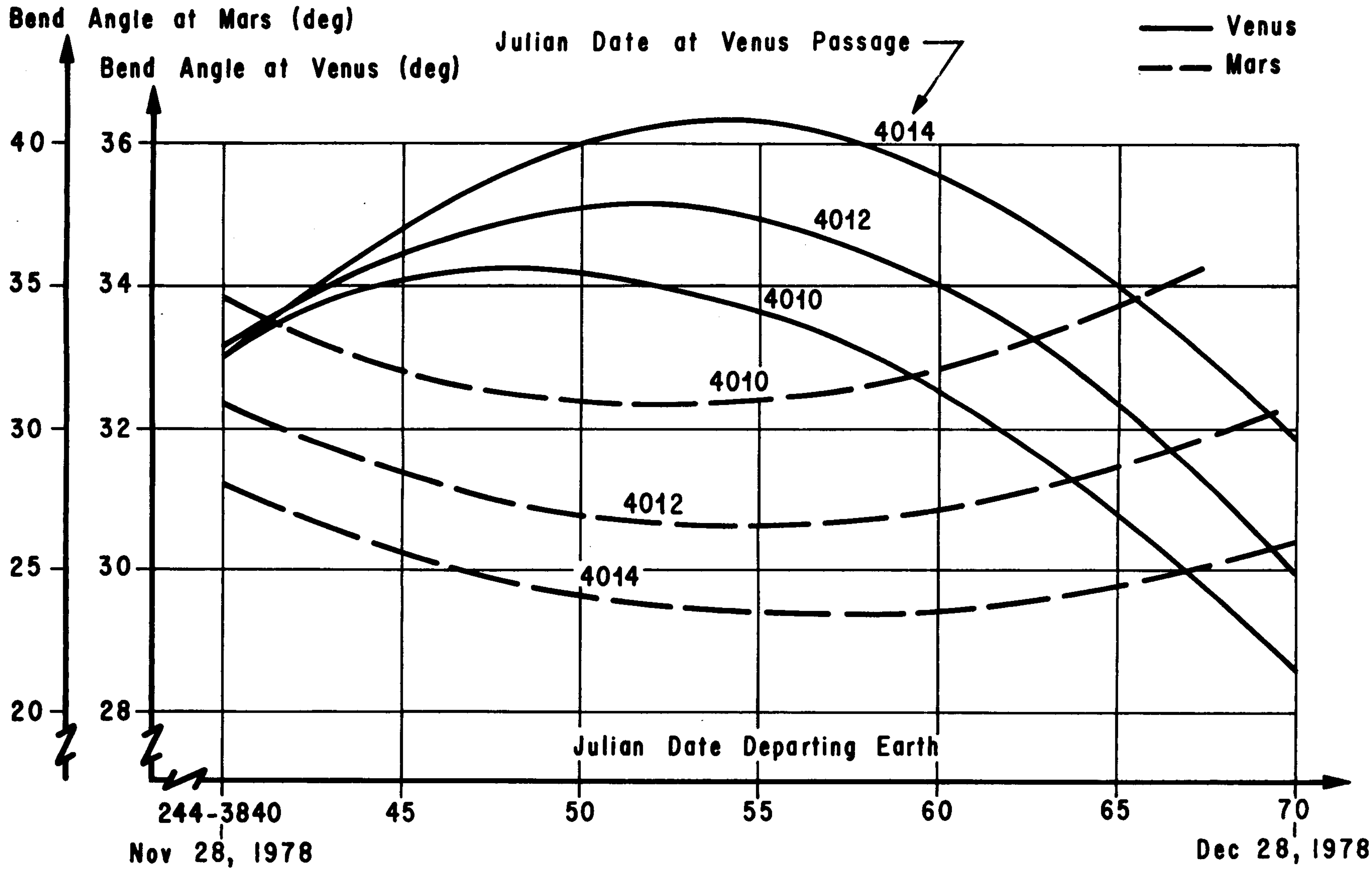


FIG. 41. 1978 FREE-RETURN DUAL PLANET FLYBY

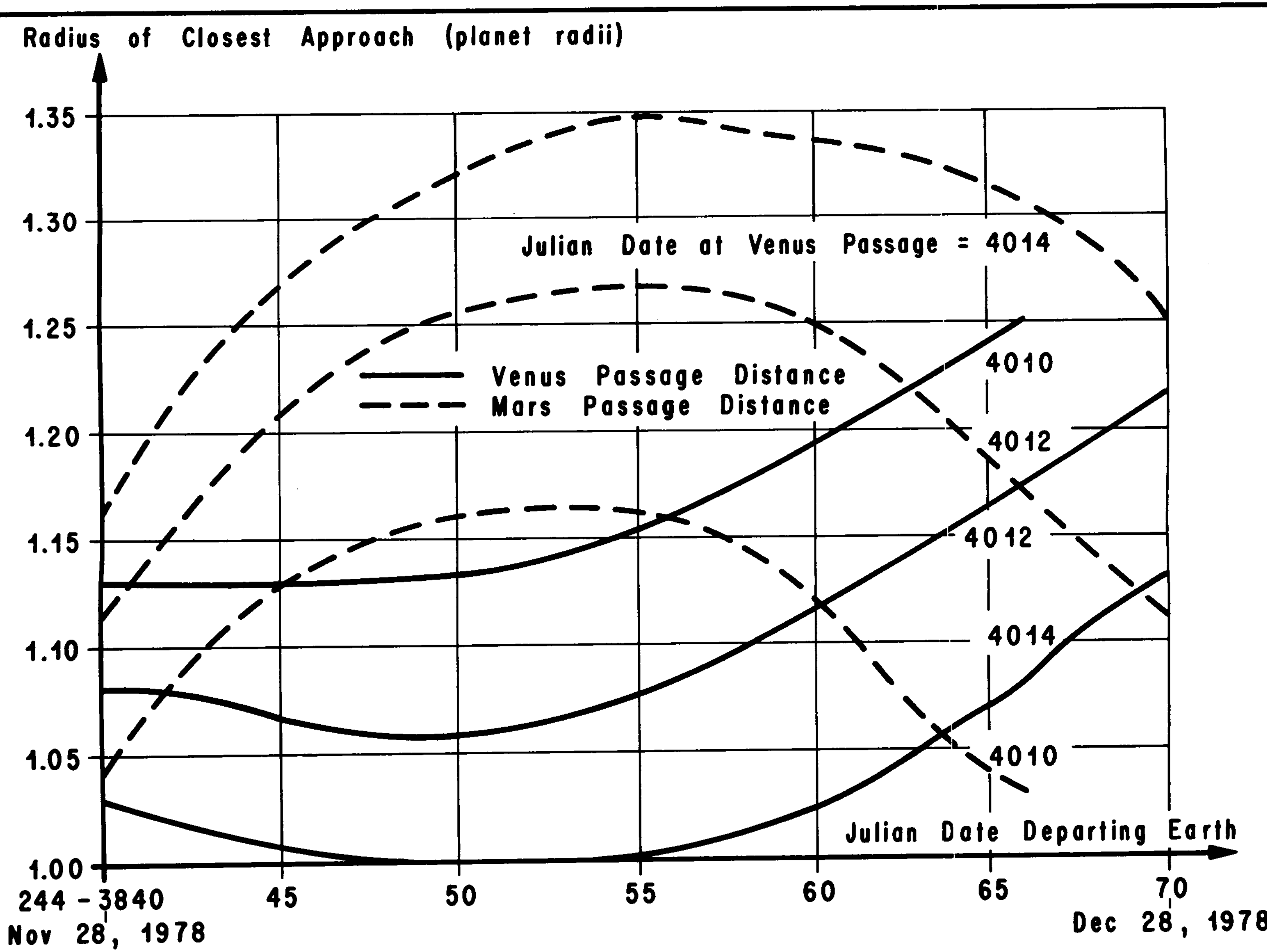


FIG. 42. 1978 FREE-RETURN DUAL PLANET FLYBY

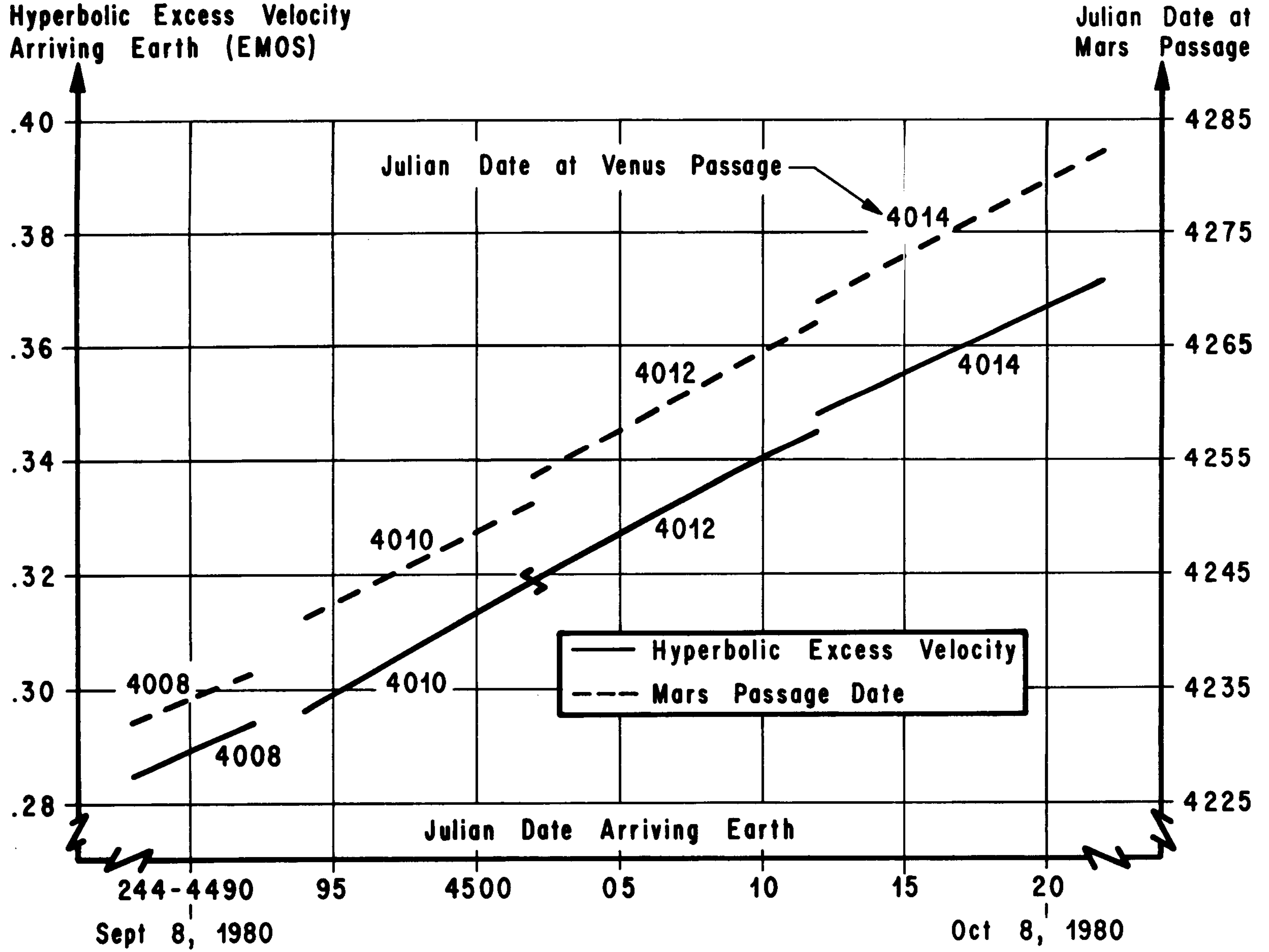


FIG. 43. 1978 FREE-RETURN DUAL PLANET FLYBY

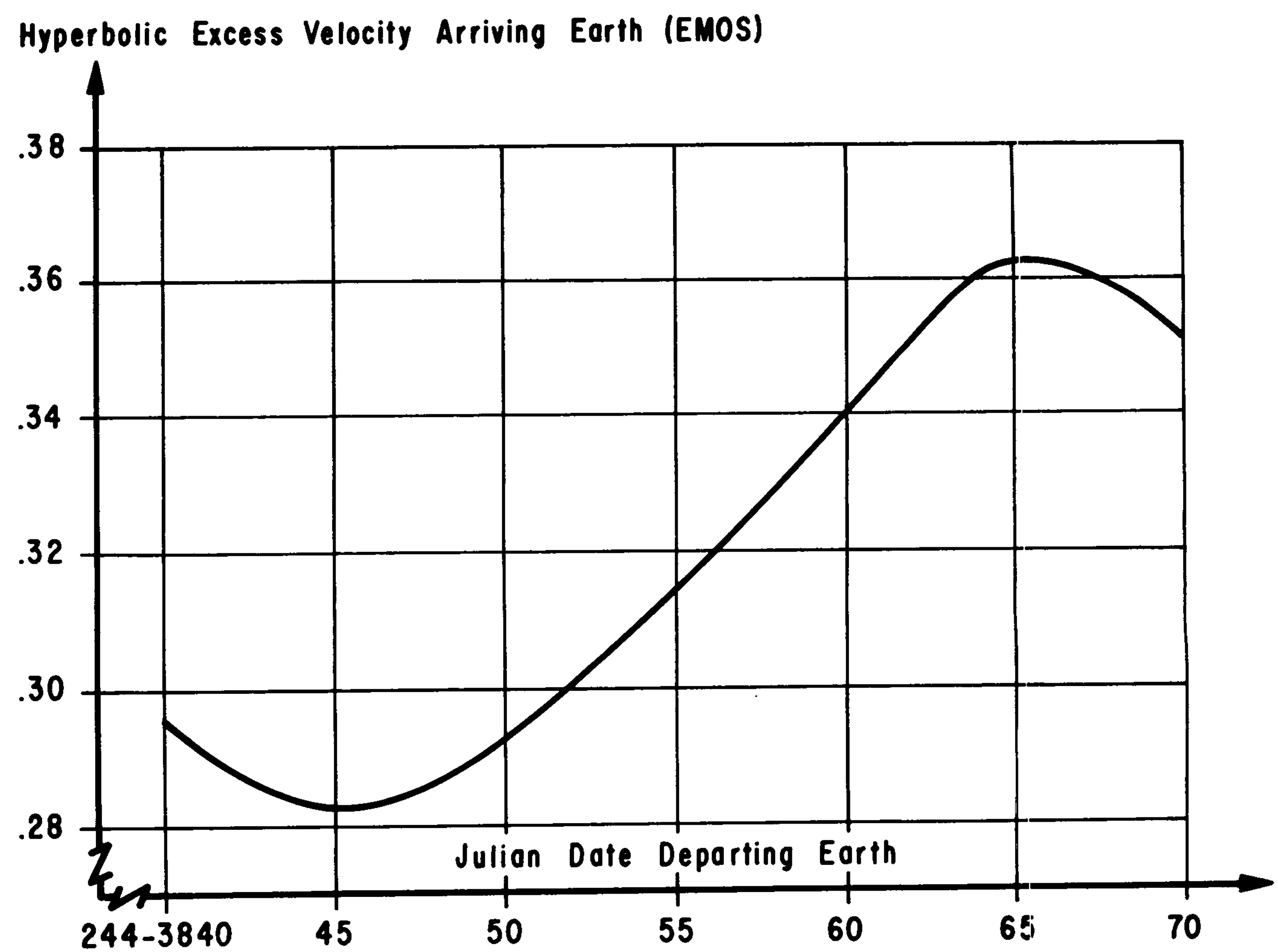


FIG. 44. HYPERBOLIC EXCESS VELOCITY ARRIVING EARTH CORRESPONDING TO THE MINIMUM HYPERBOLIC EXCESS VELOCITY ENVELOPE DEPARTING EARTH 1978 FREE-RETURN DUAL PLANET FLYBY

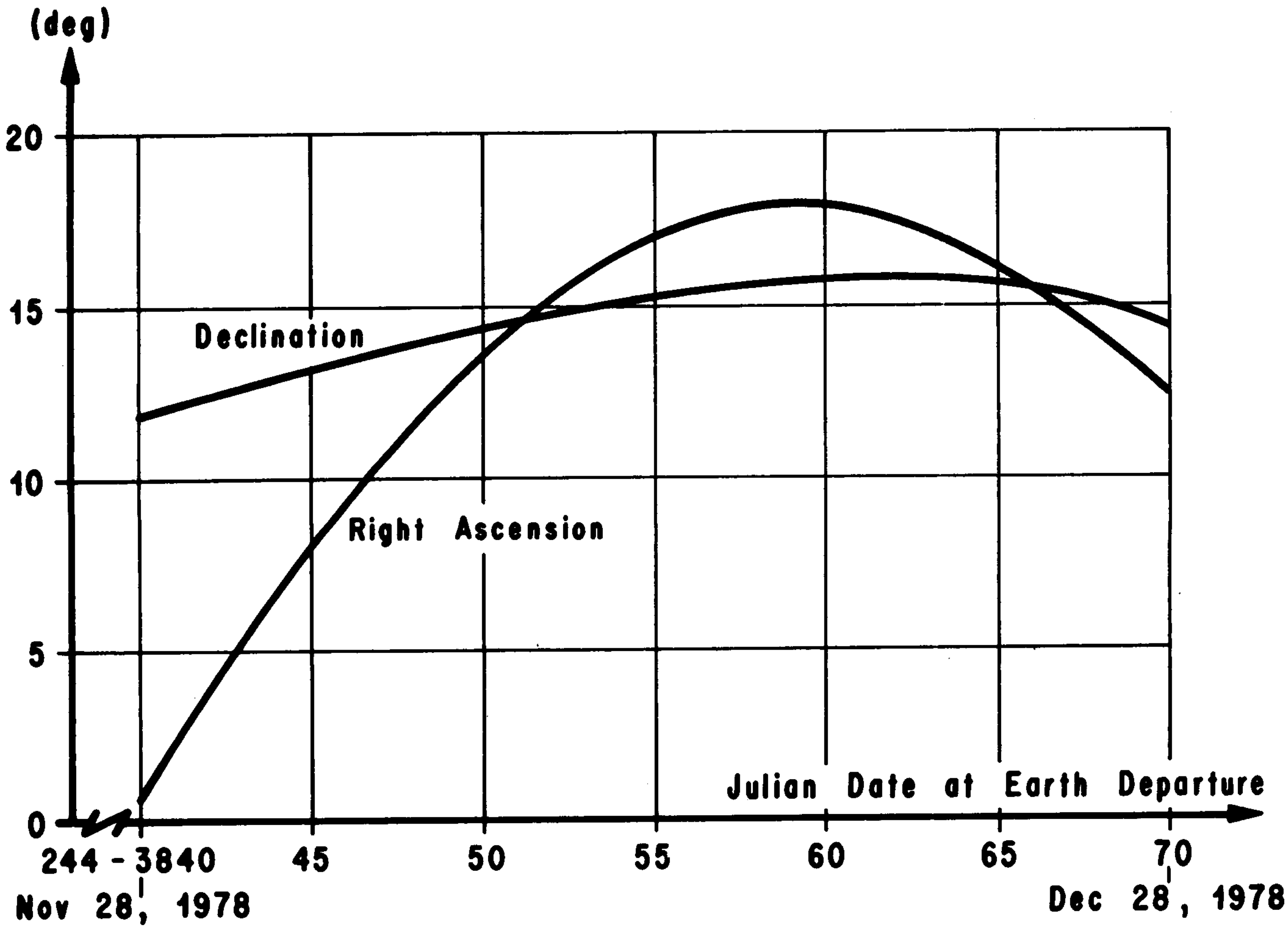


FIG. 45. 1978 FREE-RETURN DUAL PLANET FLYBY DECLINATION AND RIGHT ASCENSION OF HYPERBOLIC EXCESS VELOCITY AT EARTH ARRIVAL CORRESPONDING TO MINIMUM HYPERBOLIC EXCESS VELOCITY ENVELOPE DEPARTING EARTH

