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MEMORANDUM
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JULY 1963

VELOCITY REQUIREMENTS FOR STOPOVER ROUND TRIPS TO MARS

L. N. Rowell

PREPARED FOR:

UNITED STATES AIR FORCE PROJECT RAND

The RAND Corporation
SANTA MONICA • CALIFORNIA

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PREFACE

One imporant factor in the planning of interplanetary round-trip missions is the propulsive energy required. Because the planets move in inclined, elliptical orbits and with different periods of revolution, their relative orientations are continuously changing. This fact makes it necessary for mission planners to investigate various round trips in order to make intelligent decisions concerning tradeoffs between outbound and inbound travel times and stay times on the destination planet. Correct combinations of departure and travel times can greatly reduce the total amount of propulsive energy required for the mission.

These data are intended for use in mission planning and are presented in a form that readily permits an estimate of the required velocities for specific missions, an assessment of the velocity penalties associated with delayed departures, and an evaluation of various combinations of transfer times for each leg of the mission and stay times at Mars.

SUMMARY

The velocity increments that are required to transfer a vehicle from an Earth parking orbit to a Mars parking orbit and return are presented for a range of departure dates during the time period from 1971 to 1977. The departure dates fall before and after those for minimum-energy trajectories, i.e., May 1971, July 1973, September 1975, and October 1977. The parking orbits are circular and are at an altitude of 100 n mi.

The required velocity increments are presented primarily in graphic form. The individual and total velocity increments for one-way trips are given for transfer times ranging from 100 to 300 days, in 50-day increments.

ACKNOWLEDGMENTS

The author appreciates the assistance given by J. V. McGann in the preparation of these data. This study made use of some interplanetary trajectory data previously computed at the Lockheed Aircraft Corporation, Missiles and Space Division, Sunnyvale, California. The author is grateful to Stanley Ross for supplying these data.

CONTENTS

I. INTRODUCTION

For a vehicle to travel in a ballistic trajectory from a closed orbit around Earth to a closed orbit around Mars and return, at least four separate velocity increments must be added impulsively to the vehicle's initial velocity. In order to accomplish the mission with this minimum number of velocity increments and without changing the planes of the parking orbits, the mission must be designed to meet the following conditions:

1. The Earth parking-orbit plane must be oriented so that it contains a line that passes through the center of the Earth and parallel to the asymptote of the hyperbolic escape orbit at the time of departure from the Earth parking orbit.
2. The heliocentric transfer trajectory must be designed to intersect the sphere of influence of Mars at a particular point and with a particular velocity vector so that the resulting hyperbolic-orbit plane and consequently the Mars parking-orbit plane will be correctly oriented at the end of the stay at Mars.

The first condition may require complete freedom in choosing the azimuth of launch. This depends somewhat on the location of the launch site, the total mission time, etc.

The second condition requires that both the stay time at Mars and the return transfer trajectory be specified before departure from the Earth parking orbit.

Two important factors in determining the total energy required for a Mars mission are the distance of Mars from the Sun and its celestial latitude at the arrival time.[(1)] In 1971 both of these quantities are small, and consequently the required incremental velocities are a minimum. After this time both quantities increase in magnitude at the preferred arrival times and cause, as early as 1975, a significant increase in total energy required for a given mission. Every 15 years a given orientation of Earth and Mars relative to each other and to a reference direction will be approximately repeated, because 15 Earth years are approximately equal to 8 Mars years. Thus the most favorable departure conditions that occur in 1971 will be about the same again in 1986.

The data presented here are based on the assumptions that the mission can be accomplished with the minimum number of velocity increments and that the parking orbits are 100-n mi circular orbits.

Numerous curves are presented to show the velocity increments that must be added to the vehicle's velocity in order to depart and enter 100-n mi circular parking orbits about Earth and Mars. Also, graphs showing the sum of these velocities for each leg of the round trip are presented. Dates of departure from Earth and Mars range about the Hohmann departure dates of 1971, 1973, 1975, and 1977. The first departure from Earth is April 24, 1970, and the last is April 2, 1978.

Interplanetary trajectory data computed at Lockheed[2] served as a basis for the data presented here.

II. ANALYSIS AND DISCUSSION

The four velocity increments required to satisfy the orbital-mechanics problem for purely ballistic flight from an Earth parking orbit to a Mars parking orbit and return are defined as

ΔV_{ed} = velocity increment required to transfer from the Earth circular parking orbit to the correct hyperbolic escape orbit

ΔV_{ma} = velocity increment required to transfer from the hyperbolic escape orbit to the circular parking orbit around Mars

ΔV_{md} = velocity increment required to transfer from the Mars circular parking orbit to the correct hyperbolic escape orbit

ΔV_{ea} = velocity increment required to transfer from the hyperbolic escape orbit to the circular parking orbit around Earth

In order to accomplish a stopover round trip to Mars with minimum total velocity increment and with only four velocity increments, the parking-orbit planes must be coplanar with the planes of the hyperbolic escape orbits at the times of departure from the parking orbits. If some particular orientations of the parking-orbit planes other than those dictated by a solution of the orbit-mechanics problem are desired, additional velocity increments will be required. In general it will not be possible to correctly orient the parking-orbit planes by simply delaying departure or varying the stay time at Mars.

The four velocity increments defined above were determined with the use of heliocentric orbital-transfer data computed at Lockheed. The heliocentric transfer orbits between massless points coinciding with the centers of Earth and Mars were computed for departures from Earth and Mars for every 10 days during the period from April 1970 to October 1978. Transfer times for each departure date ranged from 40 to 480 days in 10-day increments.

For each heliocentric trajectory that was computed, the hyperbolic excess velocities relative to the departure planet and the arrival planet were determined. These velocities were used to determine the velocity increments required to leave or enter the 100-n mi circular parking orbits. The velocity increment to be added to the circular-orbit velocity in order to enter the hyperbolic escape orbit at perigee is

$$\Delta V = V_{co} - V_c = \sqrt{V_{esc}^2 + V_\infty^2} - V_c = \sqrt{2V_c^2 + V_\infty^2} - V_c \qquad (1)$$

where

V_{co} = cutoff velocity

V_c = circular-orbit velocity

V_∞ = hyperbolic excess velocity

For 100-n mi parking orbits around Earth and Mars the circular-orbit velocities are 25,570 ft/sec and 11,460 ft/sec, respectively. Equation (1) is valid only if the increment of velocity is always added collinearly to the existing velocity vectors. Because circular parking orbits are assumed, the vehicle will transfer to and from the hyperbolic escape orbits at the perigee points.

Figure 1 gives the impulsive velocity increment, ΔV, that is required for a given hyperbolic excess velocity, V_∞, when departing or entering a 100-n mi circular orbit around Earth or Mars. It is clear from the figure that ΔV is less than V_∞ if V_∞ is greater than 0.5 V_c. Also, this figure can be used to convert the ΔV's back to V_∞'s in case some satellite-orbit altitude other than 100 n mi is desired.

As mentioned earlier, the outbound heliocentric transfer orbit can be designed so that the resulting hyperbolic escape-orbit plane, and consequently the parking-orbit plane at Mars, is correctly oriented for any specified future time of departure from Mars. If some orientation of the Mars parking-orbit plane other than the one required for the return trip is desired, a plane change is necessary. For a change of θ degrees the required velocity increment is

$$\Delta V = 2 V_{cm} \sin \theta/2 \qquad (2)$$

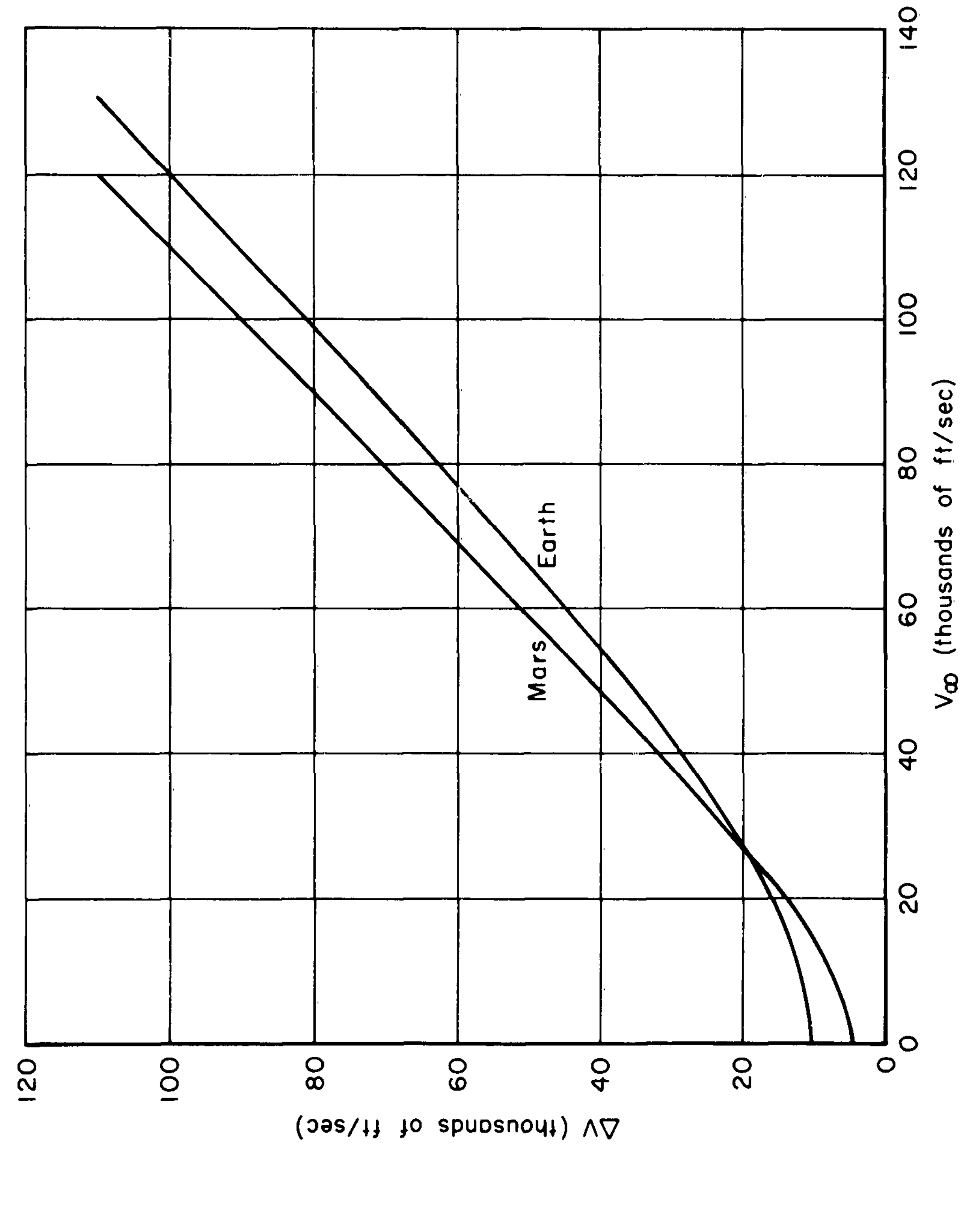

Fig.1 —Hyperbolic excess velocity versus injection-velocity increment at Earth and Mars

where V_{cm} is the vehicle velocity in the Mars circular parking orbit. In practice the desired orientation of the plane should be established by properly designing the outbound heliocentric transfer orbit. Then the orientation of the parking-orbit plane would be changed to the correct value for the return trip.

III. RESULTS

The data presented in Figs. 2a through 9c are based on transfers between circular parking orbits of 100-n mi altitude and the assumption that the heliocentric motion is Keplerian; i.e., all perturbations are ignored. Because perturbations are neglected and the conic sections are patched together to form the complete transfer trajectory, the velocity increments are approximate. In any case the error in a velocity increment obtained using these approximations will not exceed 200 ft/sec.

The dates of departure for Hohmann transfer trajectories for the two-dimensional circular planetary orbits are April 1971, June 1973, September 1975, and November 1977. These dates are approximately the center dates of the data presented in Figs. 2 through 9. Data for these Hohmann departure dates are given by Figs. 2 and 3 for the 1971 date, Figs. 4 and 5 for the 1973 date, Figs. 6 and 7 for the 1975 date, and Figs. 8 and 9 for the 1977 date. Total velocity increment for each leg of the trip is shown, as well as the individual velocity increments. Thus, the graphs in the figures can be used not only for planning round-trip stopover missions, but also for planning fly-by missions or missions that employ atmospheric drag to accomplish a velocity change.

MISSION EXAMPLES

In order to illustrate the use of the graphs two examples are given.