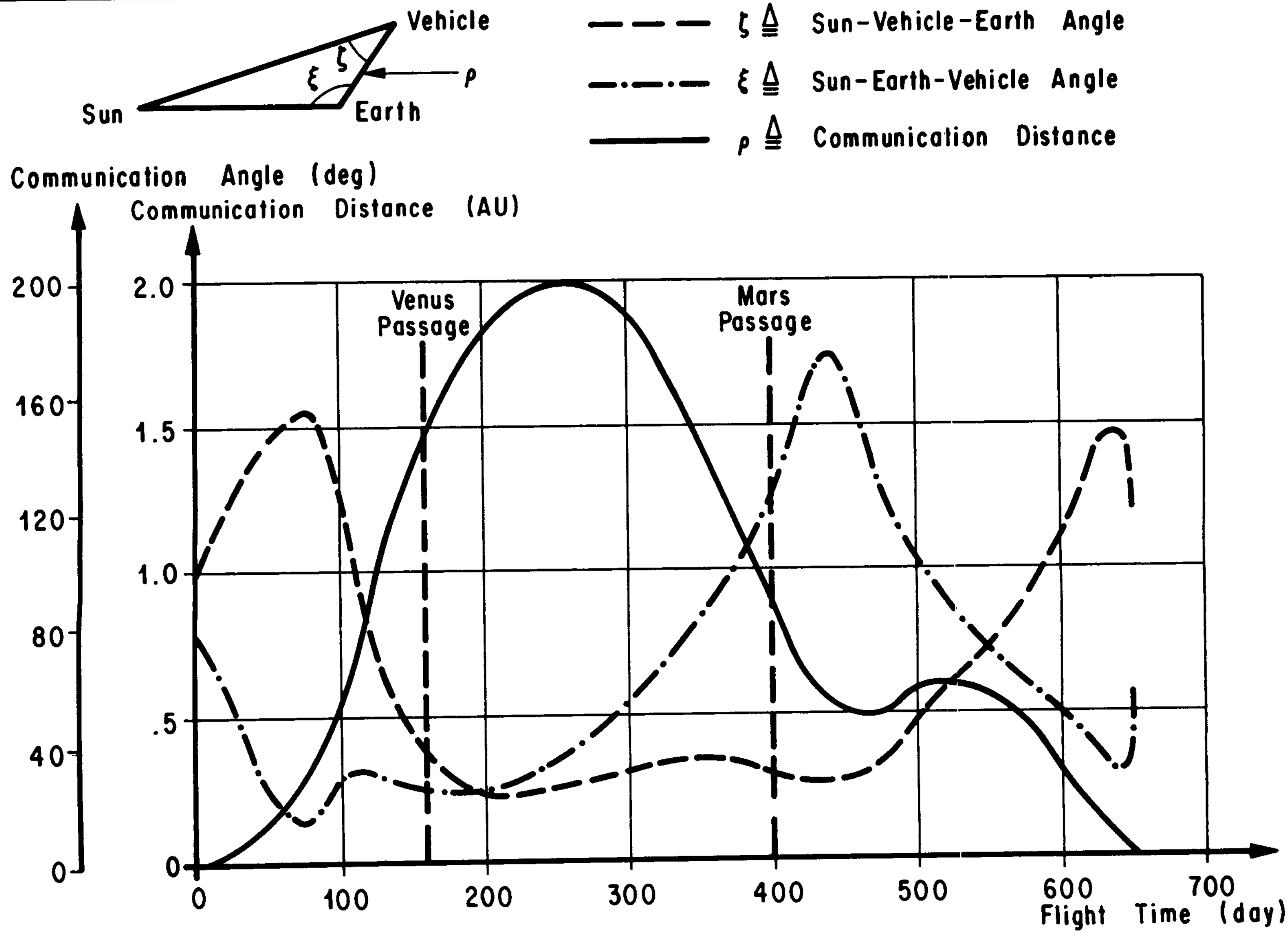


FIG. 46. 1978 FREE-RETURN DUAL PLANET FLYBY COMMUNICATION DISTANCE AND ANGLES FOR EARTH

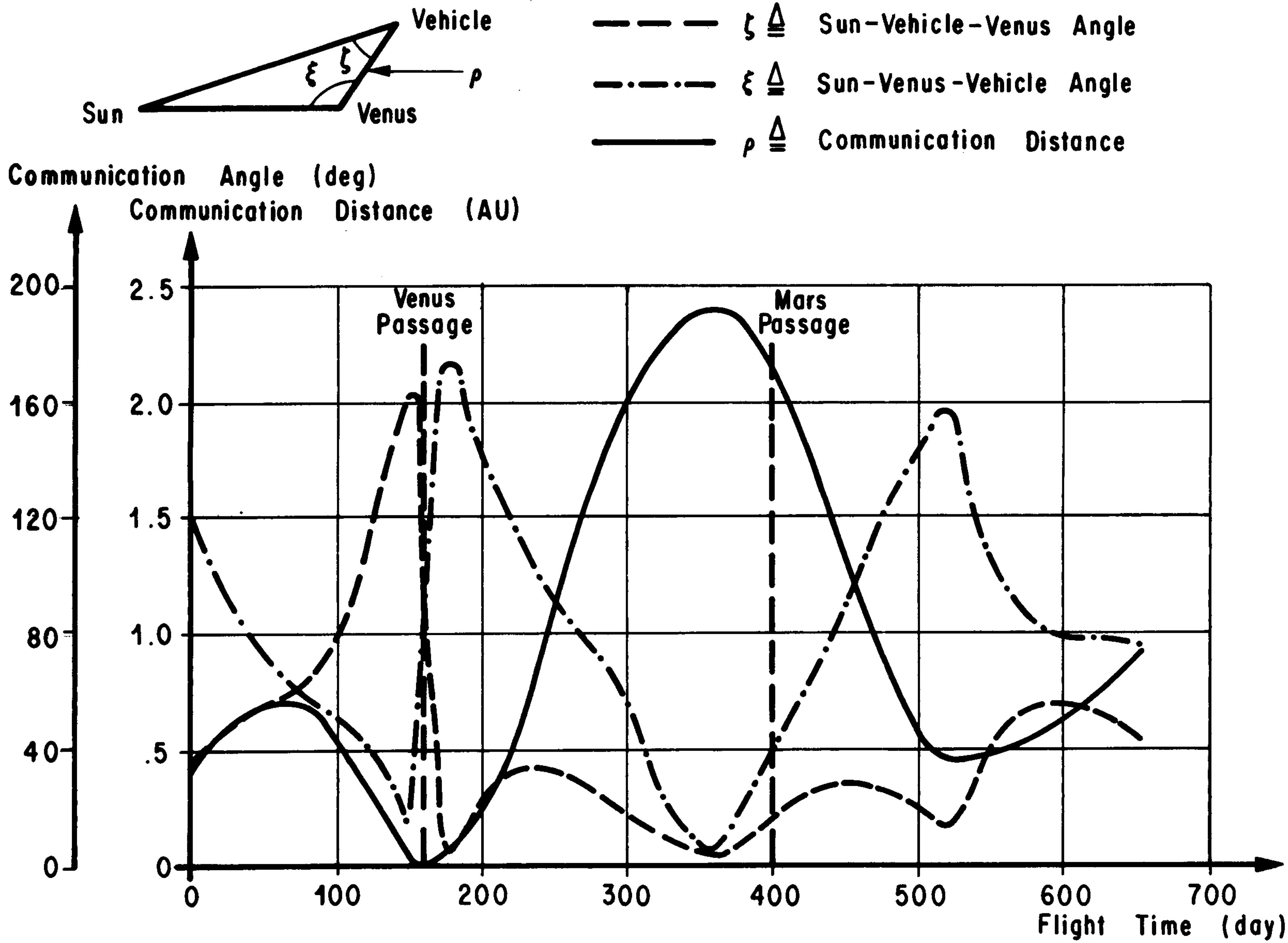


FIG. 47. 1978 FREE-RETURN DUAL PLANET FLYBY COMMUNICATION DISTANCE AND ANGLES FOR VENUS

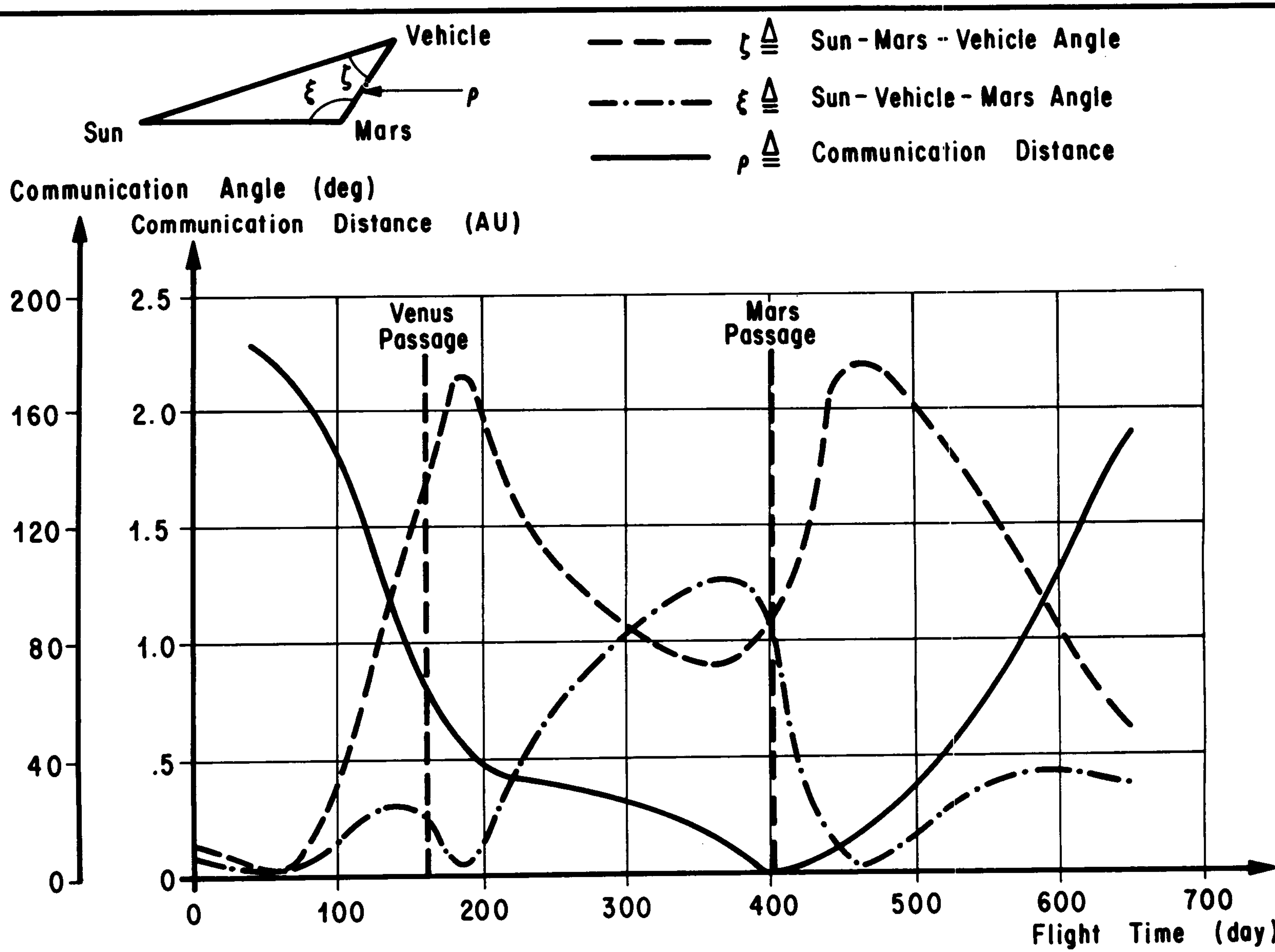


FIG. 48. 1978 FREE-RETURN DUAL PLANET FLYBY COMMUNICATION DISTANCE AND ANGLES FOR MARS

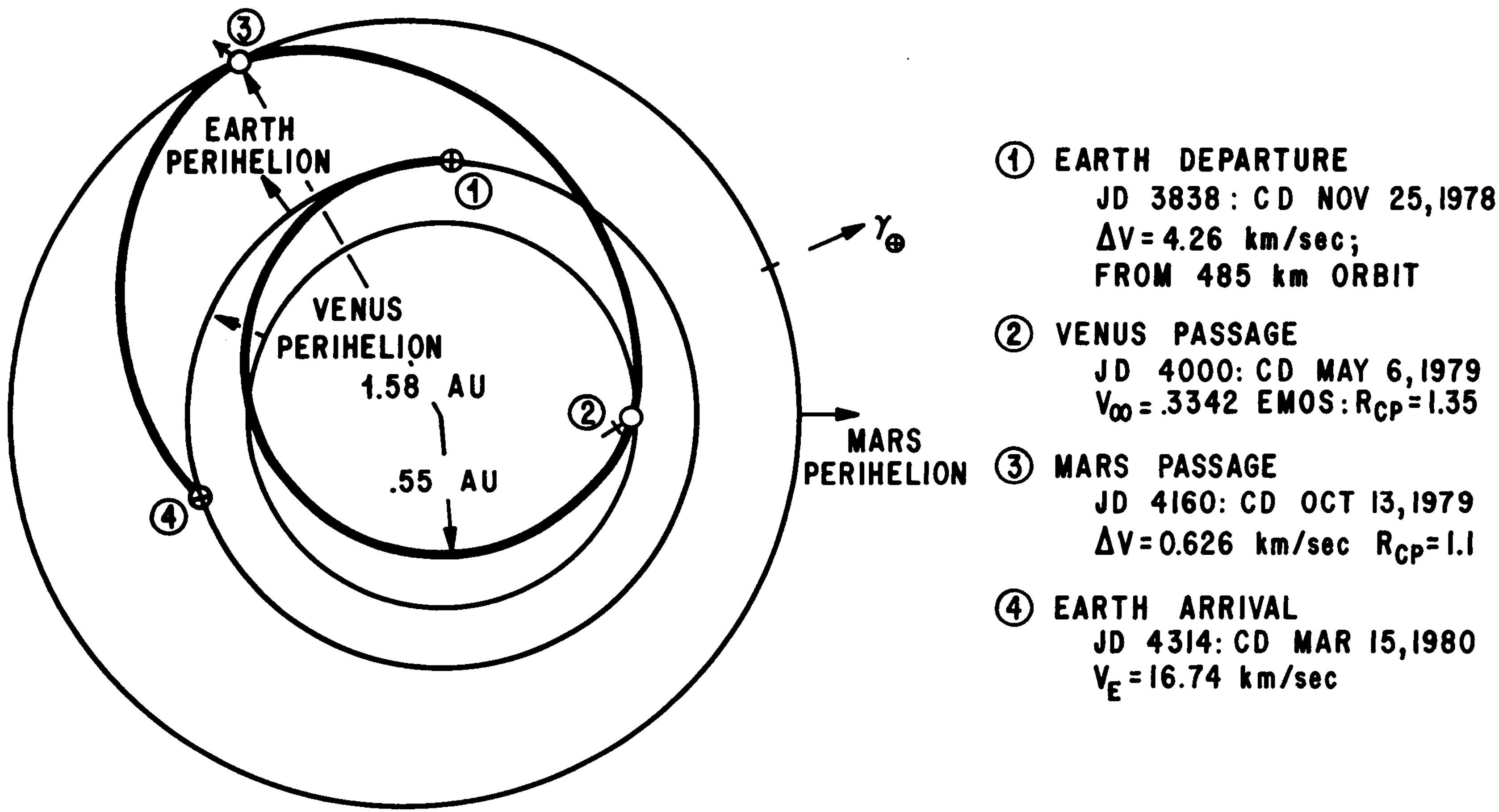


FIG. 49. 1978 DUAL PLANET POWERED FLYBY TYPICAL TRAJECTORY PROFILE

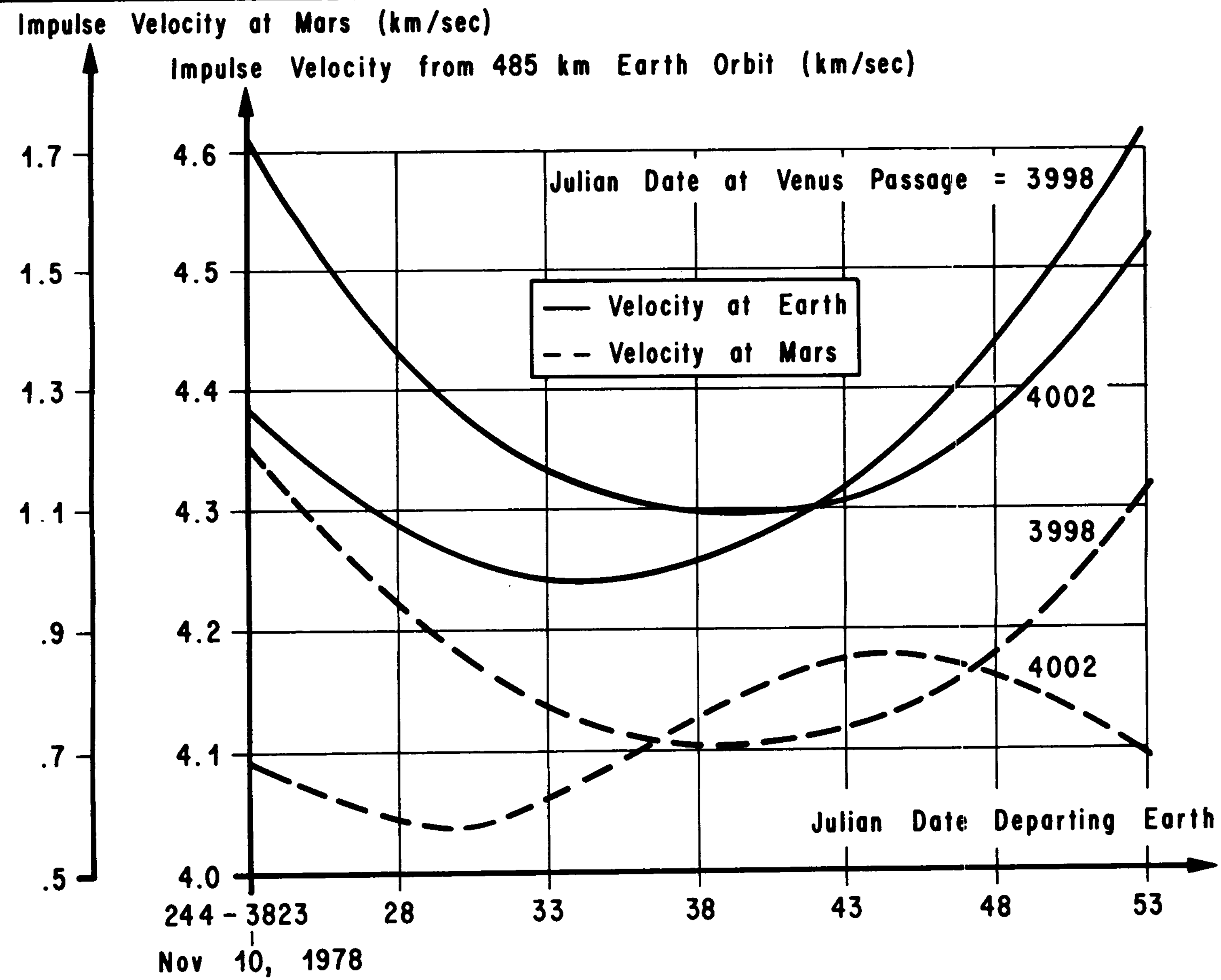


FIG. 50. 1978 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

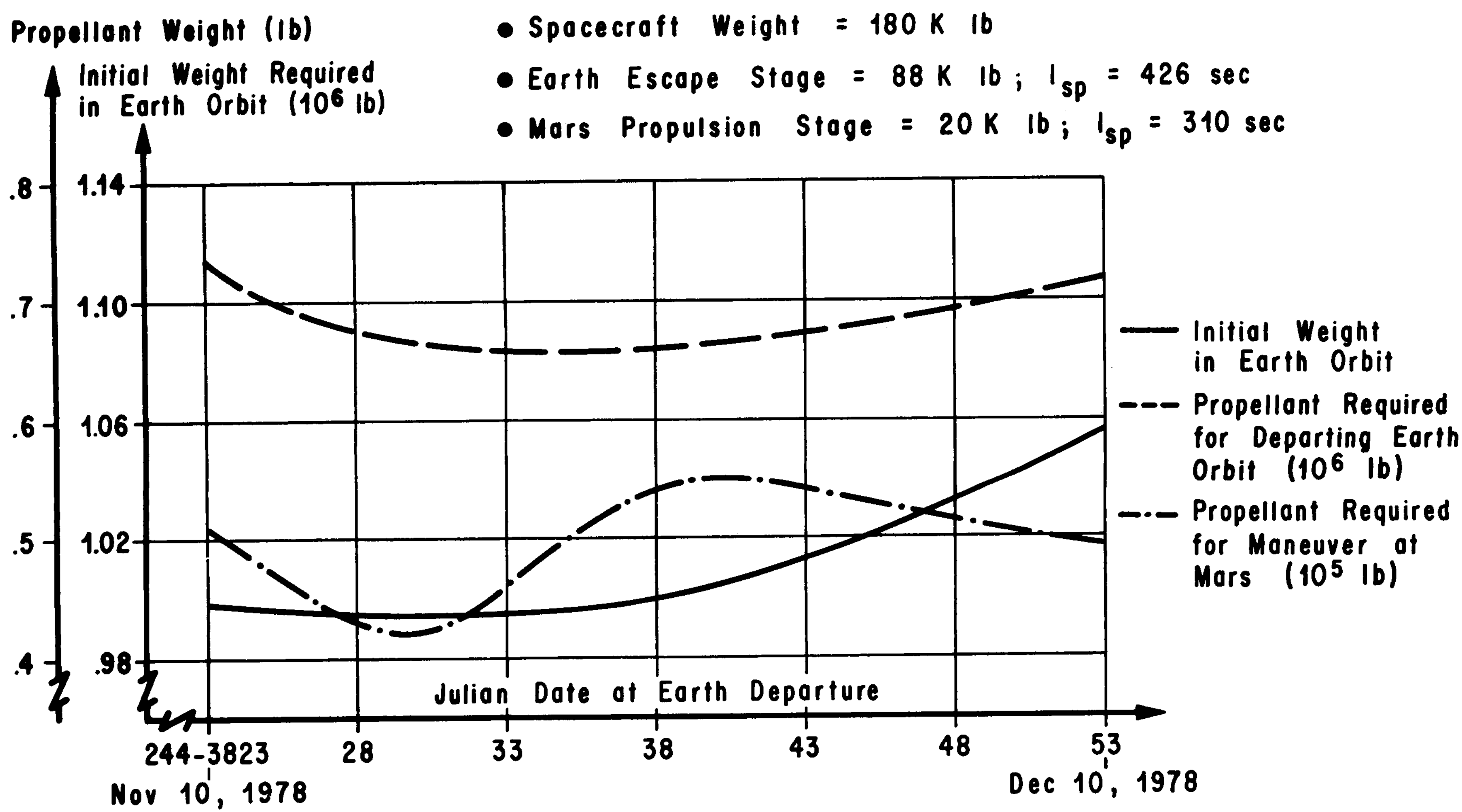


FIG. 51. 1978 DUAL PLANET FLYBY

POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

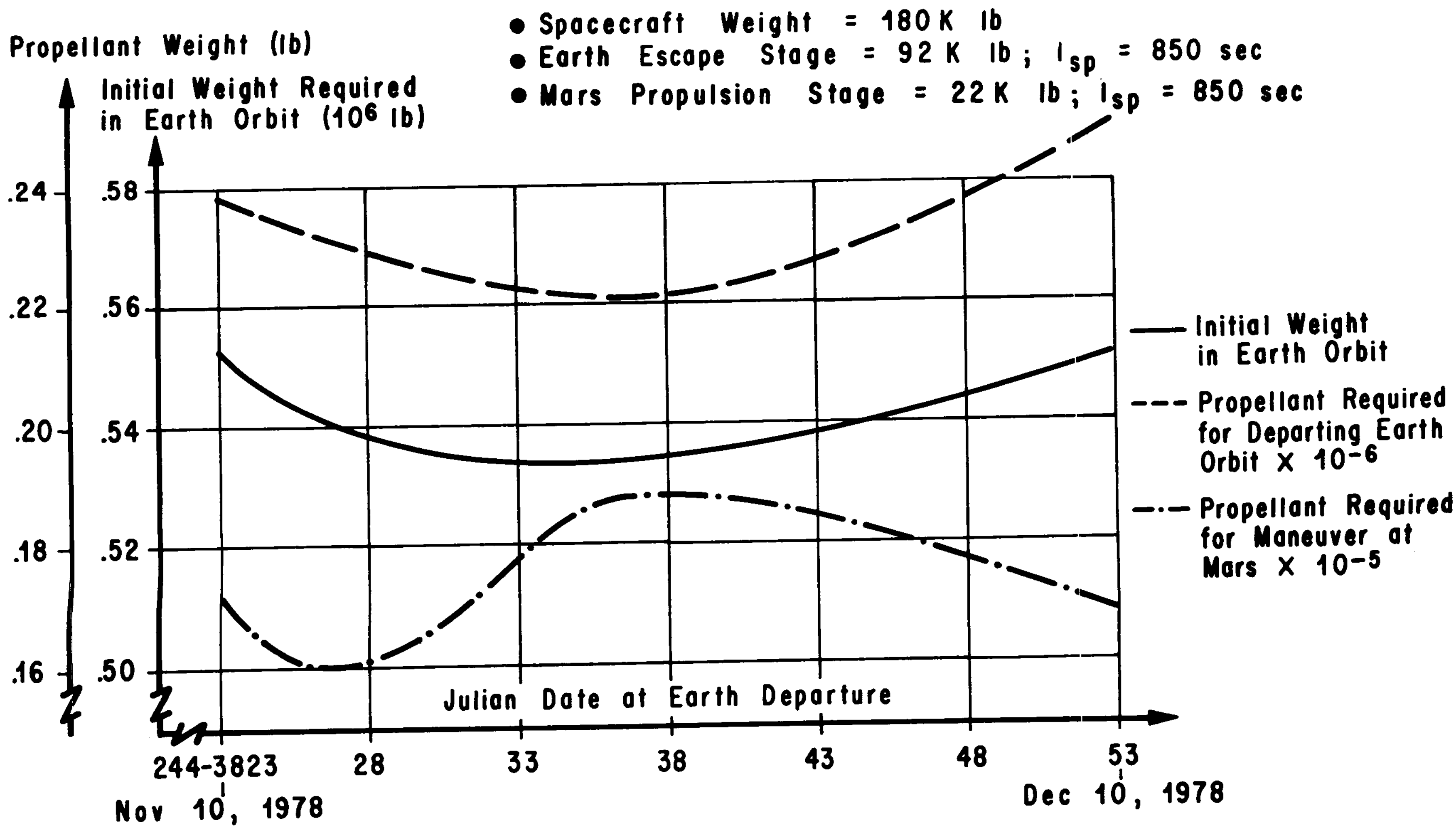