Example 1

Assume the two following hypothetical missions are desired:

	Time (days)	
	Mission 1	Mission 2
Earth-to-Mars transfer time	150	200
Stay time in Mars parking orbit	0	0
Mars-to-Earth transfer time	200	150

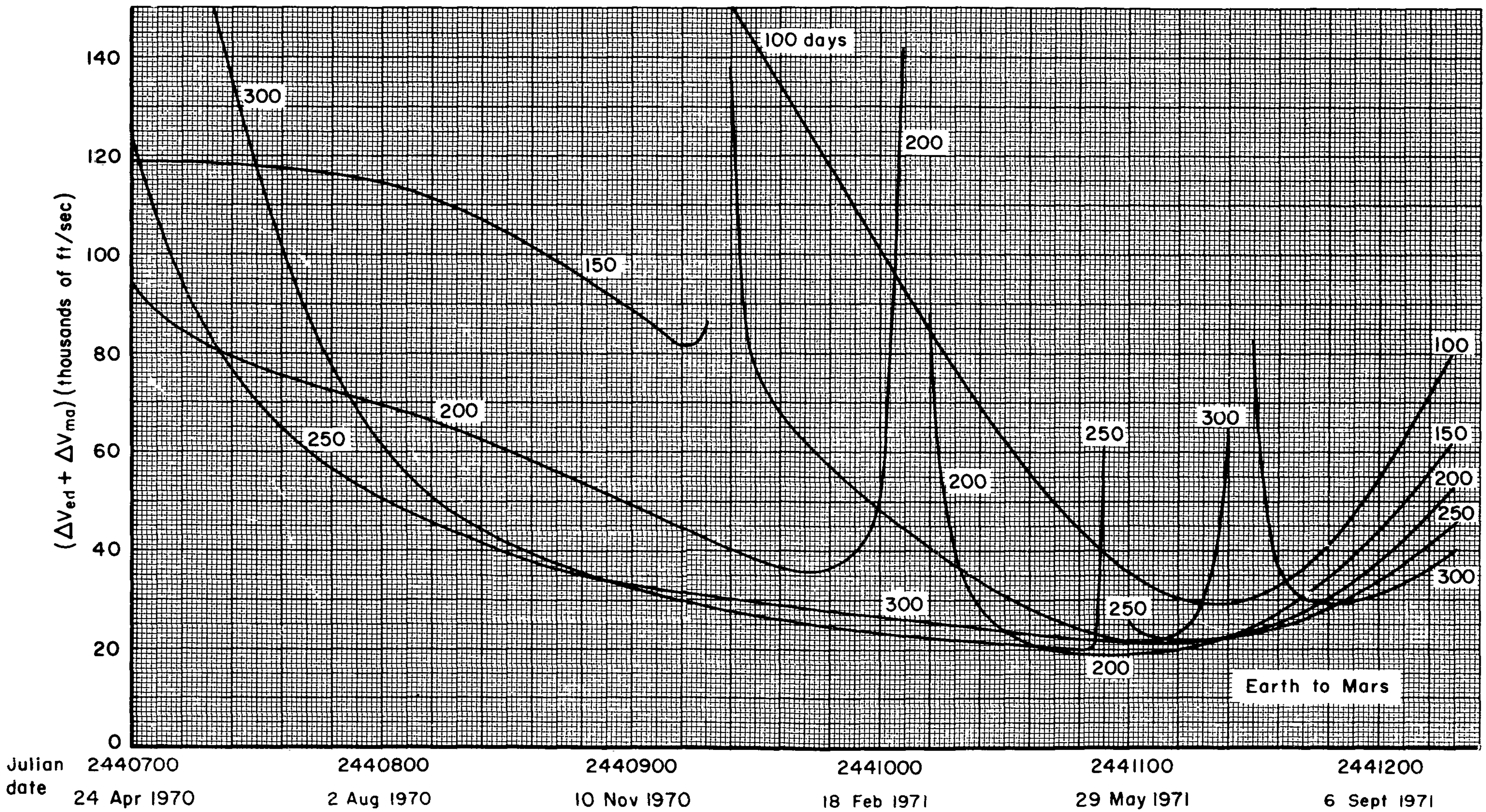

Fig. 2a— Earth departure date versus ($\Delta V_{ed} + \Delta V_{ma}$) for constant transfer times (24 Apr 1970 - 6 Sept 1971)

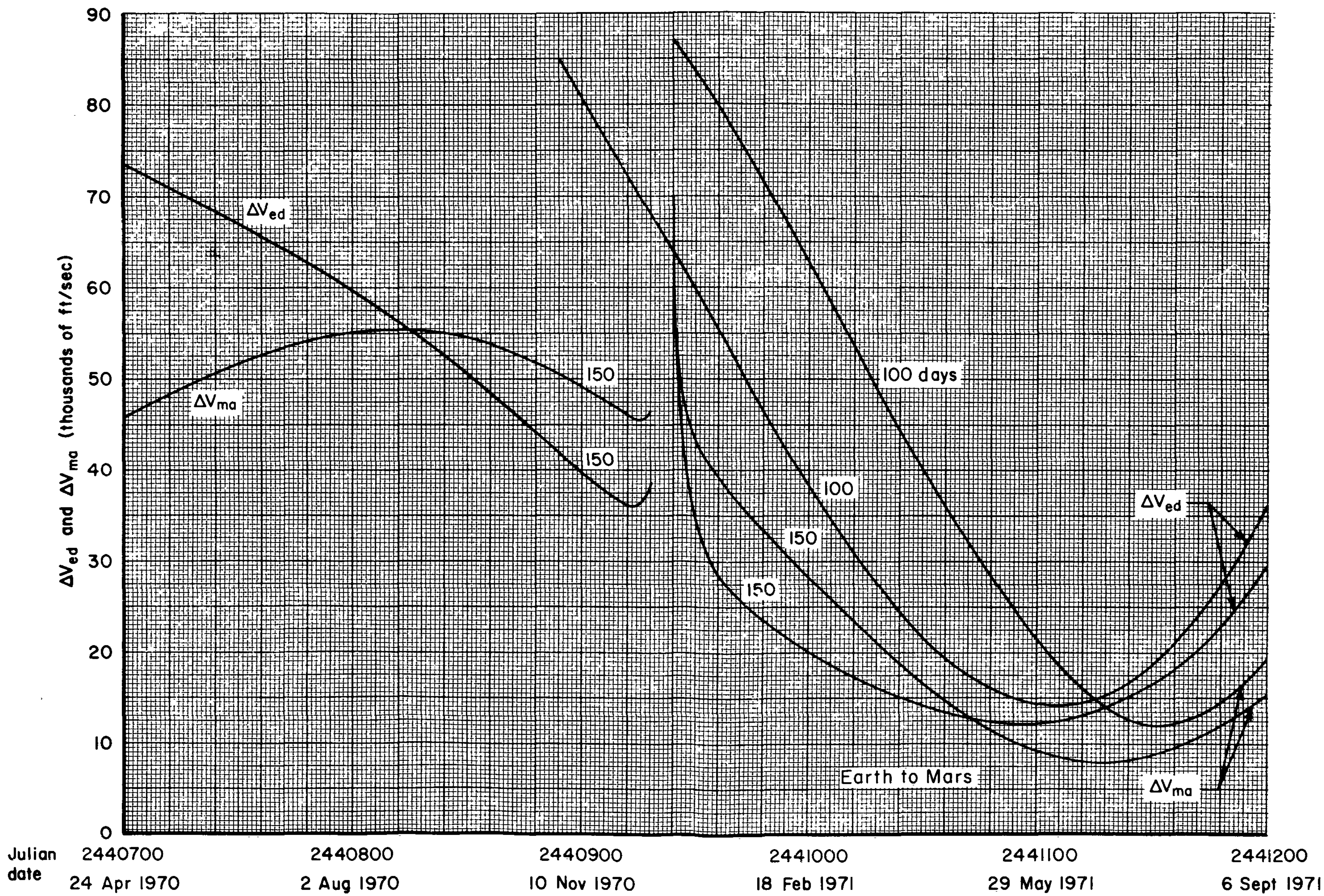

Fig. 2b — Earth departure date versus ΔV_{ed} and ΔV_{ma} for constant transfer times (100, 150 days)

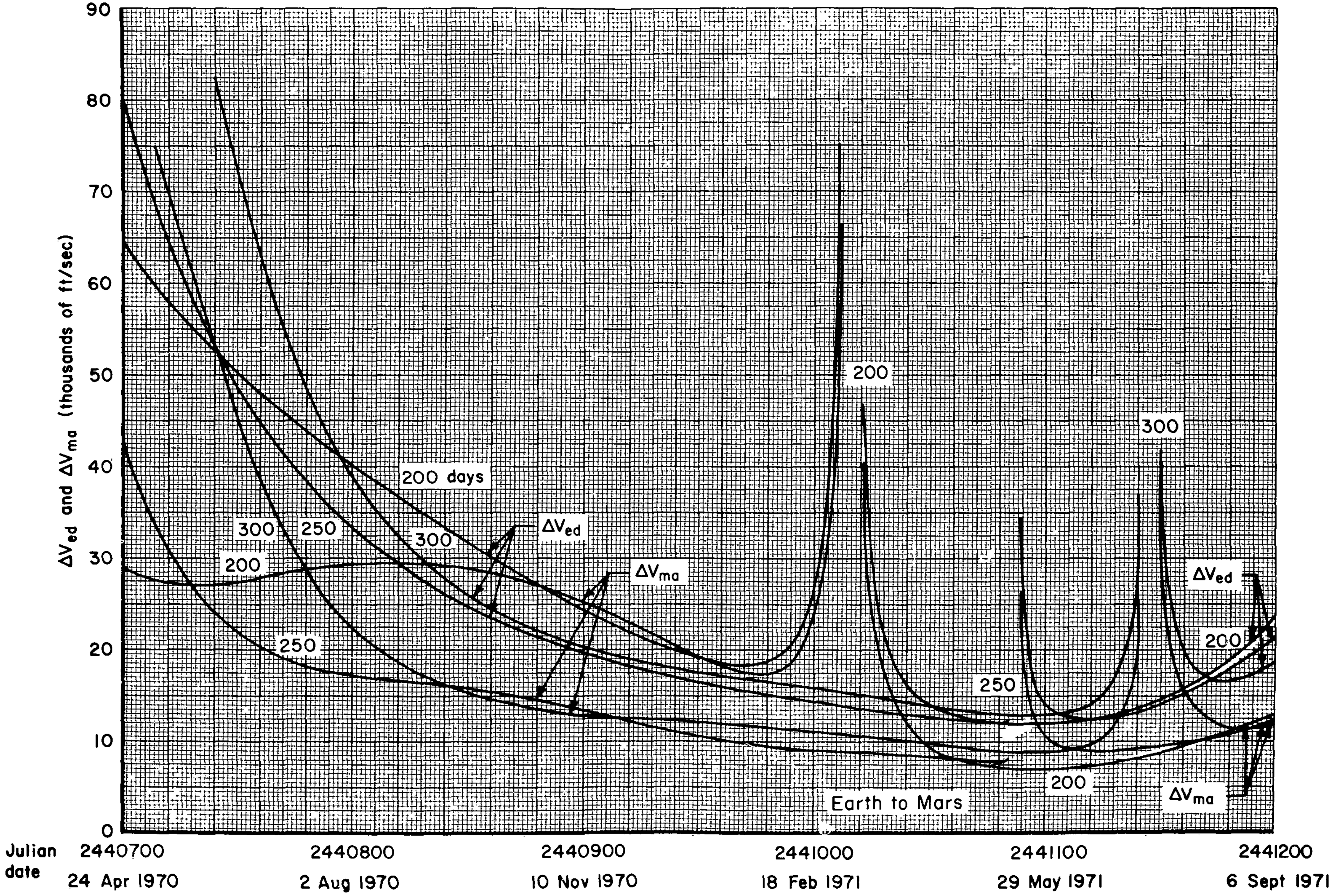

Fig. 2c—Earth departure date versus ΔV_{ed} and ΔV_{ma} for constant transfer times (200, 250, 300 days)