FIG. 52. 1978 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

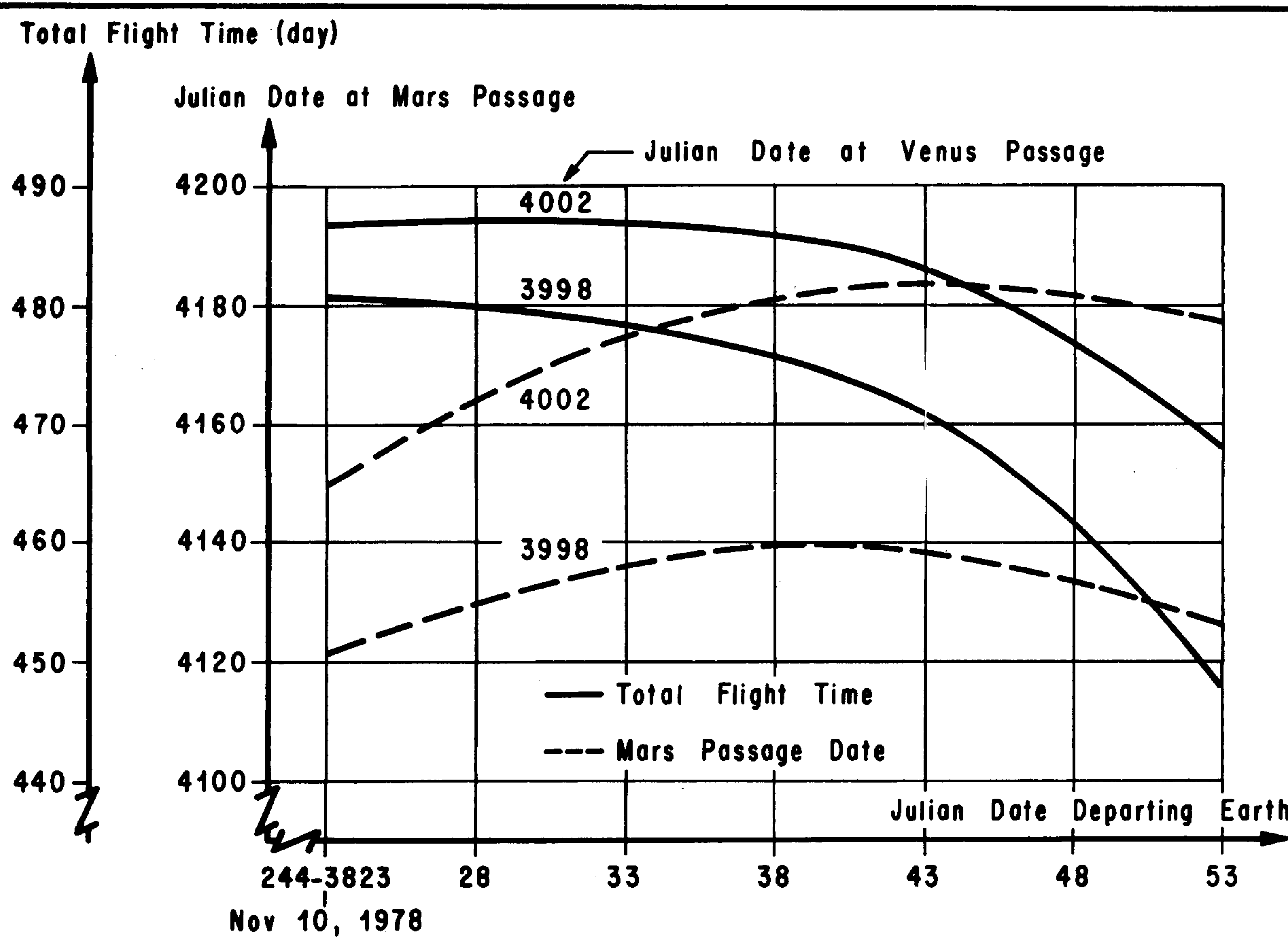
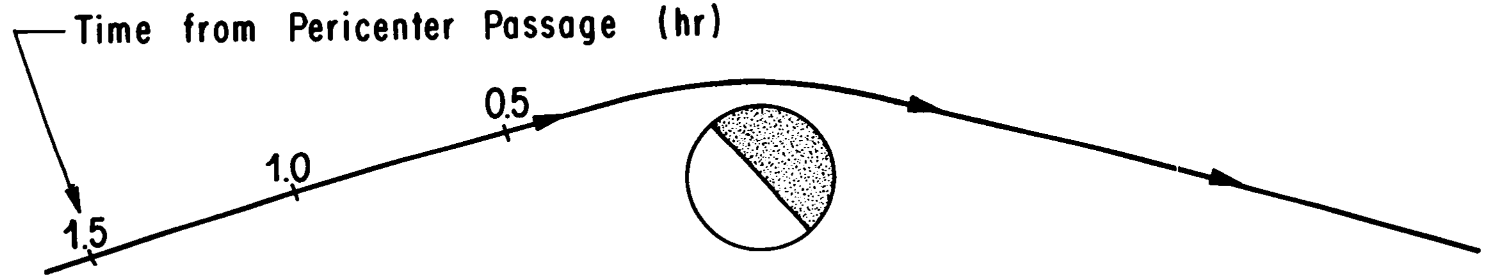


FIG. 53. 1978 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS – FREE FLIGHT AT VENUS PASSAGE



Time from Pericenter Passage
Is 3.26 hr at 20 planet radii

Radius of Closest Approach = 1.35 planet radii
Hyperbolic Excess Velocity = 9.954 km/sec
Velocity at Pericenter Passage = 13.319 km/sec

FIG. 54. 1978 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE
HYPERBOLIC TRAJECTORY PROFILE RELATIVE TO VENUS AT VENUS PASSAGE

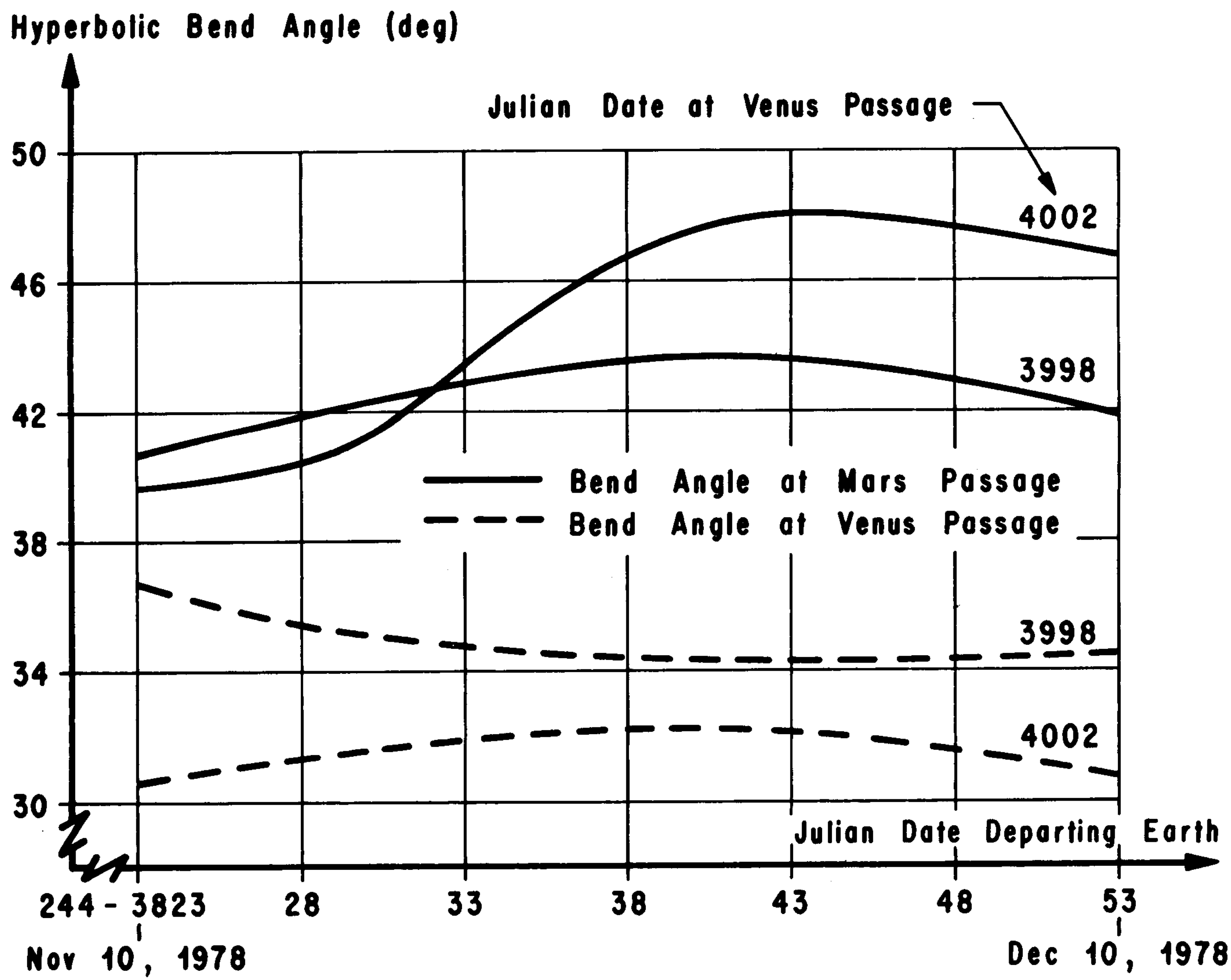


FIG. 55. 1978 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

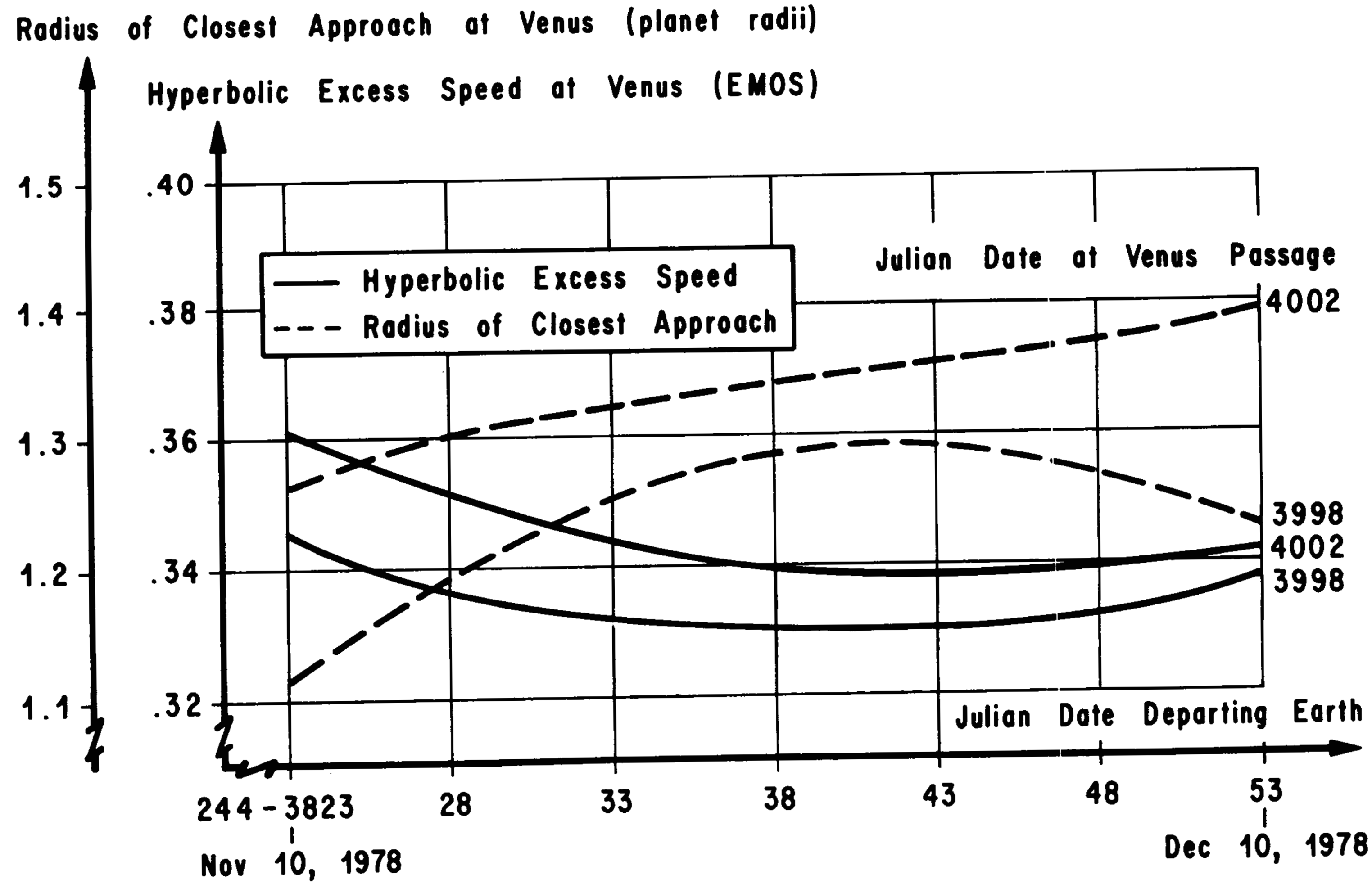


FIG. 56. 1978 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS – FREE FLIGHT AT VENUS PASSAGE