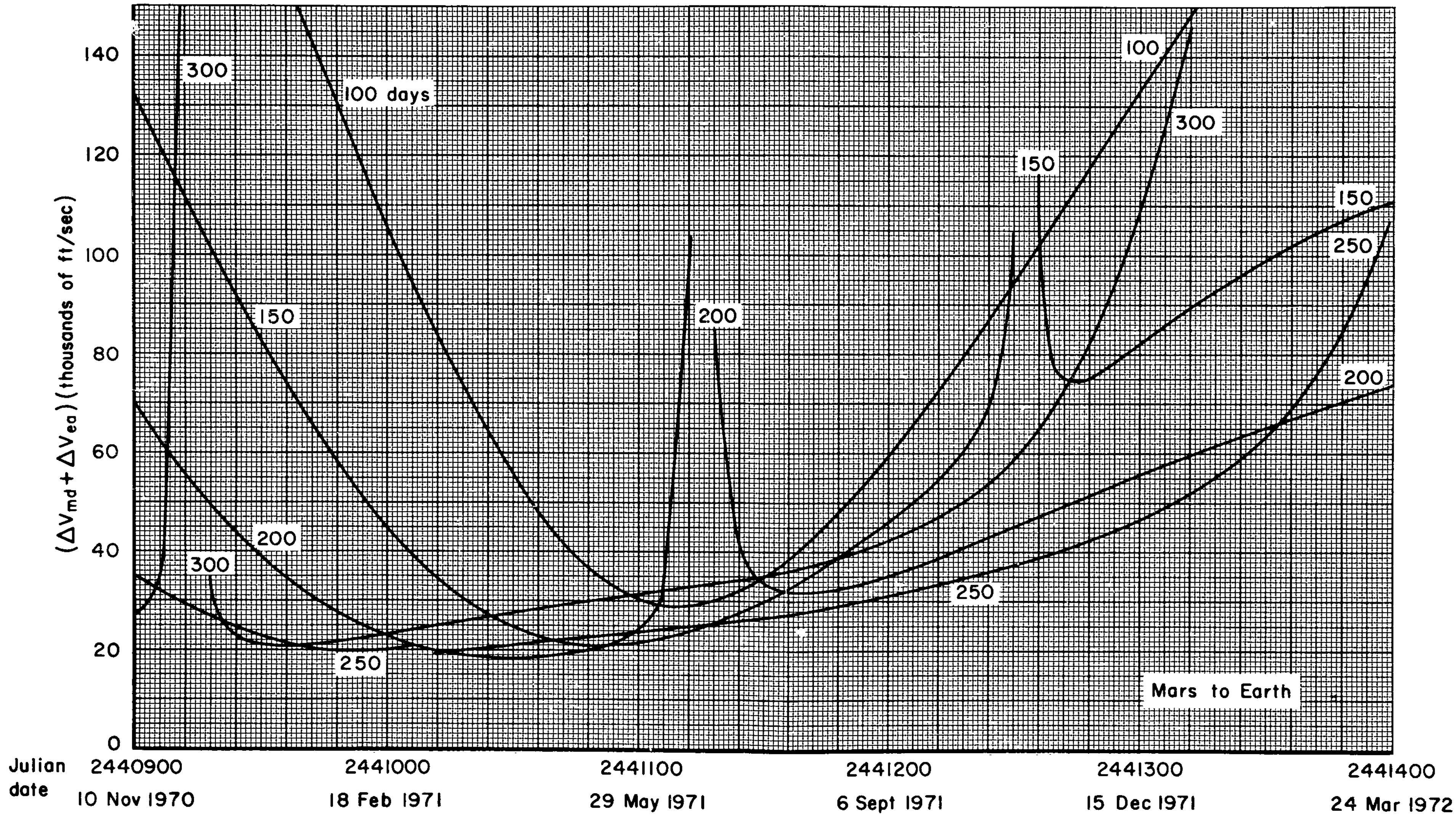

Fig. 3a— Mars departure date versus ($\Delta V_{md} + \Delta V_{ea}$) for constant transfer times (10 Nov 1970 – 24 Mar 1972)

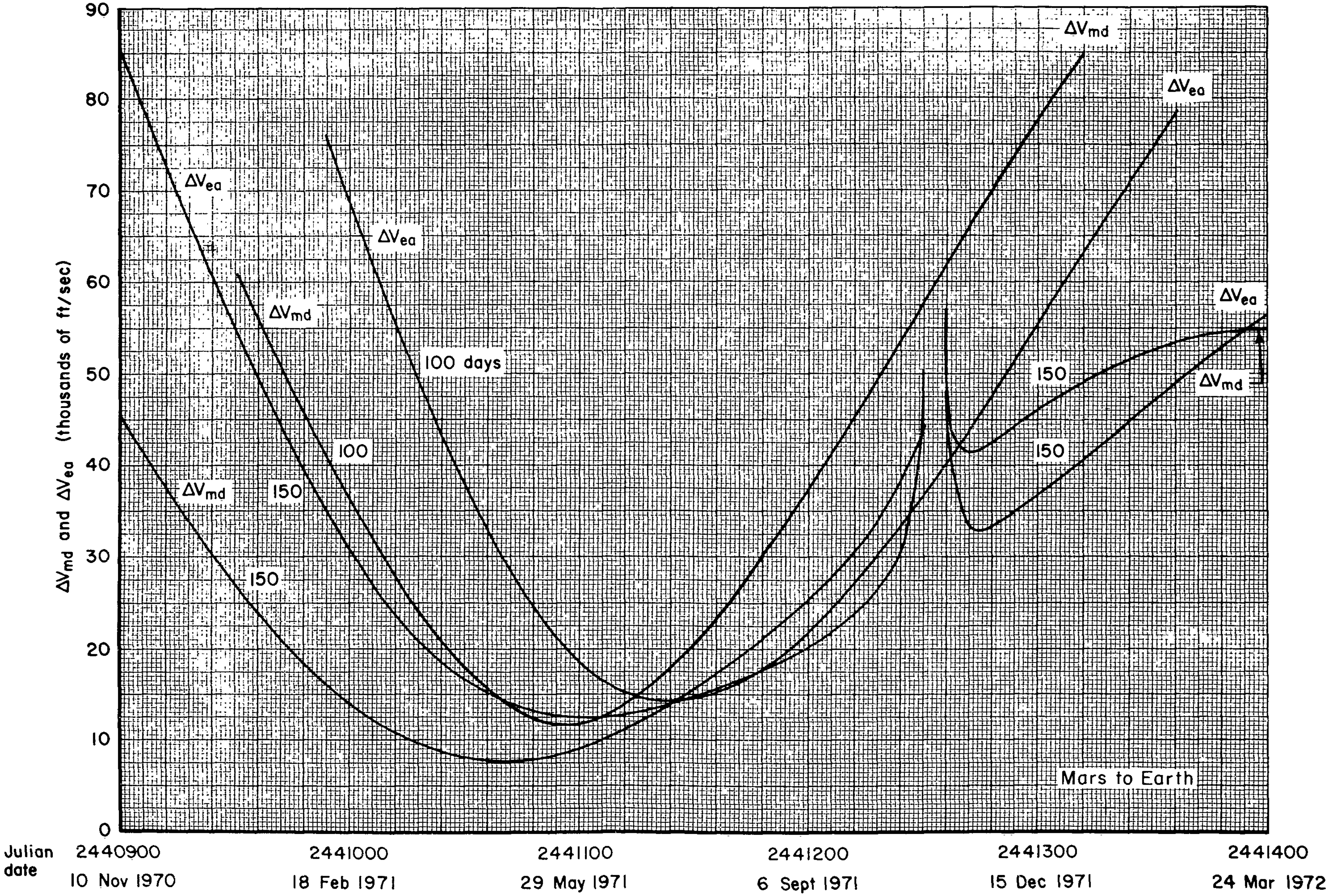

Fig. 3b—Mars departure date versus ΔV_{md} and ΔV_{ea} for constant transfer times (100, 150 days)