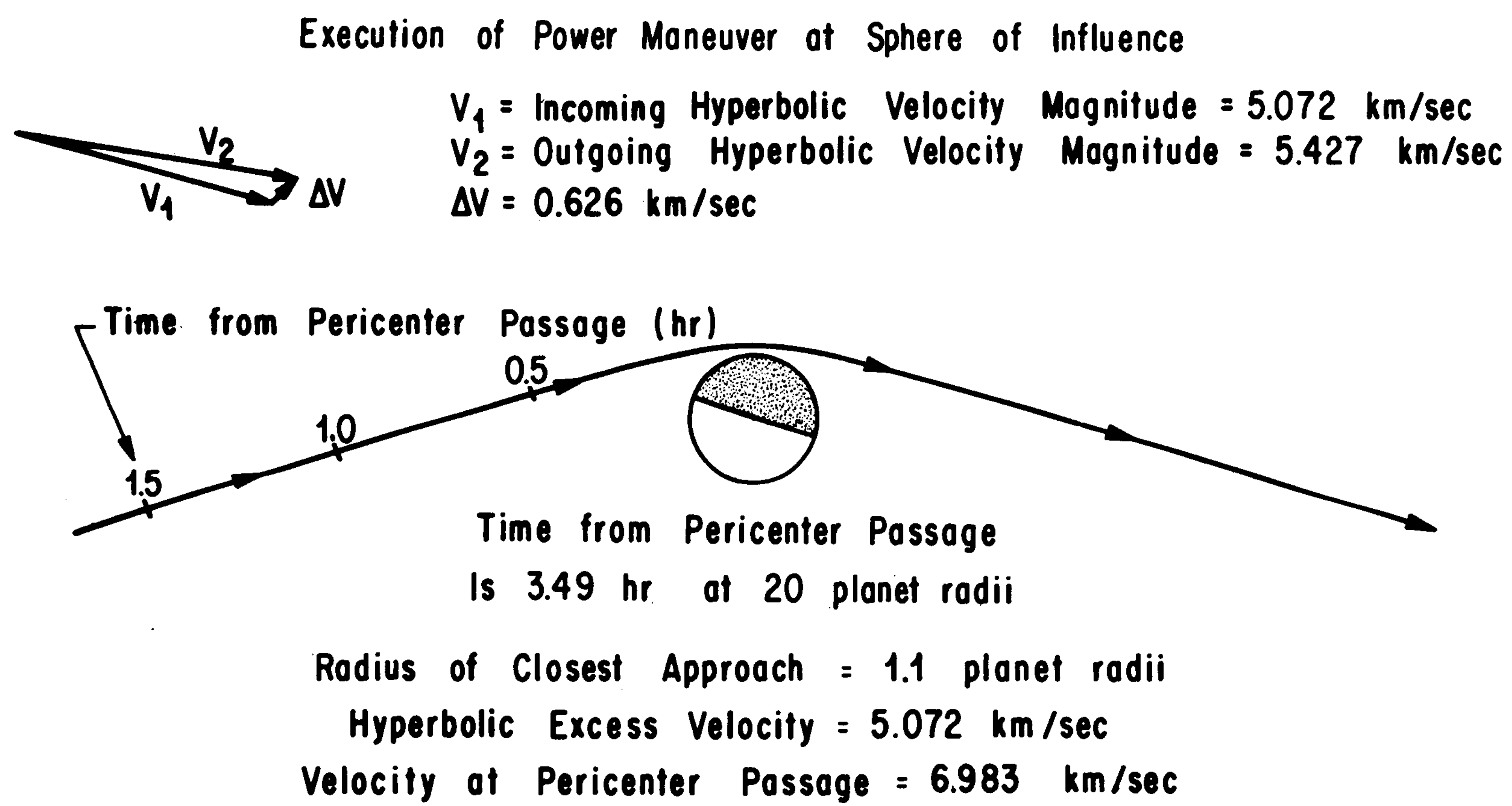


FIG. 57. 1978 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE
HYPERBOLIC TRAJECTORY PROFILE RELATIVE TO MARS AT VENUS PASSAGE

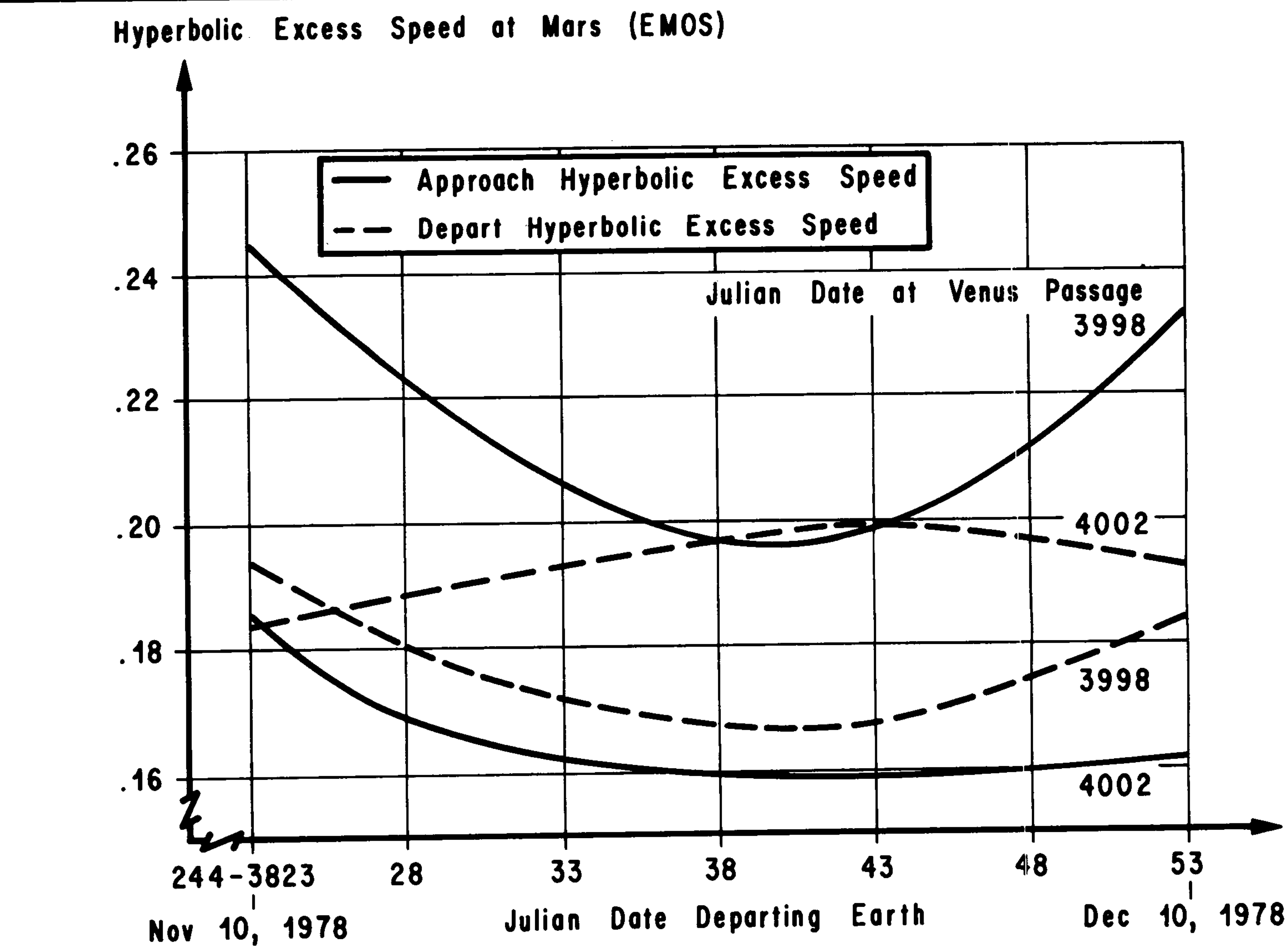


FIG. 58. 1978 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

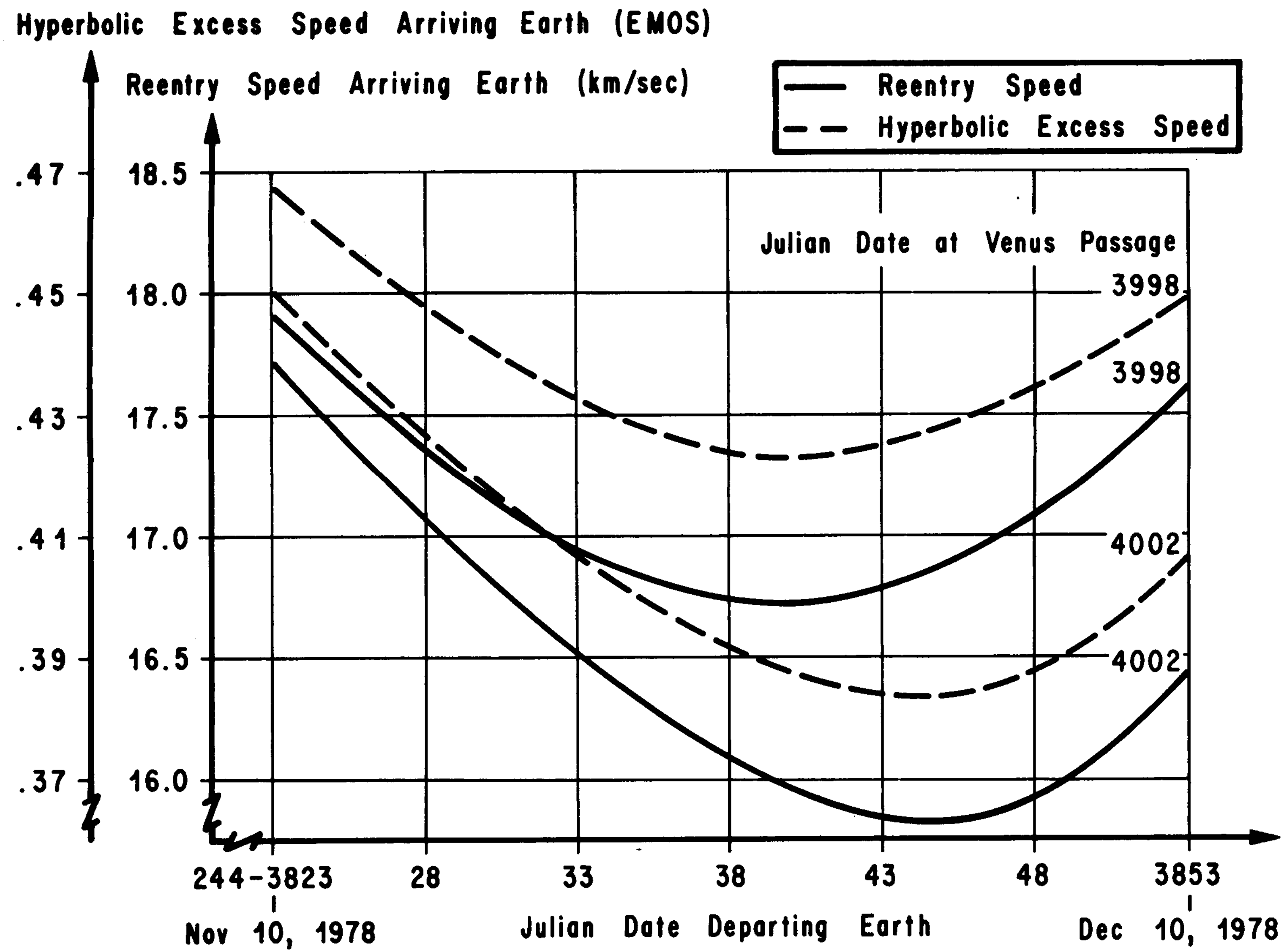


FIG. 59. 1978 DUAL PLANET FLYBY
POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

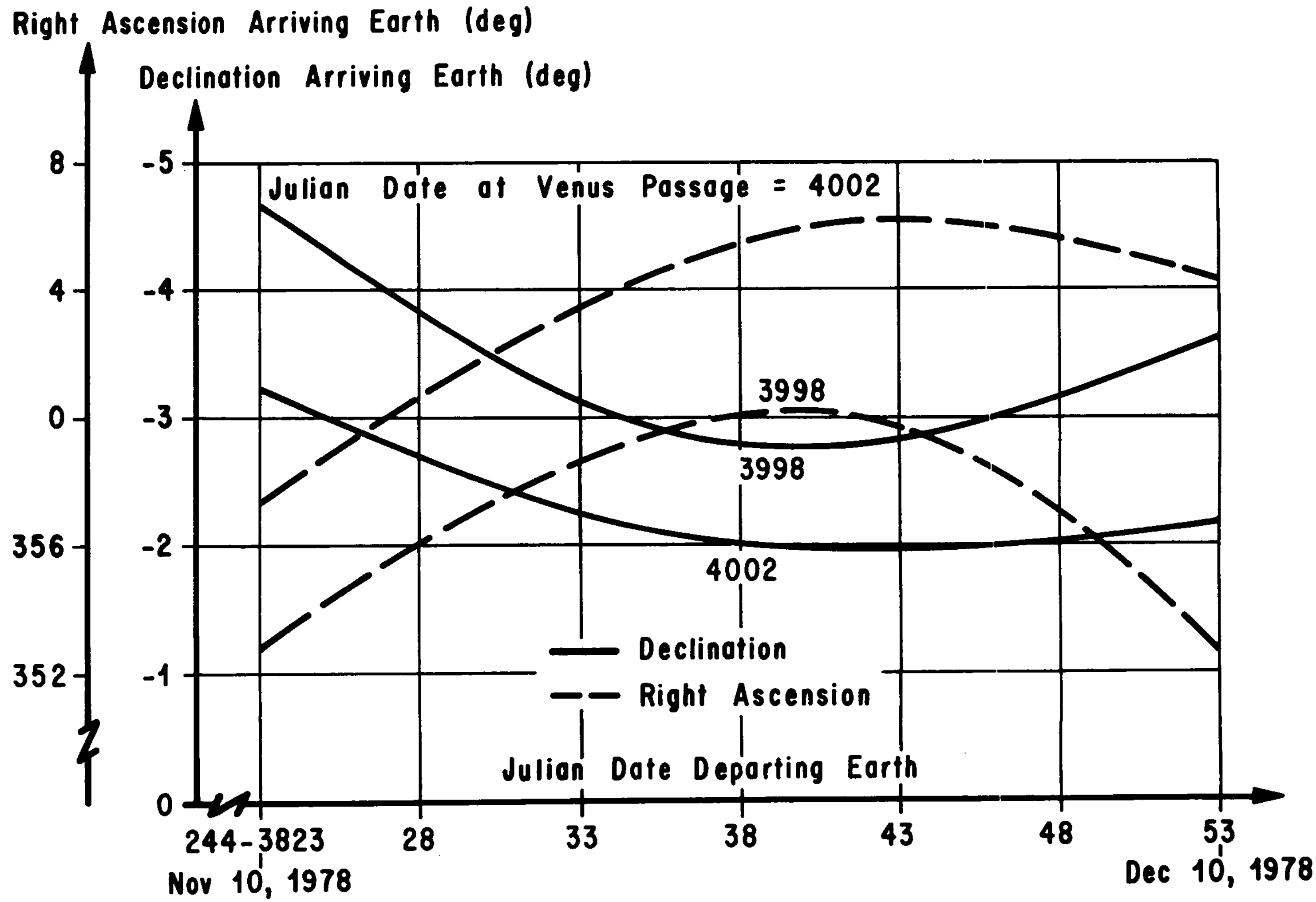


FIG. 60. 1978 DUAL PLANET FLYBY

POWERED MANEUVER AT MARS — FREE FLIGHT AT VENUS PASSAGE

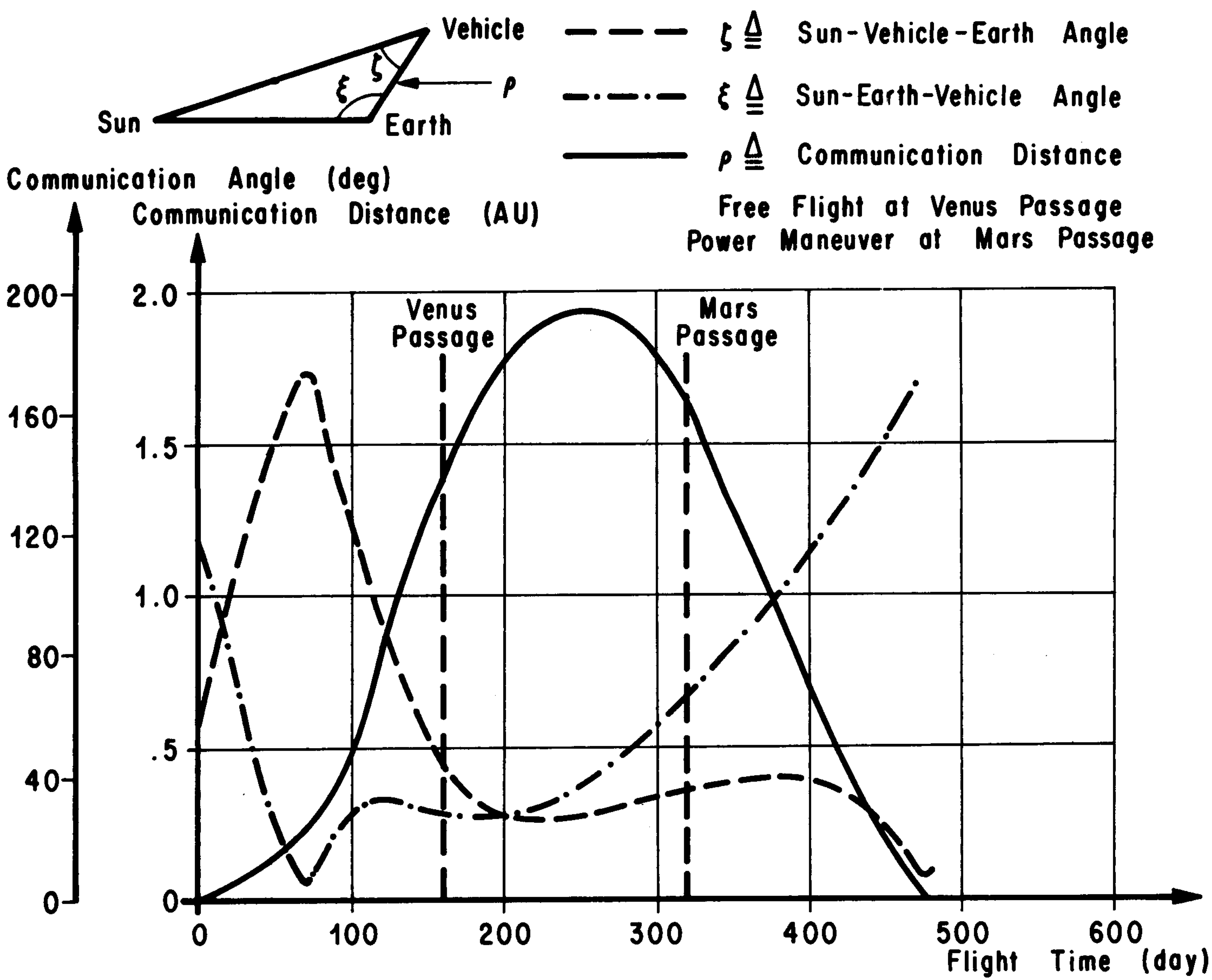


FIG. 61. 1978 DUAL PLANET FLYBY COMMUNICATION DISTANCE AND ANGLES FOR EARTH

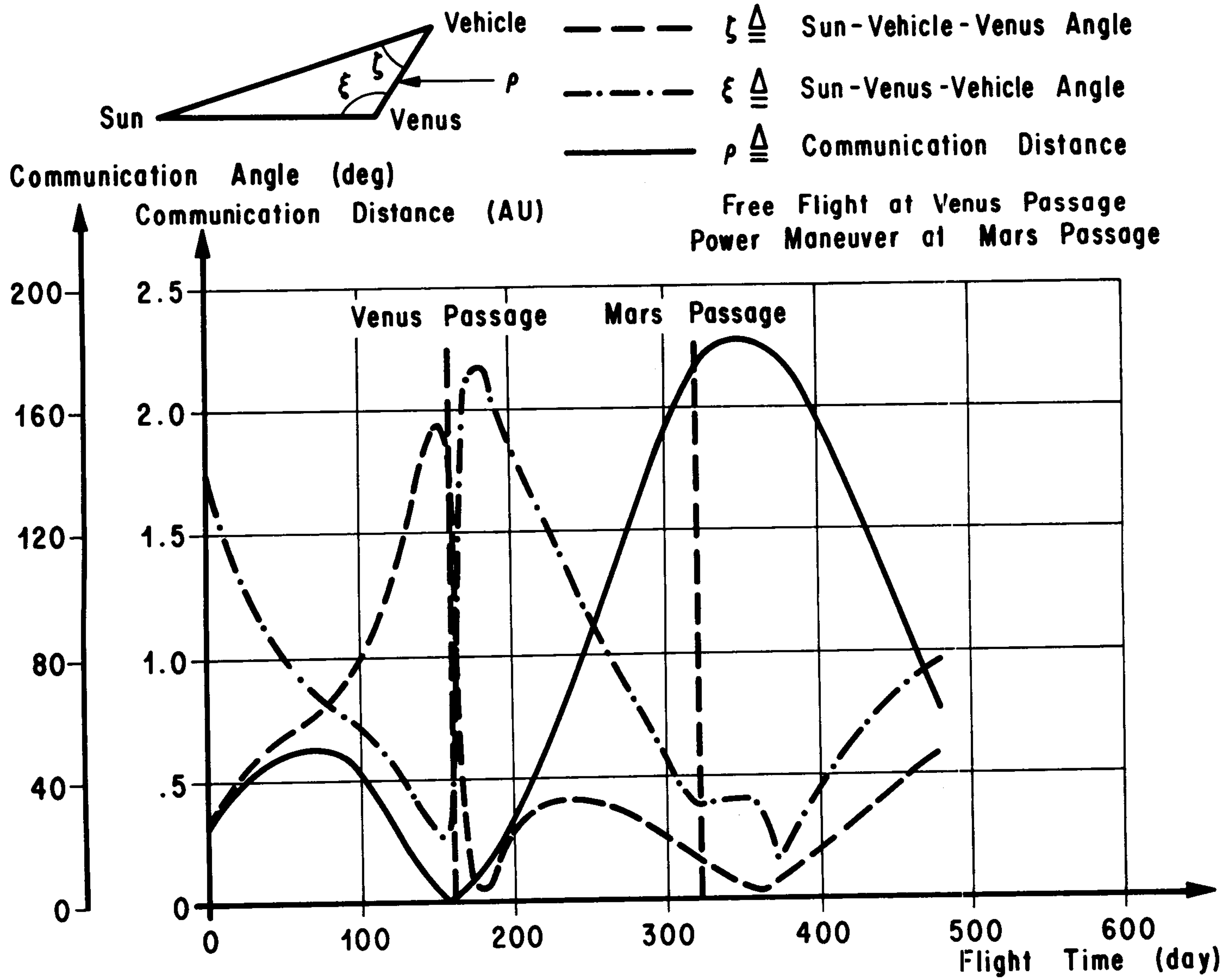


FIG. 62. 1978 DUAL PLANET FLYBY COMMUNICATION DISTANCE AND ANGLES FOR VENUS

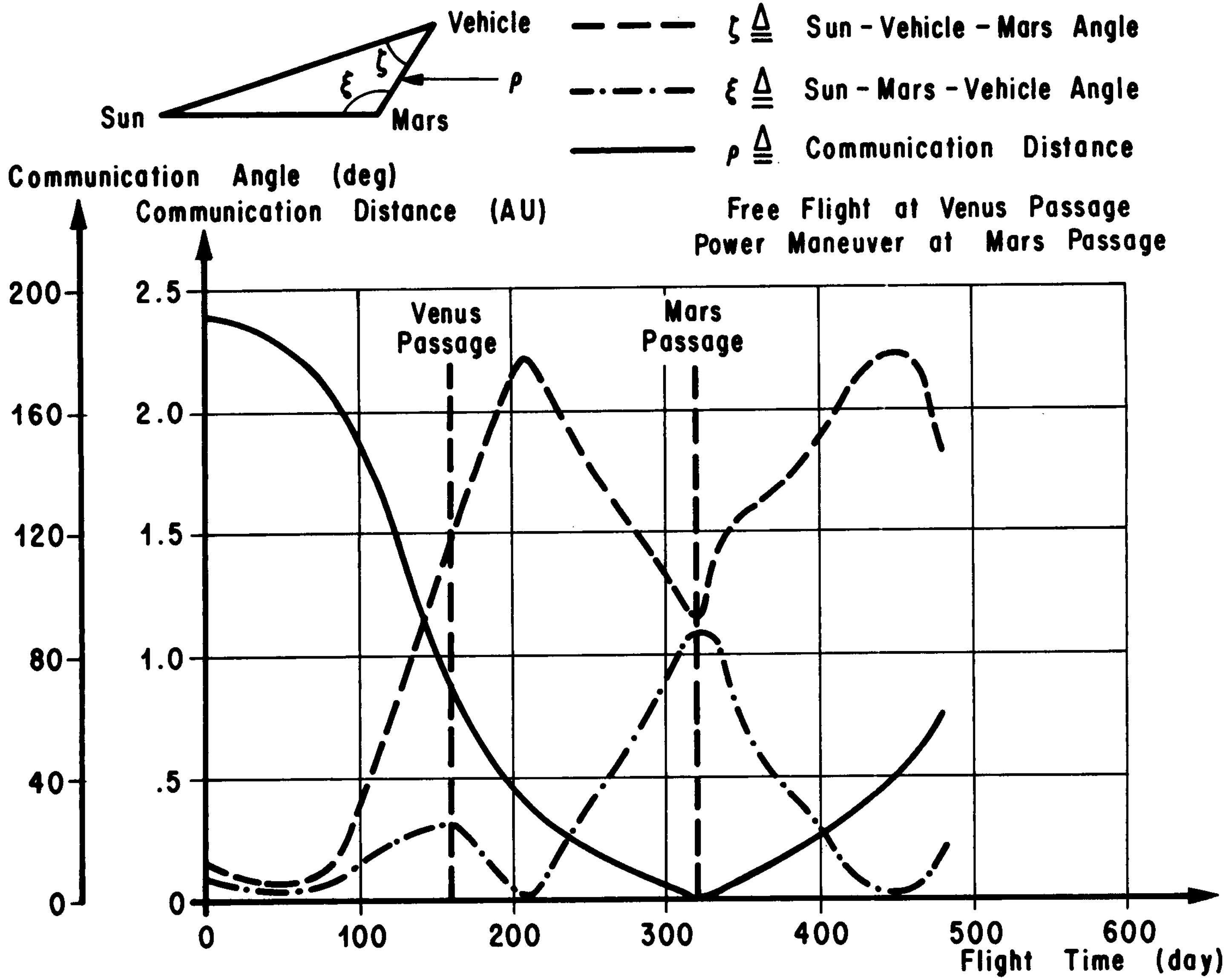


FIG. 63. 1978 DUAL PLANET FLYBY COMMUNICATION DISTANCE AND ANGLES FOR MARS

		EARTH DEPART DATA		VENUS PASSAGE DATA				MARS PASSAGE DATA				EARTH RETURN DATA	
Opportunity Year and Mission Type	Mission Duration (Max. Day)	JD 244-	Max ΔV of Launch Window (km/sec)	JD 244-	Rcp (Planet Radii)	Max. Velocity of Passage Window (km/sec)	Time Within Sphere of Influence (hrs)	JD 244-	Rcp (Planet Radii)	Max. Velocity of Passage Window (km/sec)	Time Within Sphere of Influence (hrs)	JD 244-	Max. Return Velocity (km/sec)
1975 Venus	368	2556 2584	3.76	2686 2689	1.1	10.84	60	-	-	-	-	2924 2952	13.42
1975 Dual Planet Powered Flyby	640	2575 2605	6.16	3046 3050	1.3	15.40	25	2800 2850	1.1	7.20	59	3165 3210	14.50
1975 Mars	683	2662 2690	4.80	-	-	-	-	2802 2814	1.25	9.63	37	3344 3352	14.23
1977 Venus	388	3140 3170	3.82	3270 3276	1.1	11.00	58	-	-	-	-	3522 3532	13.50
1977 Triple Planet Power at Venus 1st Passage	689	3185 3205	5.04	3306 3316	1.1	11.87	48	3474 3506	2.0	6.58	58	3864 3883	13.78
1977 Mars	690	3427 3455	4.70	-	-	-	-	3584 3592	1.25	10.21	34	4120 4126	13.84
1978 Venus	385	3722 3750	3.66	3852 3857	1.1	11.43	55	-	-	-	-	4092 4111	13.72
1978 Dual Planet Power Flyby	485	3823 3853	4.56	3998 4002	1.4	13.30	33	4124 4182	1.1	8.40	44	4306 4326	17.80
1978 Dual Planet Free Return Flyby	654	3840 3870	4.84	4008 4014	1.05	14.94	29	4225 4280	1.2	7.7	55	4495 4525	15.42
1979 Mars	692	4191 4219	4.63	-	-	-	-	4345 4352	1.25	11.43	30	4883 4887	13.84

FIGURE 64. LOW ENERGY SINGLE AND MULTIPLE PLANET FLYBY MISSION CHARACTERISTICS FOR 1975 TO 1980 TIME PERIOD

OPPORTUNITY YEARS AND MISSION TYPE	1975							
	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN
1975 VENUS								
1975 DUAL PLANET POWERED FLYBY								
1975 MARS								
1977 VENUS								
1977 TRIPLE PLANET POWERED FLYBY AT VENUS 1st PASSAGE								
1977 MARS								
1978 VENUS								
1978 DUAL PLANET POWERED FLYBY								
1978 DUAL PLANET FREE RETURN FLYBY								
1979 MARS								

75-1

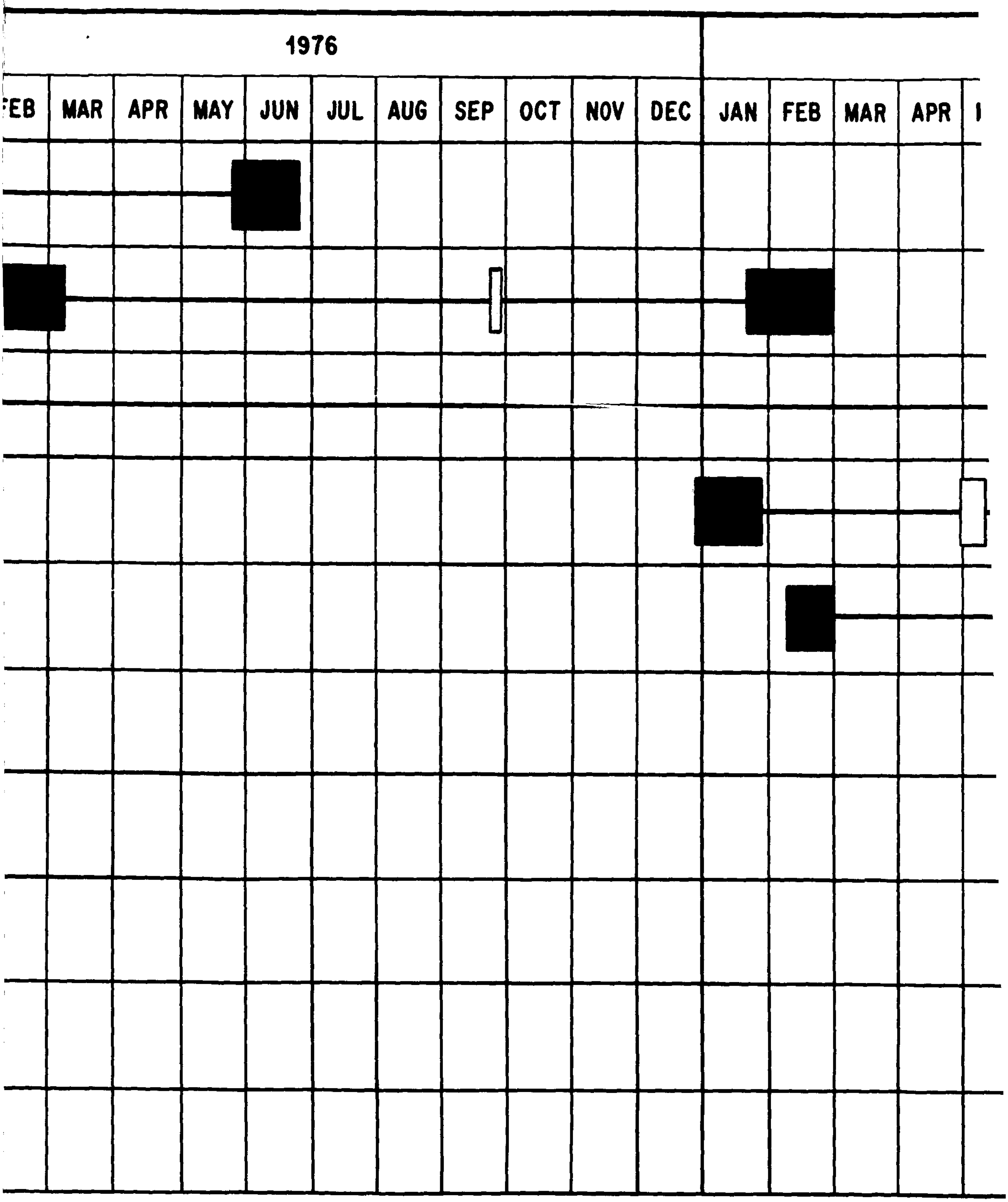
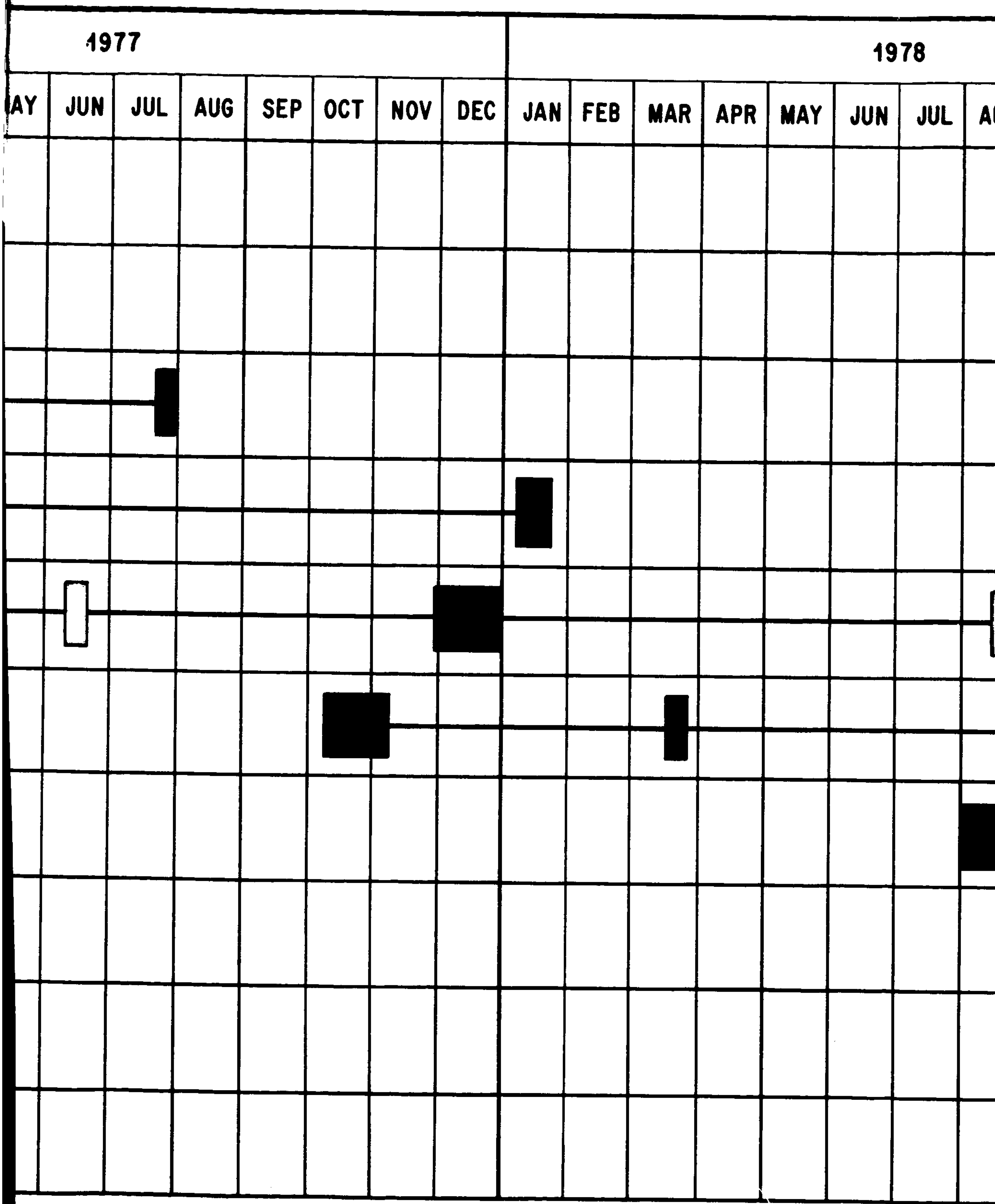
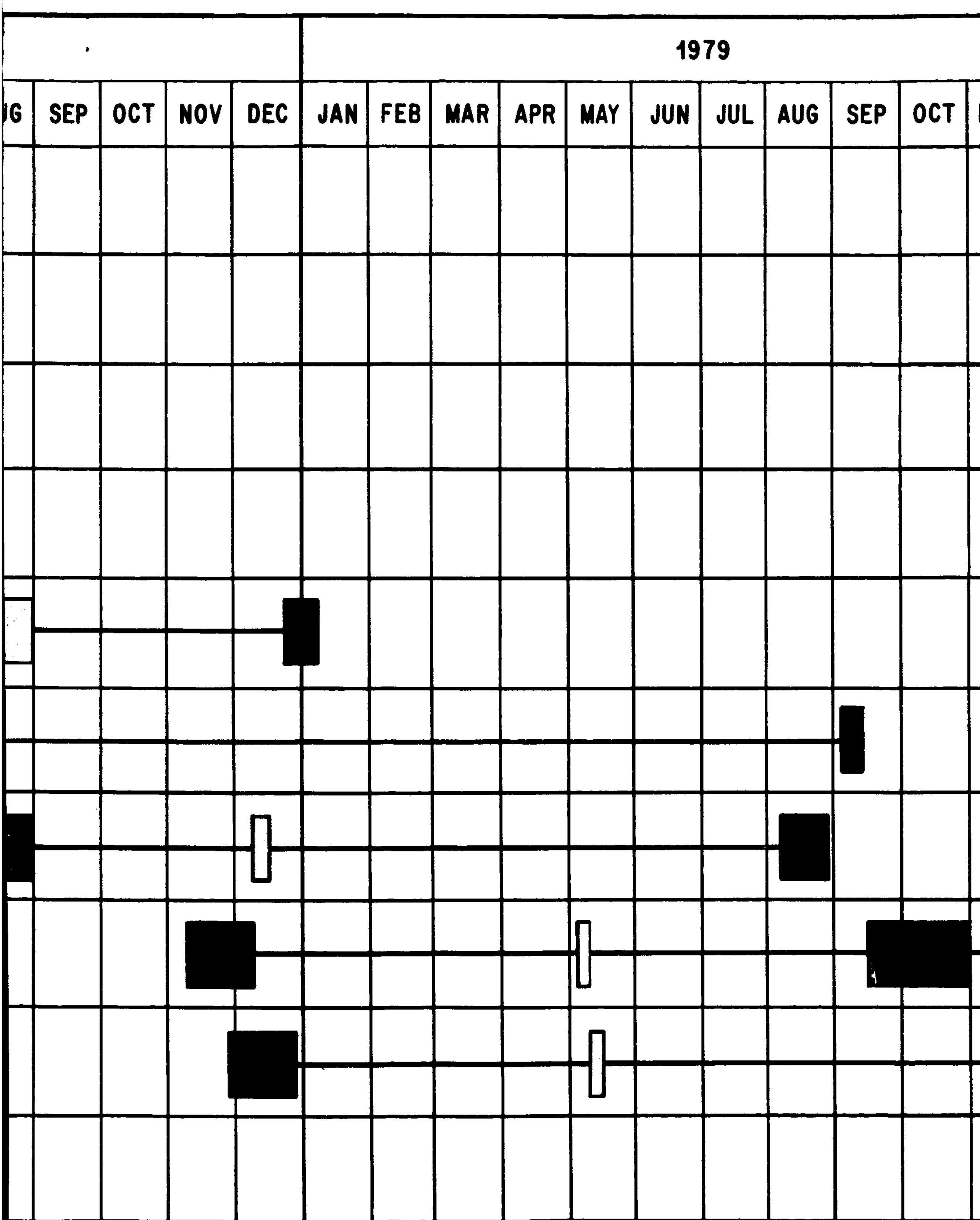