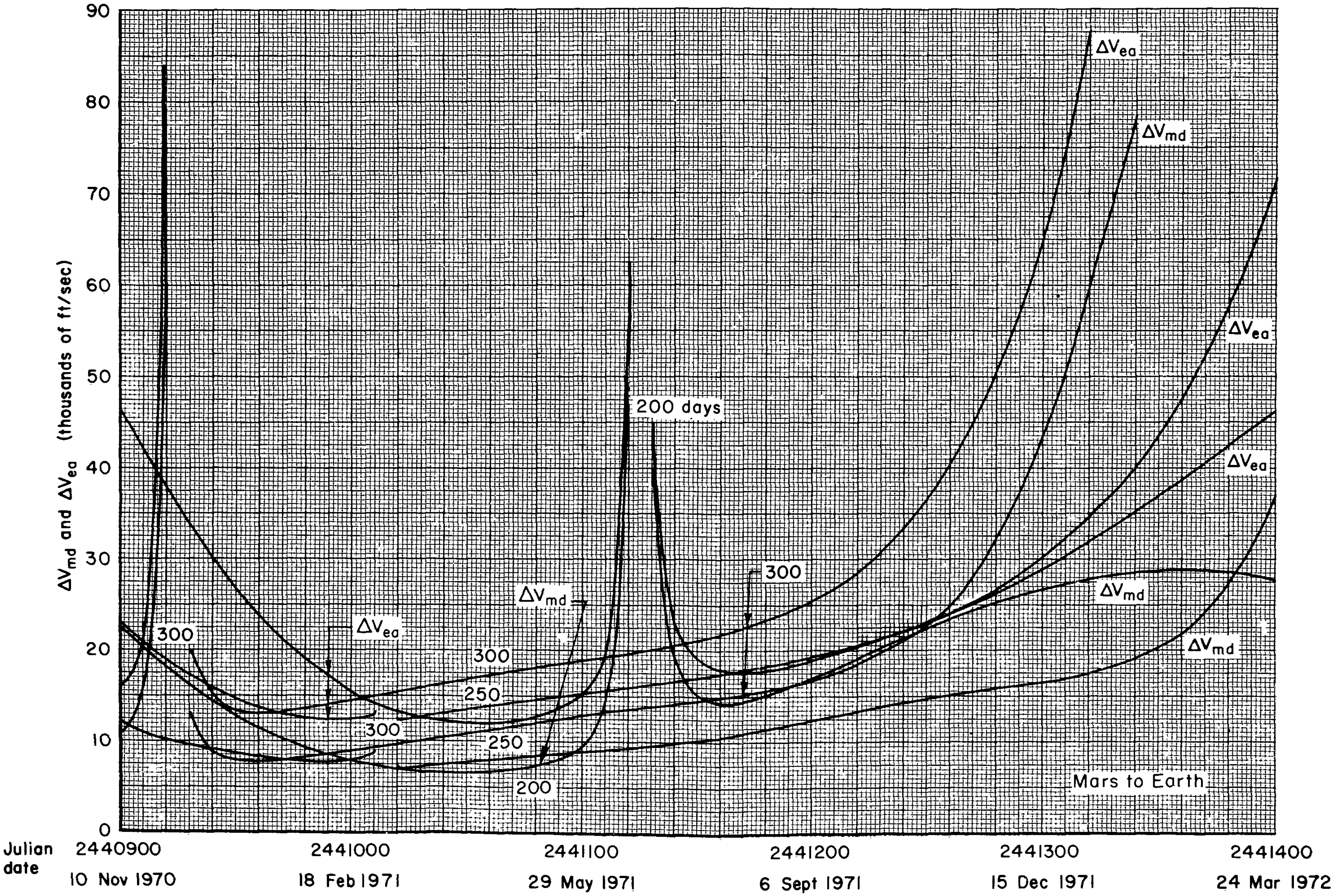

Fig. 3c — Mars departure date versus ΔV_{md} and ΔV_{ea} for constant transfer times (200, 250, 300 days)