FIG. 65. TIME EVENTS FOR LOW ENE



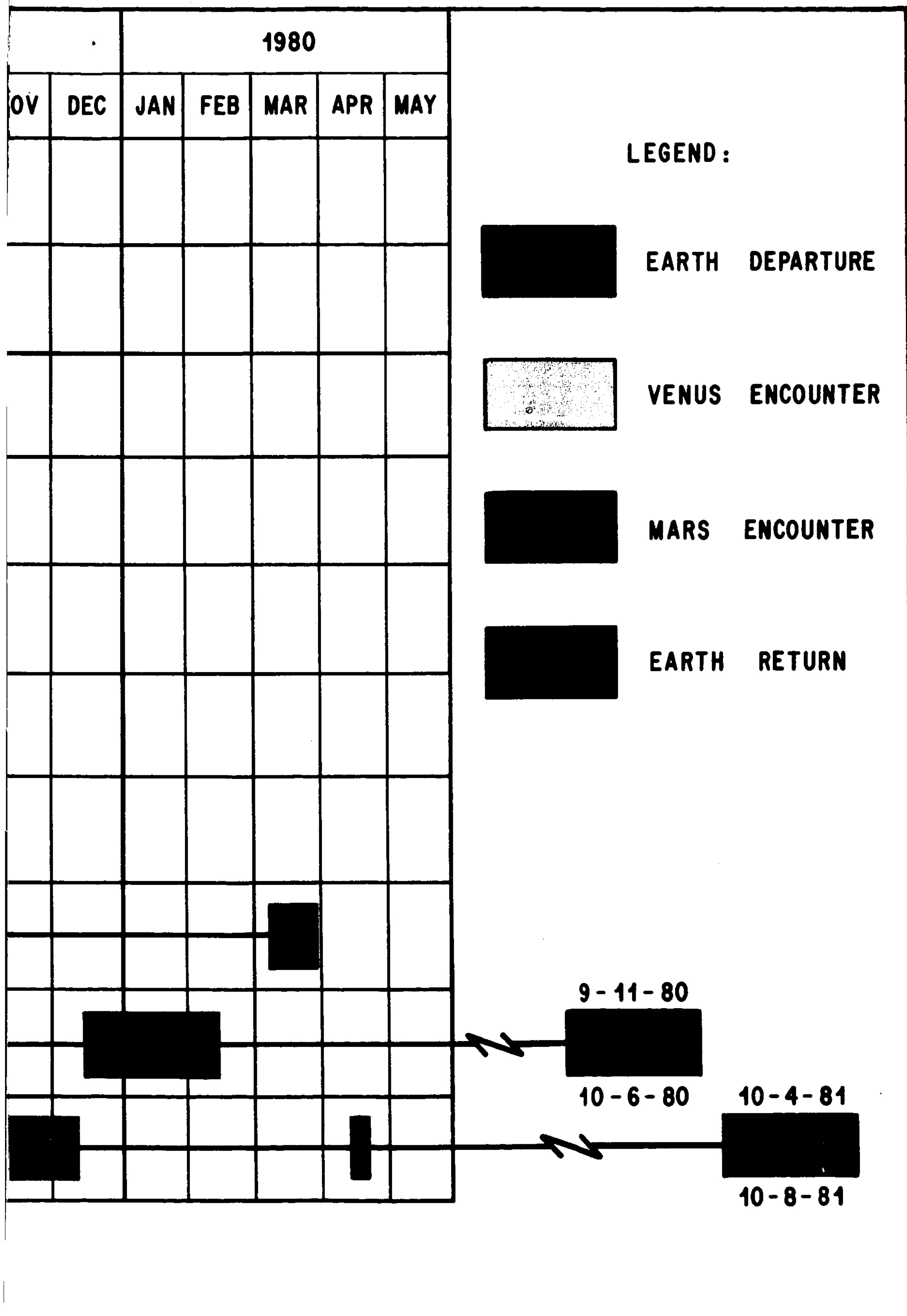
GY SINGLE AND MULTIPLE FLYBY MISSIONS –

75-3



1975 THROUGH 1980 TIME PERIOD

75-4


1980
OV
DEC
JAN
FEB
MAR
APR
MAY
LEGEND:
EARTH DEPARTURE
VENUS ENCOUNTER
MARS ENCOUNTER
EARTH RETURN
9-11-80
10-6-80
10-4-81
10-8-81

APPENDIX A

Time Within Sphere of Influence

Figure A-1 gives the time (in hours) within the sphere of influence for Venus and Mars versus hyperbolic excess speed, the radius of closest approach being 1.1 planet radii.

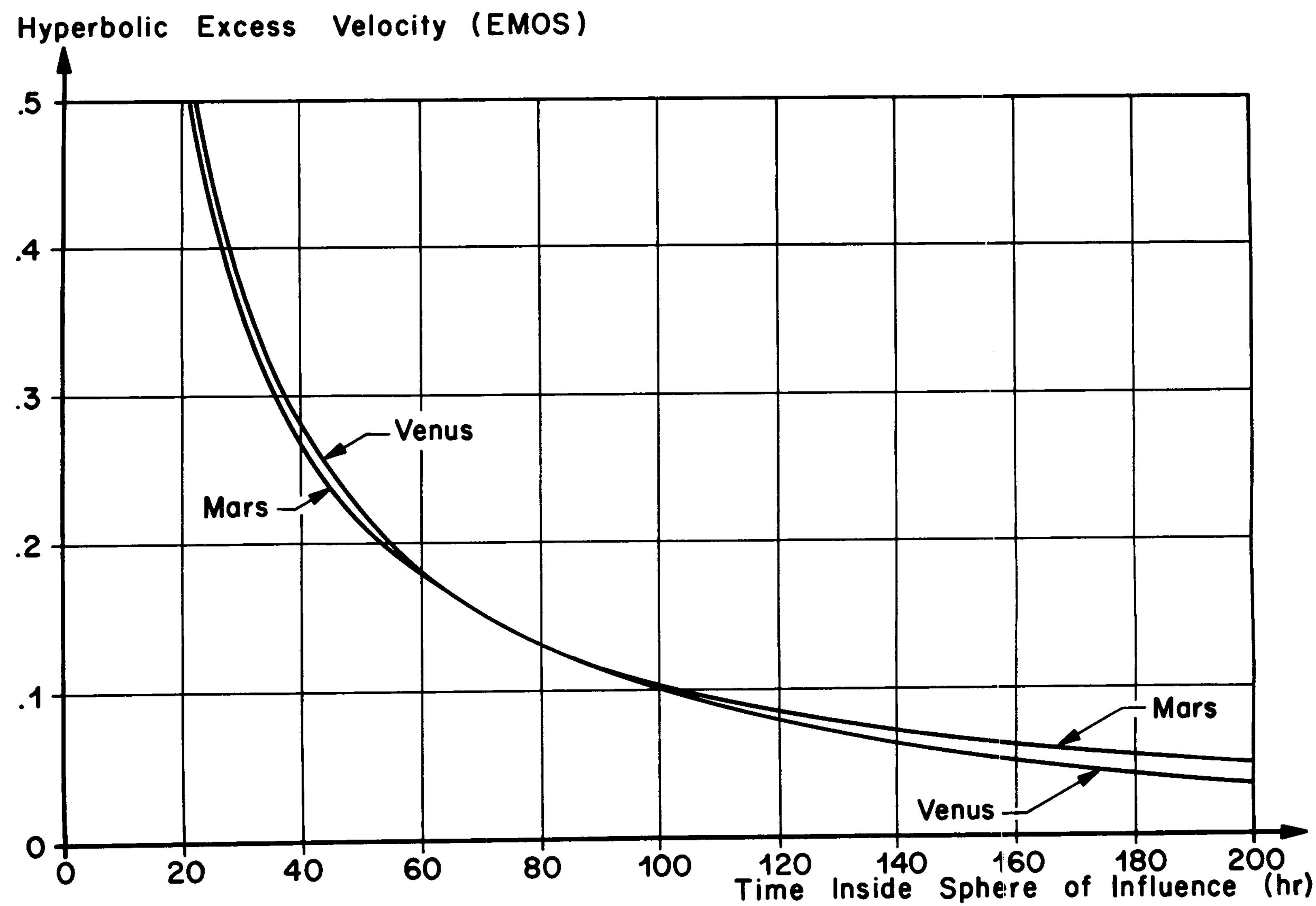


FIG. A1. TIME INSIDE SPHERE OF INFLUENCE FOR MARS AND VENUS VERSUS HYPERBOLIC EXCESS VELOCITY (RADIUS OF CLOSEST APPROACH EQUAL 1.1 PLANET RADII)

APPENDIX B

Hyperbolic Bend Angle

The hyperbolic bend angle due to Venus and Mars gravity field versus hyperbolic excess speed is given in Figures B-1 and B-2, respectively.

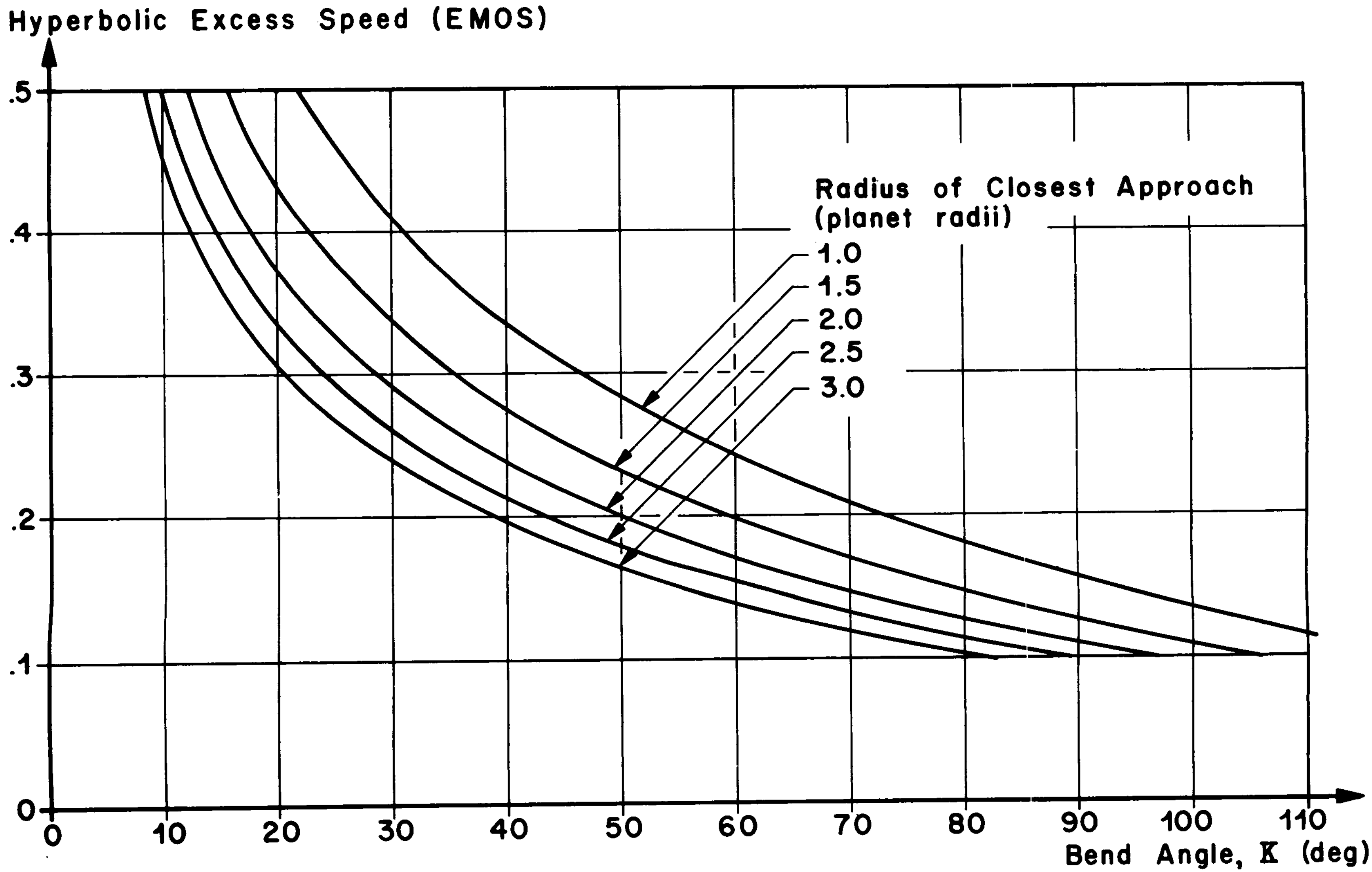


FIG. B1. HYPERBOLIC ASYMPTOTE DEFLECTION ANGLE DUE TO VENUS GRAVITY FIELD

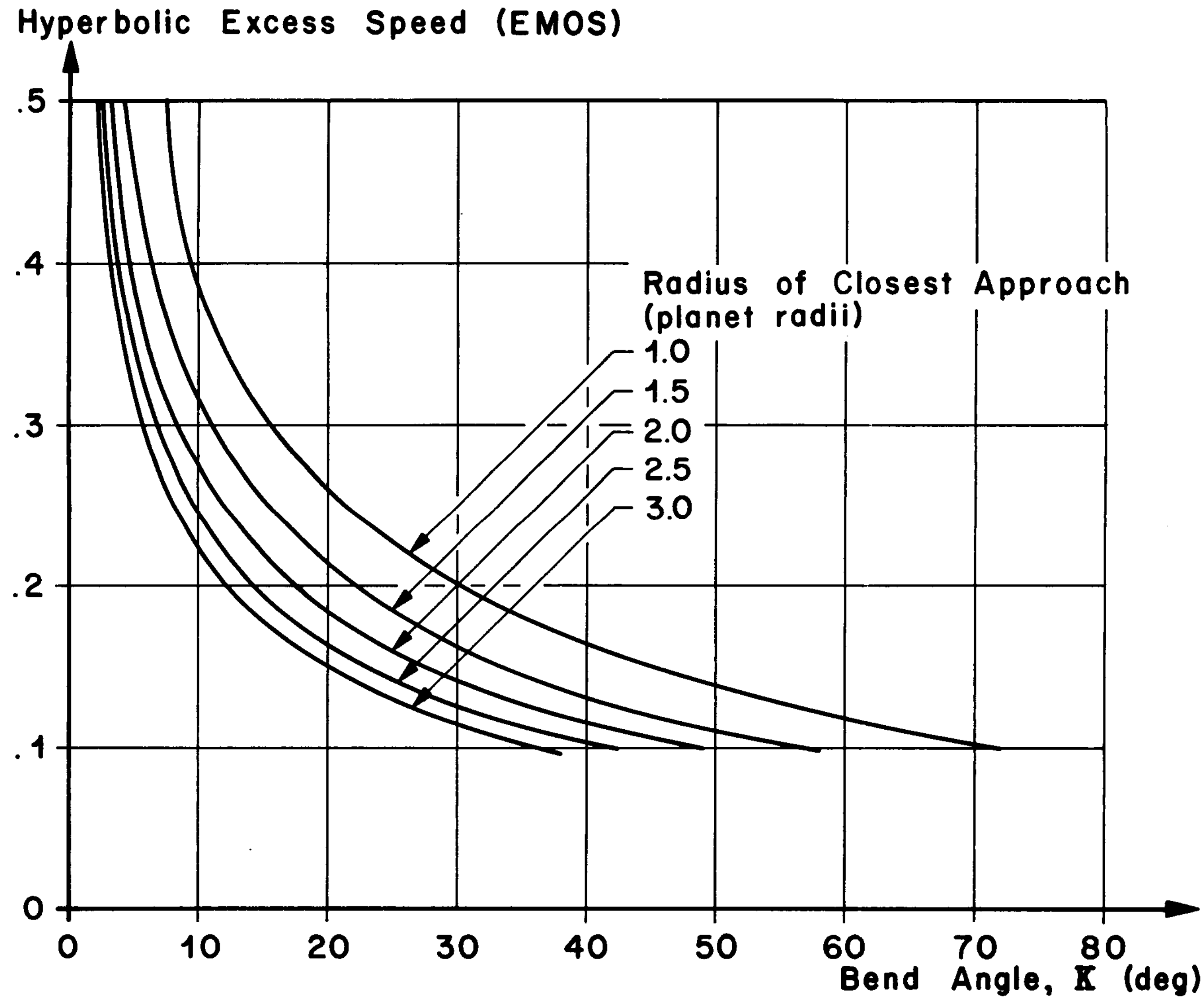


FIG. B2. HYPERBOLIC ASYMPTOTE DEFLECTION ANGLE DUE TO MARS GRAVITY FIELD

APPENDIX C

Optimum Impulsive Velocity Requirement for Hyperbolic Transfer at Venus and Mars

Powered flyby data for Venus and Mars are presented parametrically. Figure C-1 represents the geometry of the problem, and Figure C-2 gives the vector diagram of the powered maneuver.

A single-impulse maneuver for transfer between hyperbolic orbits at Venus is given in Figures C-3 through C-7 and for Mars in Figures C-8 through C-12. Relative to a passage planet, if the incoming and outgoing hyperbolic excess speeds have the same magnitude but due to a passage distance constraint the natural gravity bend angle is different from the actual bend angle between $\bar{V}_{\infty 1}$ and $\bar{V}_{\infty 2}$, a powered maneuver is necessary such that the combined results of gravity turn and powered turn yield the actual bend angle. This situation is depicted in Figures C-3 and C-8 for a closest approach radius of 1.1 planet radii; the powered maneuver is executed at the sphere of influence to yield minimum impulsive velocity. If the magnitudes of incoming and outgoing hyperbolic excess speed are different, and the natural bend from the planet's gravity field is different from the actual bend angle,then the propulsion system has to change the magnitude and direction of the velocity vector; this condition is given in Figures C-4 through C-12 excluding Figure C-8.

The results of the numerical calculation are presented with impulsive velocity as the ordinate and required bend angle as abscissa. In each figure, the ratio of $V_{\infty 2}/V_{\infty 1}$ has been fixed, and the curves are loci of constant $V_{\infty 1}$. The subscripts of the V_{∞}'s can be interchanged for actual conditions where $V_{\infty 1}$ is greater than $V_{\infty 2}$.

As an aid in reading the results, consider a Venus passage with a $V_{\infty 1}$ equal to 0.30 EMOS, a $V_{\infty 2}$ equal to 0.42, and a required bend angle of 50 degrees. The ratio of $V_{\infty 2}/V_{\infty 1}$ equal 1.4 therefore refer to Figure C-5 read vertically from the bend angle of 50 degrees on the $V_{\infty 1}$ equal 0.30 EMOS curve the resulting impulsive velocity requirement is 3.40 km/sec.

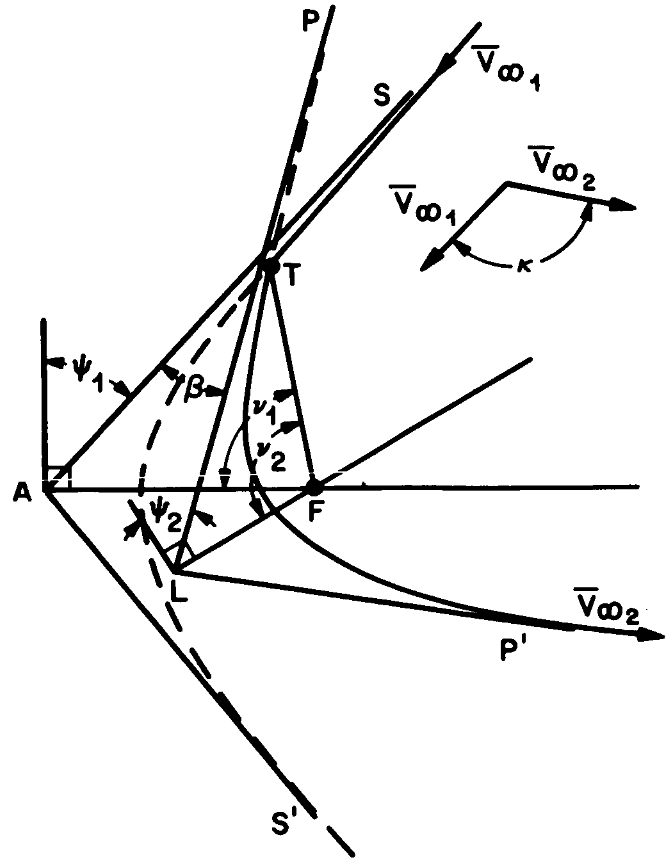


FIG. C1. GEOMETRY OF HYPERBOLIC TRANSFER MANEUVER

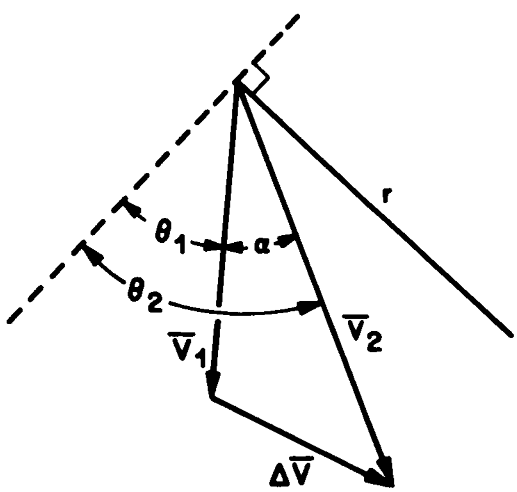


FIG. C2. VECTOR DIAGRAM OF TRANSFER MANEUVER

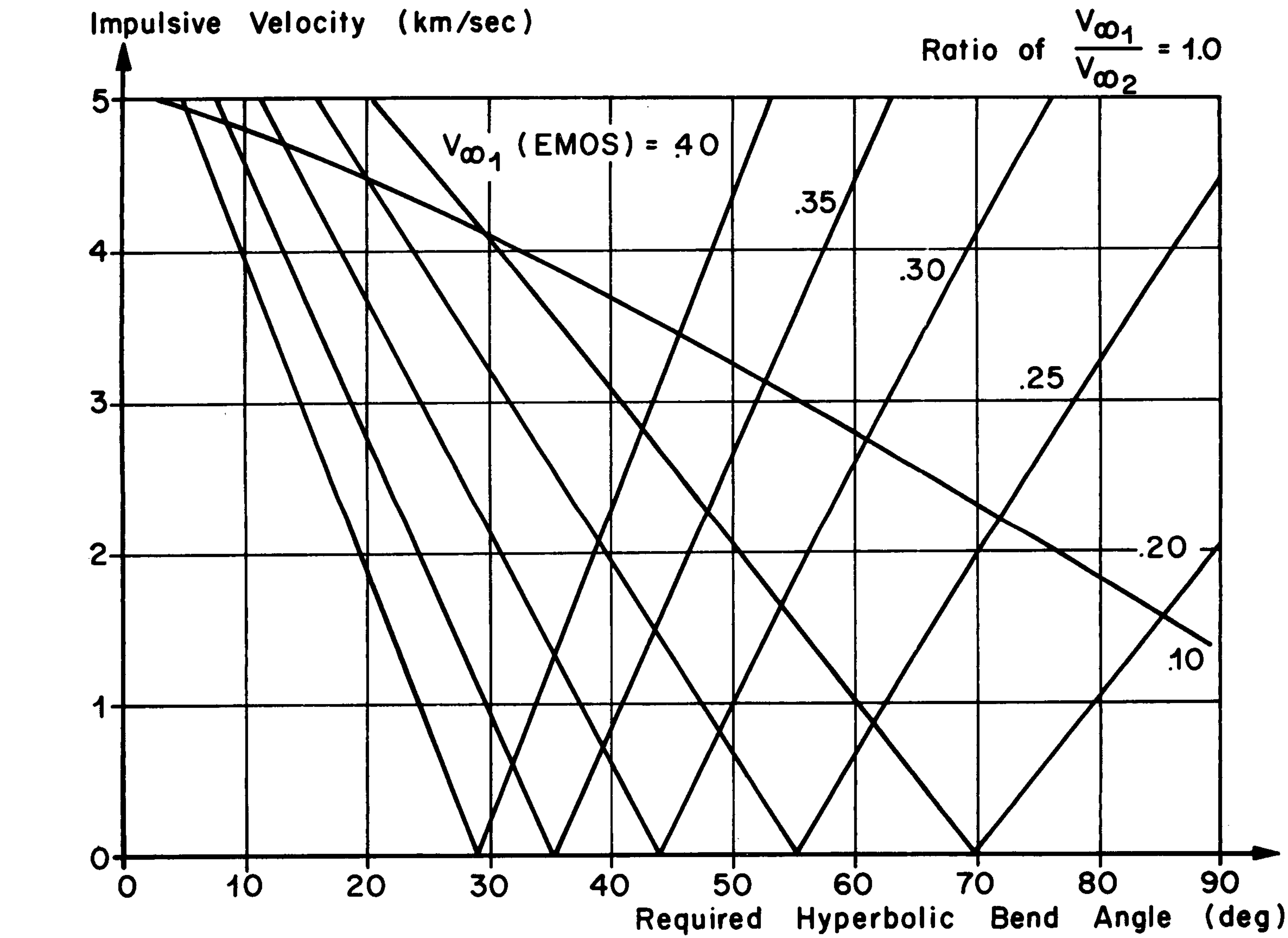


FIG. C3. IMPULSIVE VELOCITY REQUIREMENT VERSUS HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT VENUS

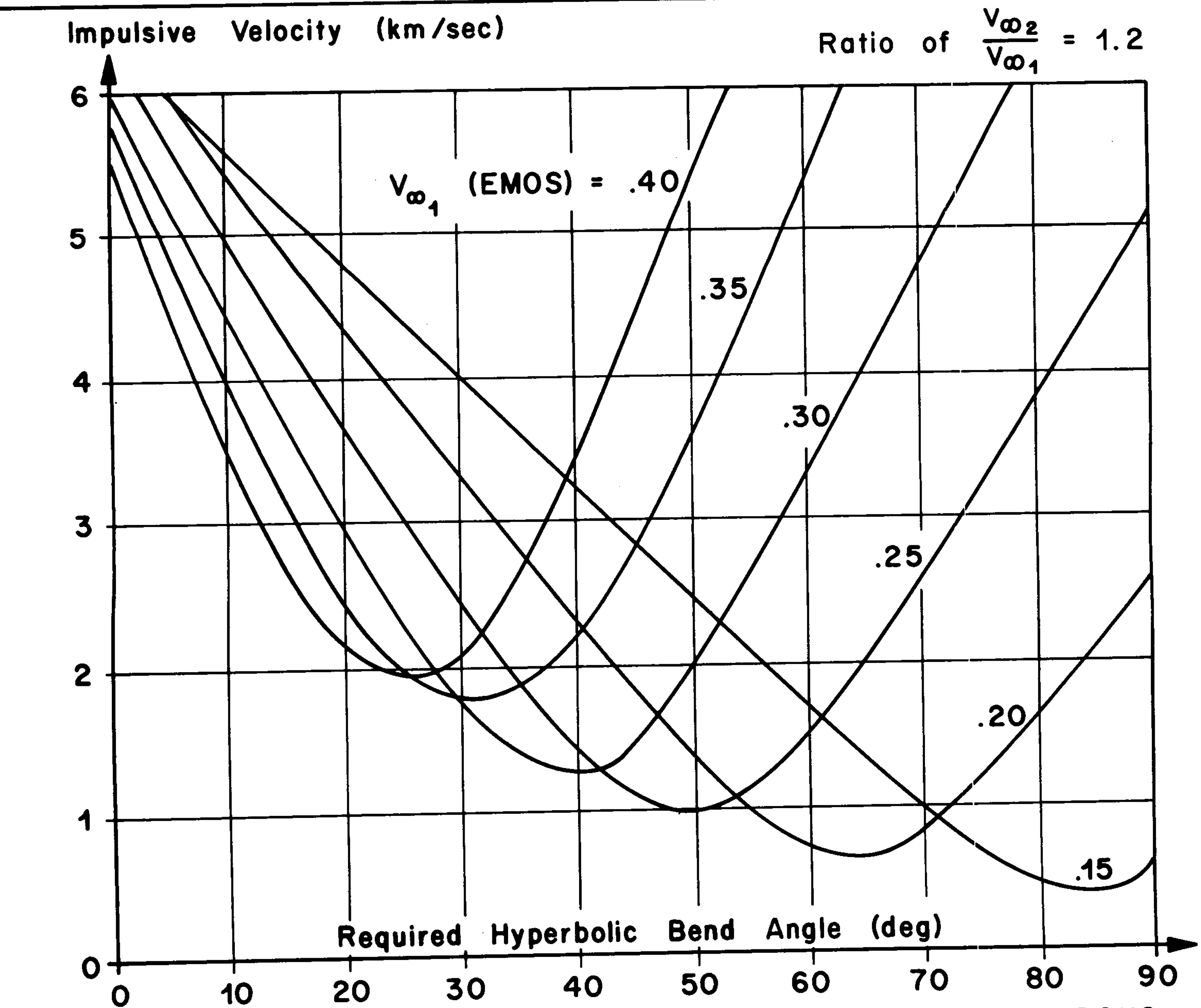


FIG. C4. IMPULSIVE VELOCITY REQUIREMENT VERSUS HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT VENUS

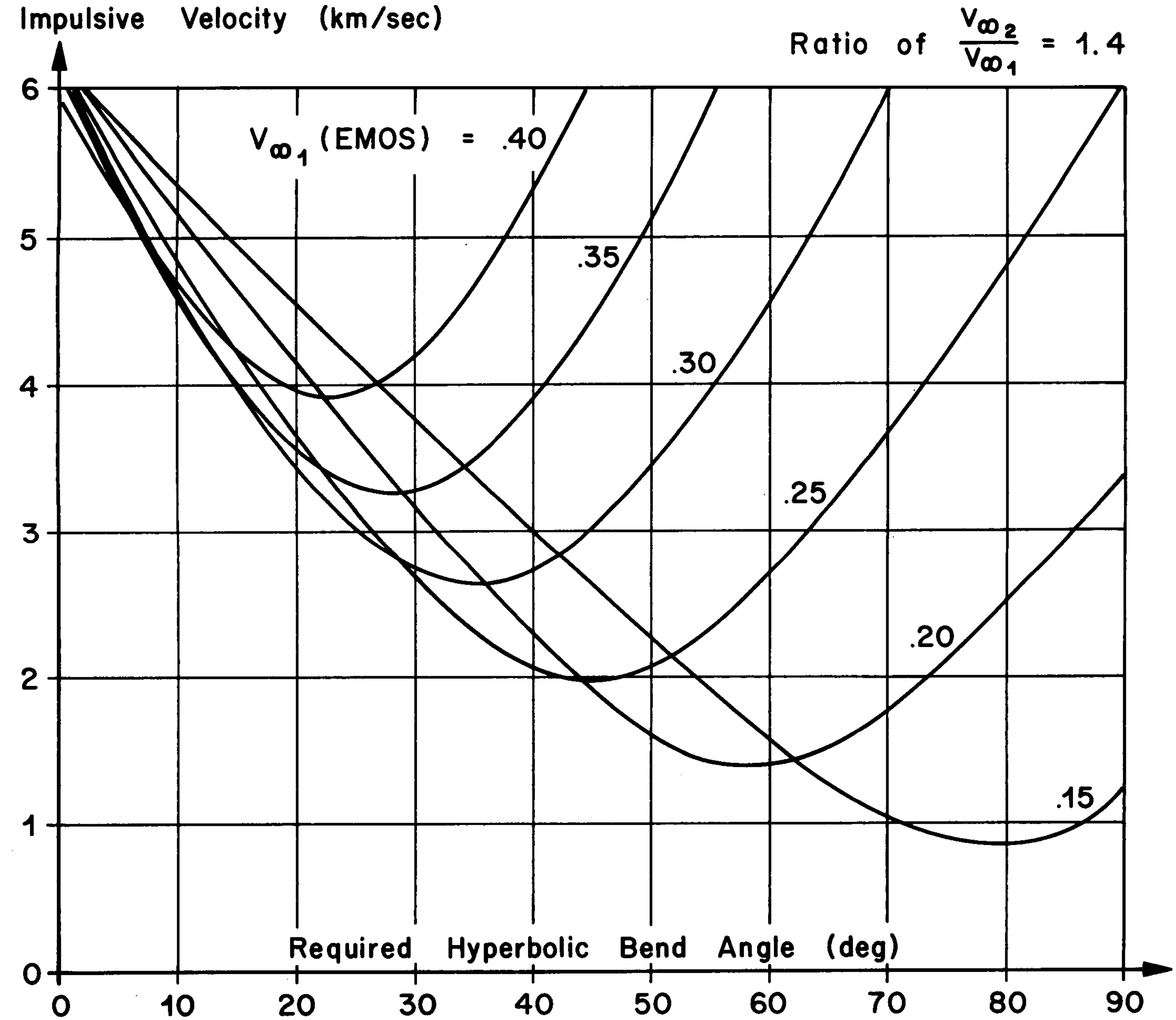


FIG. C5. IMPULSIVE VELOCITY REQUIREMENT VERSUS HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT VENUS

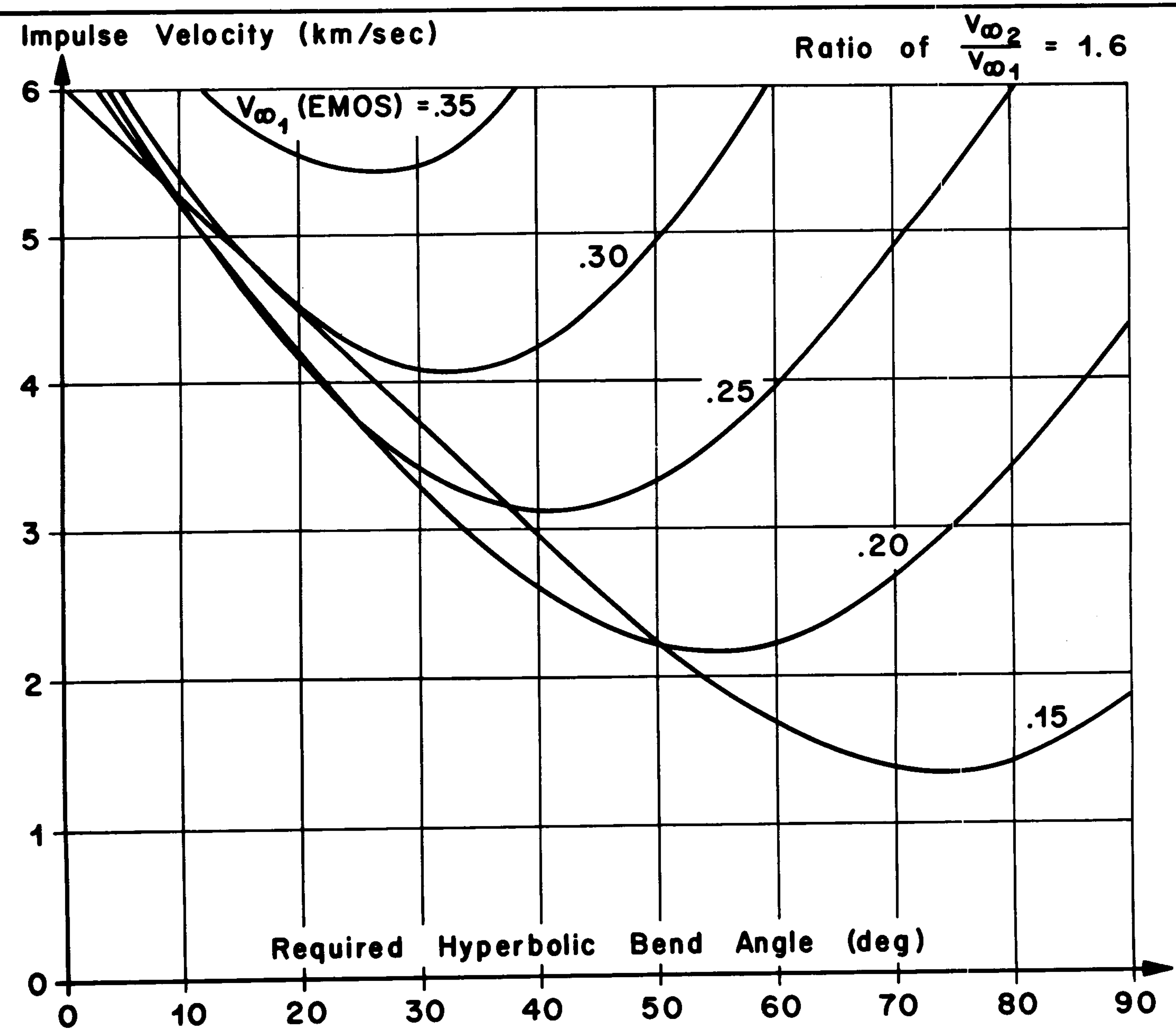


FIG. C6. IMPULSIVE VELOCITY REQUIREMENT VERSUS HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT VENUS

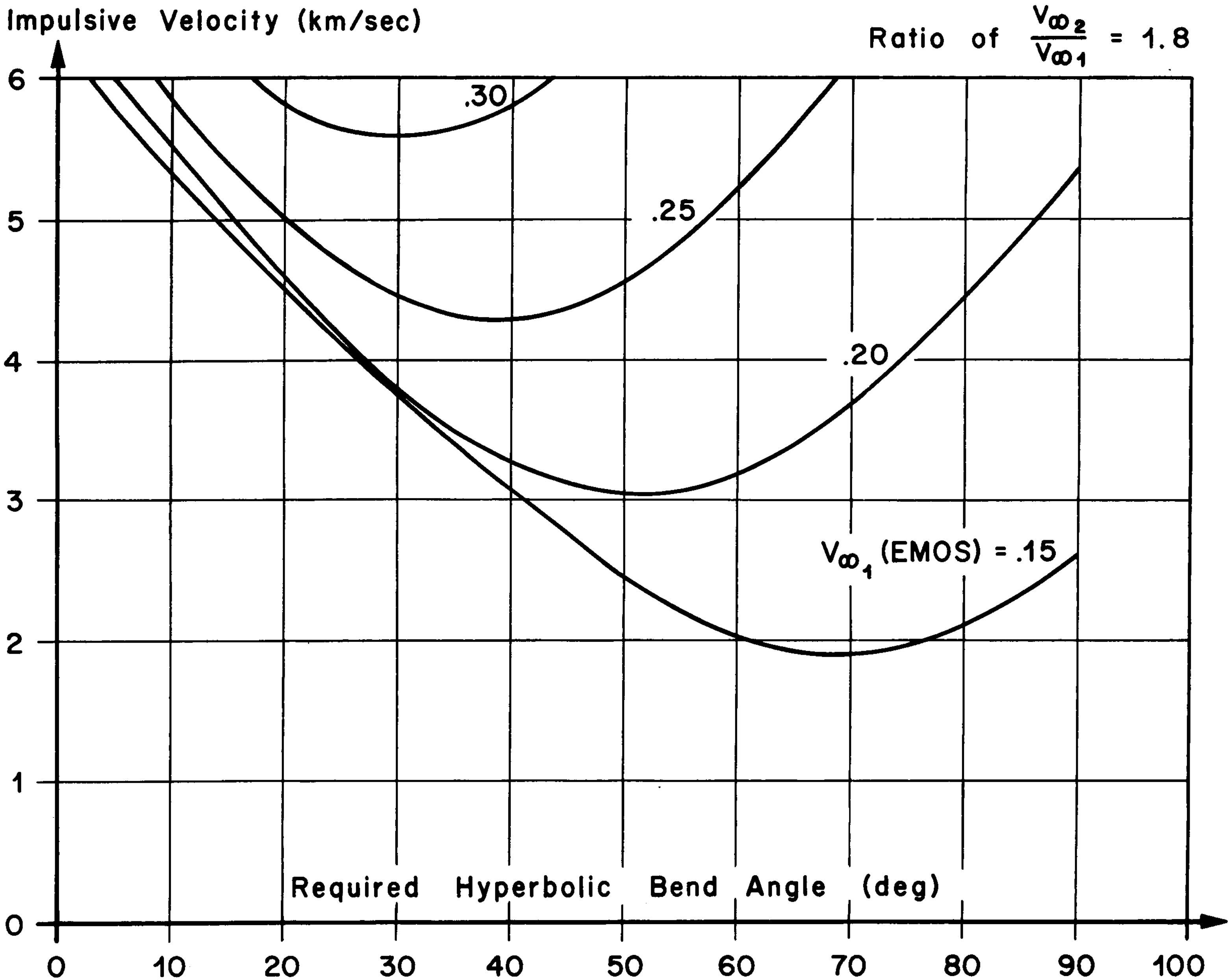


FIG. C7. IMPULSIVE VELOCITY REQUIREMENT VERSES HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT VENUS