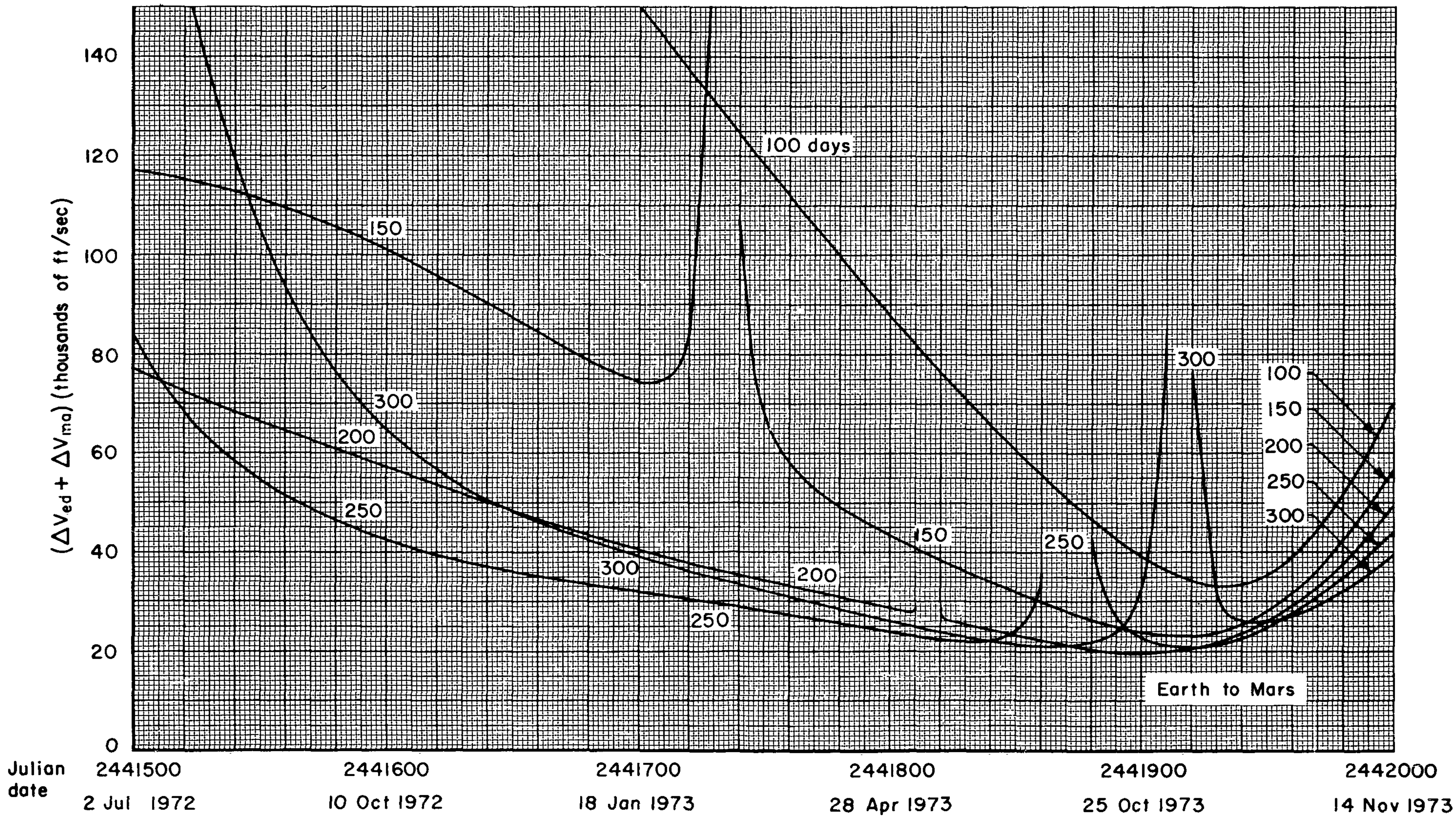

Fig. 4a— Earth departure date versus $(\Delta V_{ed} + \Delta V_{ma})$ for constant transfer times (2 Jul 1972 – 14 Nov 1973)

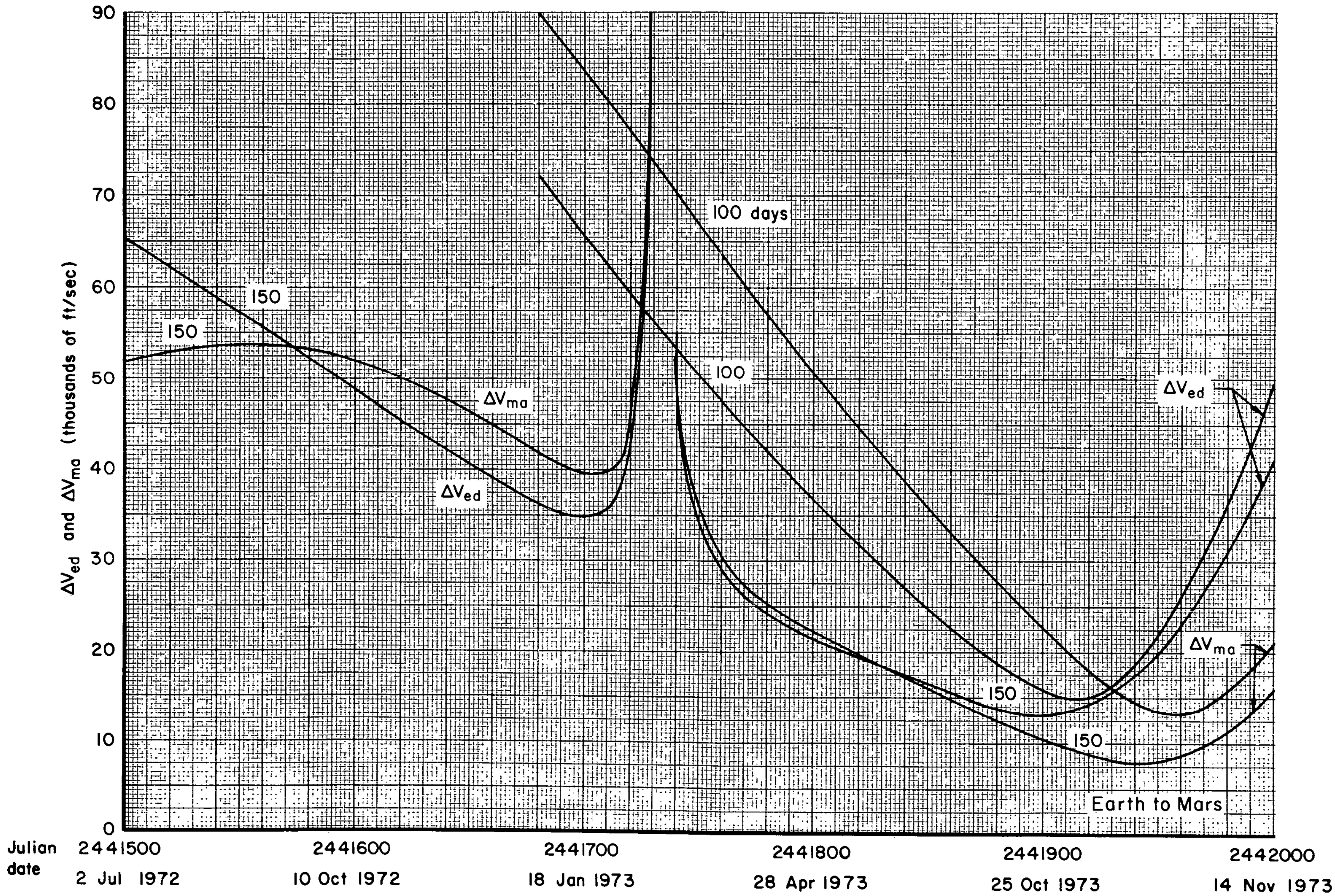

Fig. 4b — Earth departure date versus ΔV_{ed} and ΔV_{ma} for constant transfer times (100, 150 days)