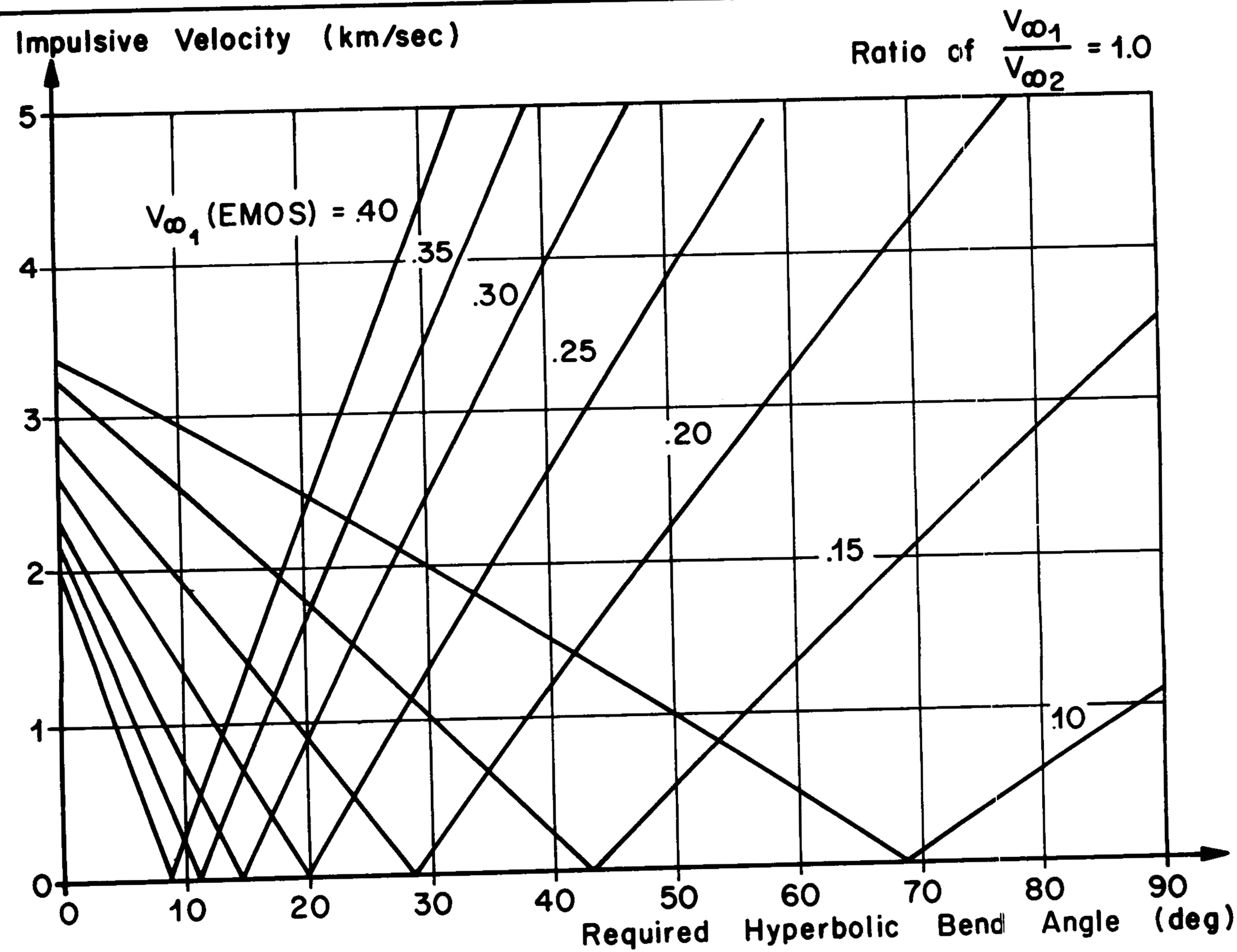


FIG. C8. IMPULSIVE VELOCITY REQUIREMENT VERSUS HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT MARS

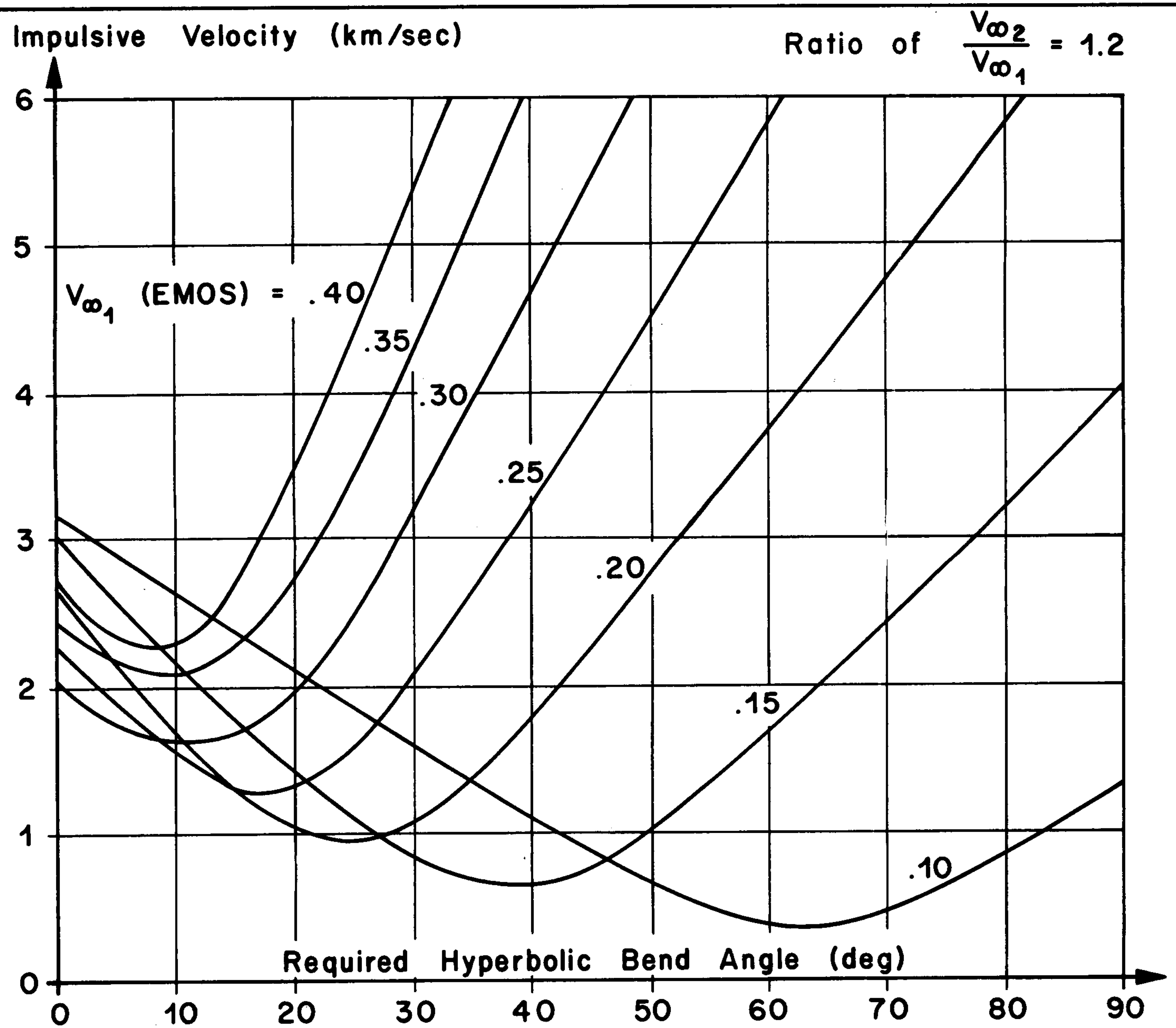


FIG. C9. IMPULSIVE VELOCITY REQUIREMENT VERSUS HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT MARS

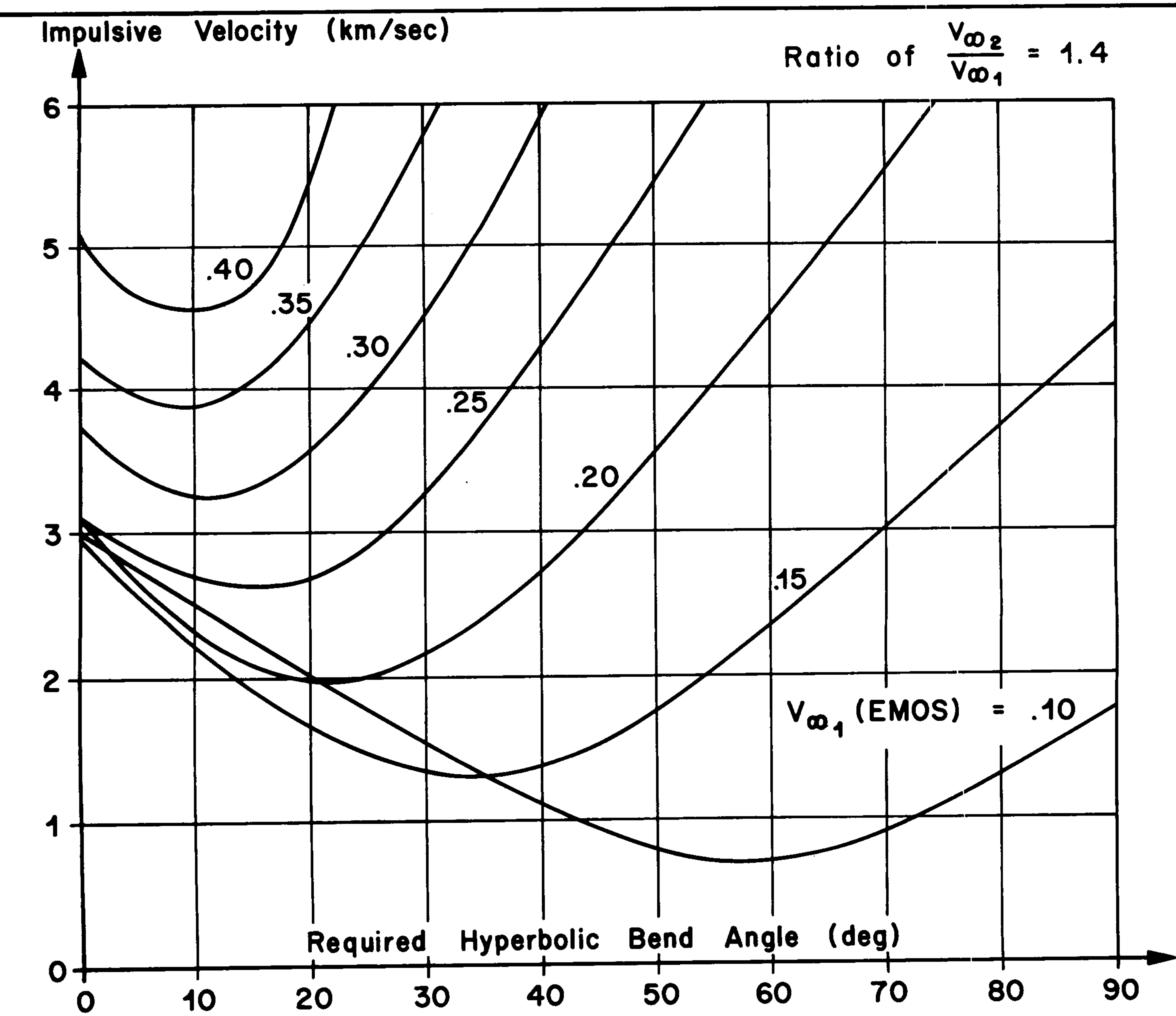


FIG. C10. IMPULSIVE VELOCITY REQUIREMENT VERSUS HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT MARS

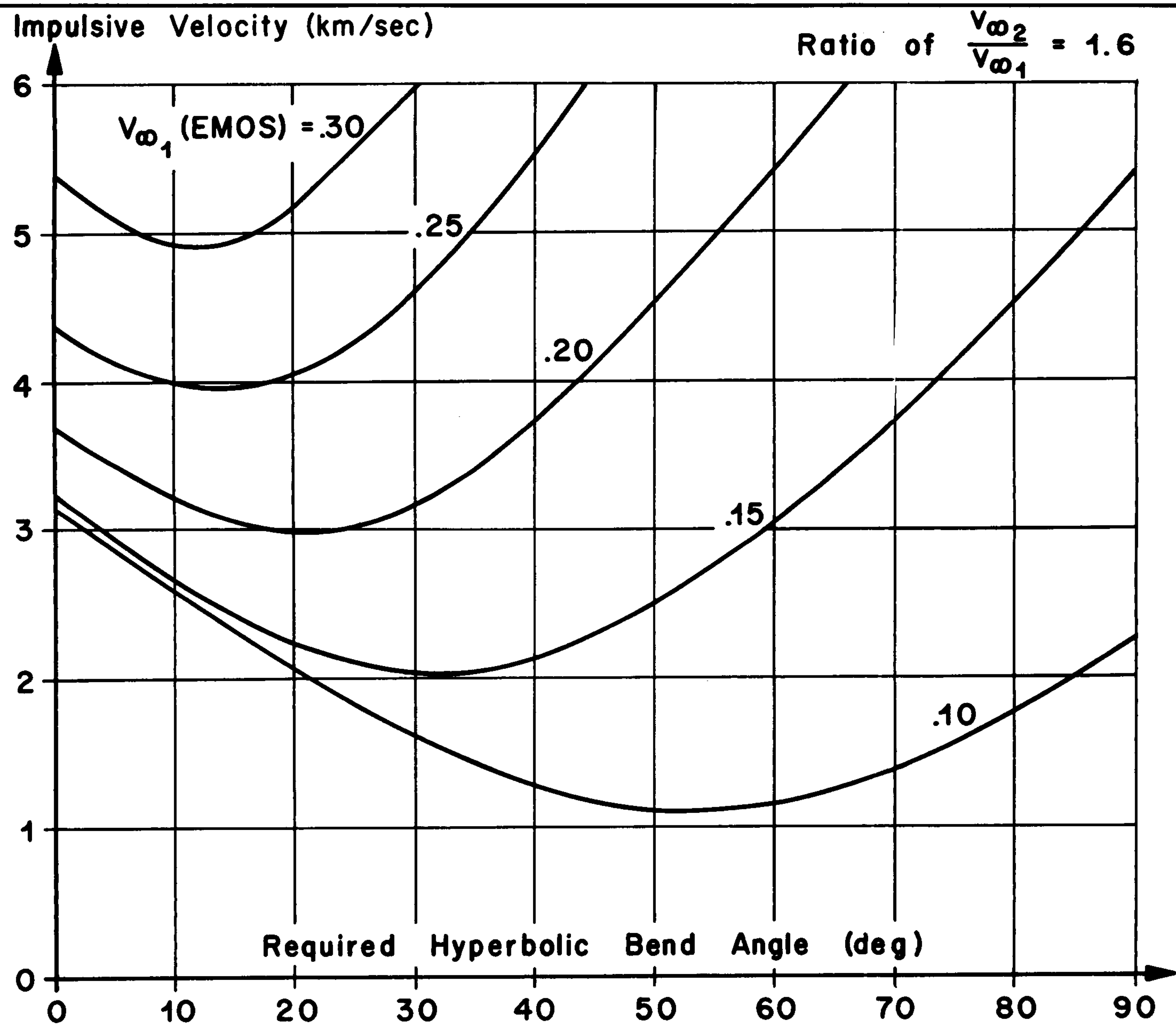


FIG. C11. IMPULSIVE VELOCITY REQUIREMENT VERSUS HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT MARS

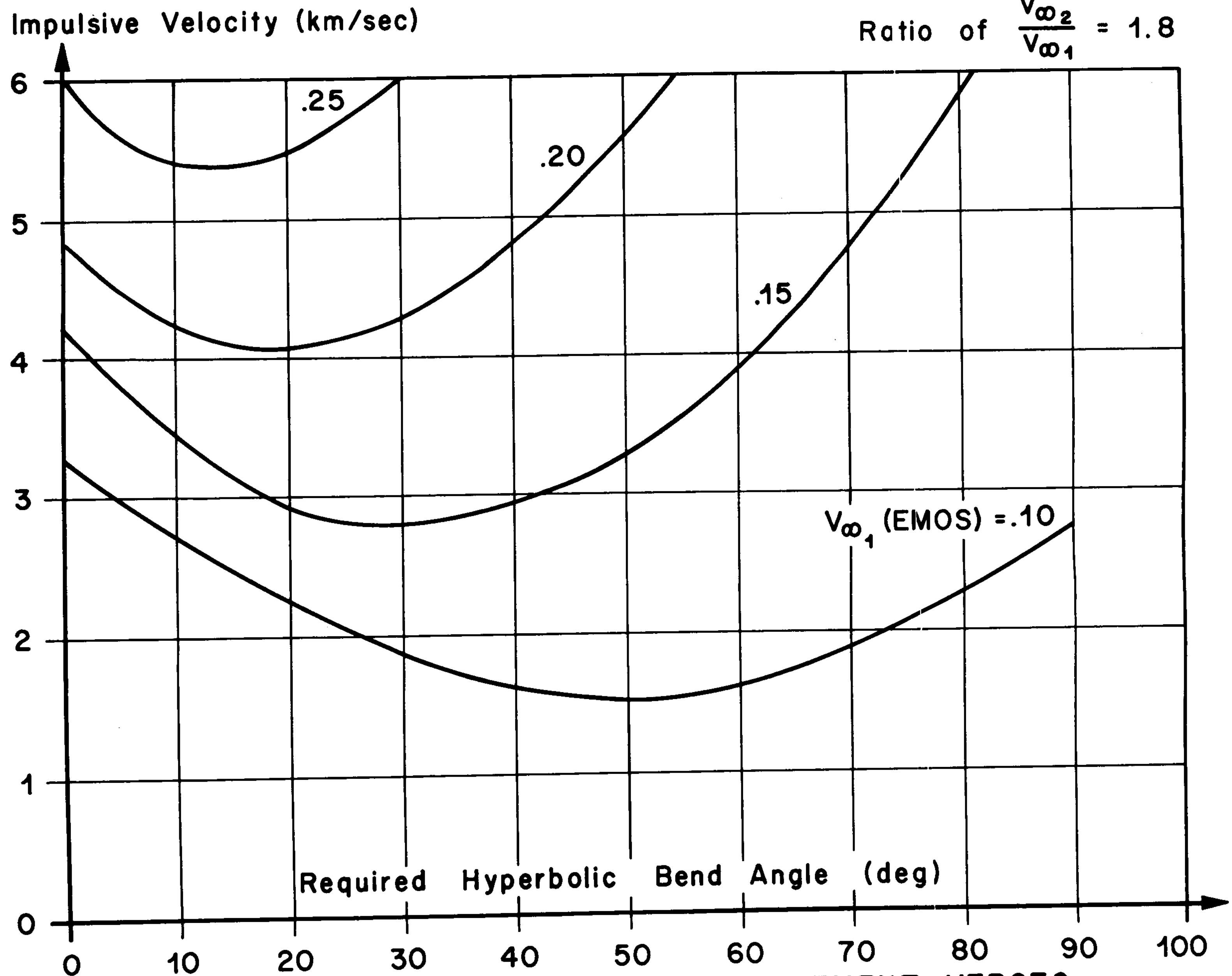


FIG. C12. IMPULSIVE VELOCITY REQUIREMENT VERSES HYPERBOLIC BEND ANGLE FOR HYPERBOLIC TRANSFER AT MARS

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APPROVAL NASA TM X-53511

MULTIPLE PLANET FLYBY MISSIONS TO VENUS AND MARS IN 1975 TO 1980 TIME PERIOD

by Archie C. Young

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