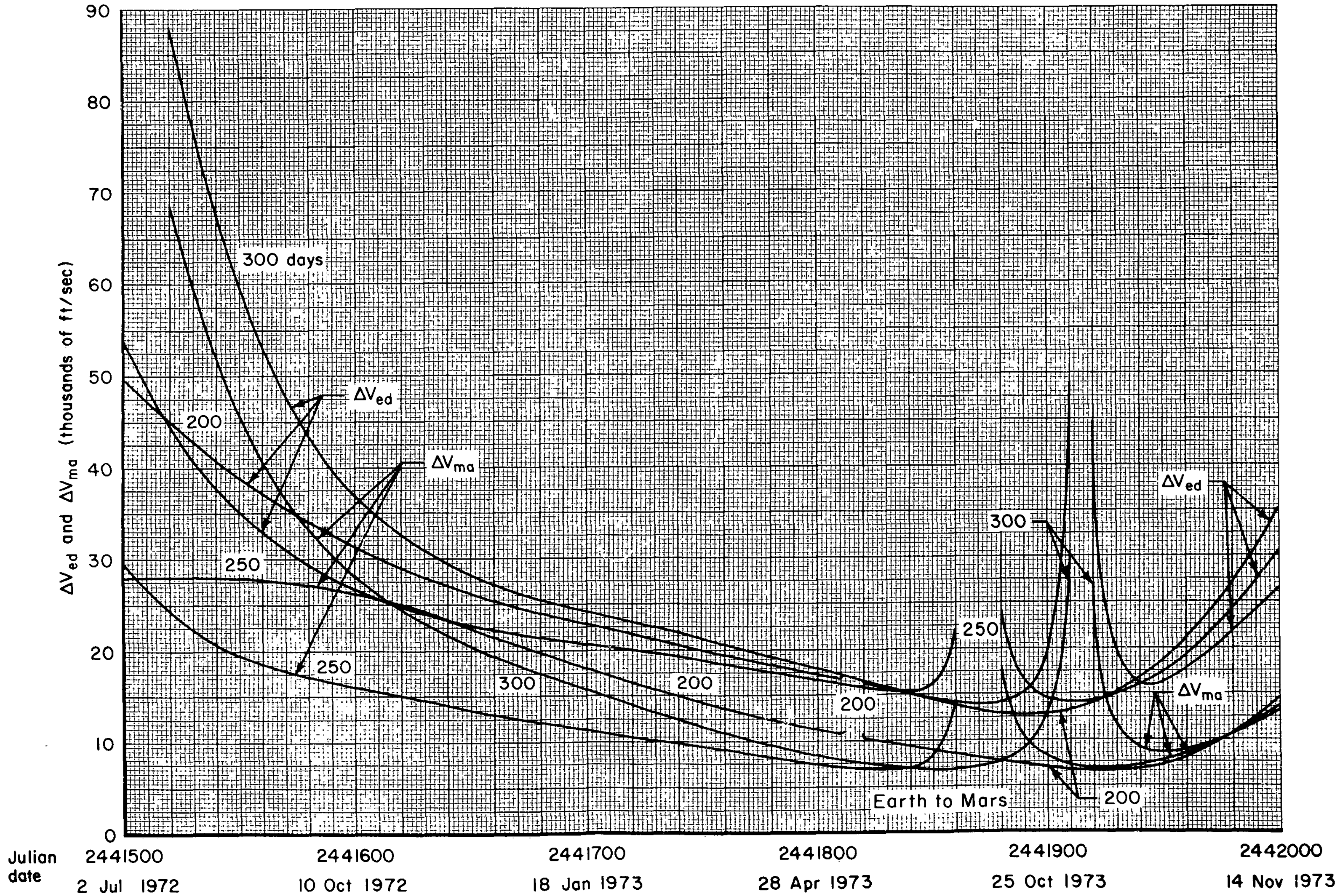

Fig. 4c — Earth departure date versus ΔV_{ed} and ΔV_{ma} for constant transfer times (200, 250, 300 days)

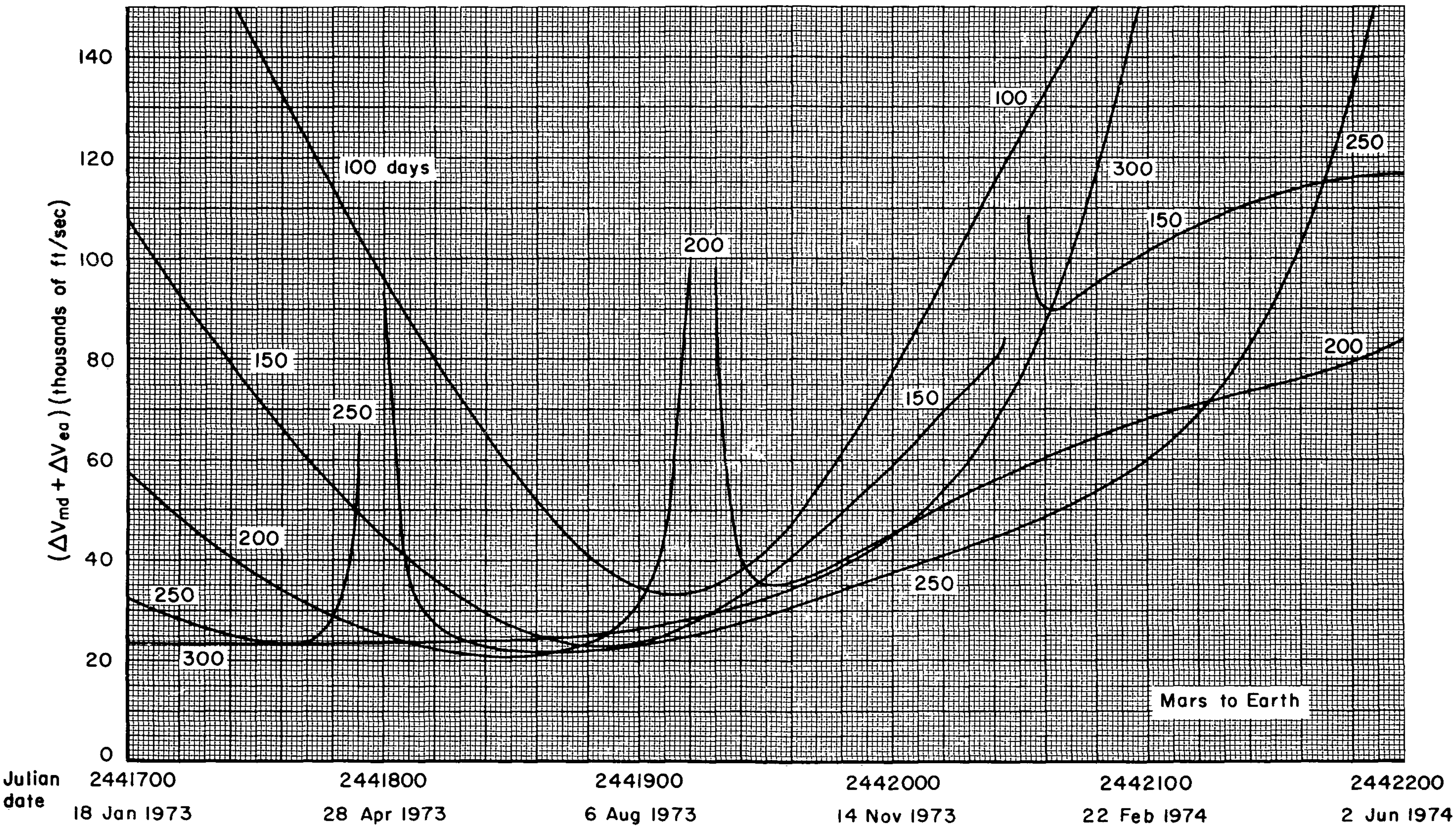

Fig. 5a— Mars departure date versus $(\Delta V_{md} + \Delta V_{ea})$ for constant transfer times (18 Jan 1973 - 2 Jun 1974)

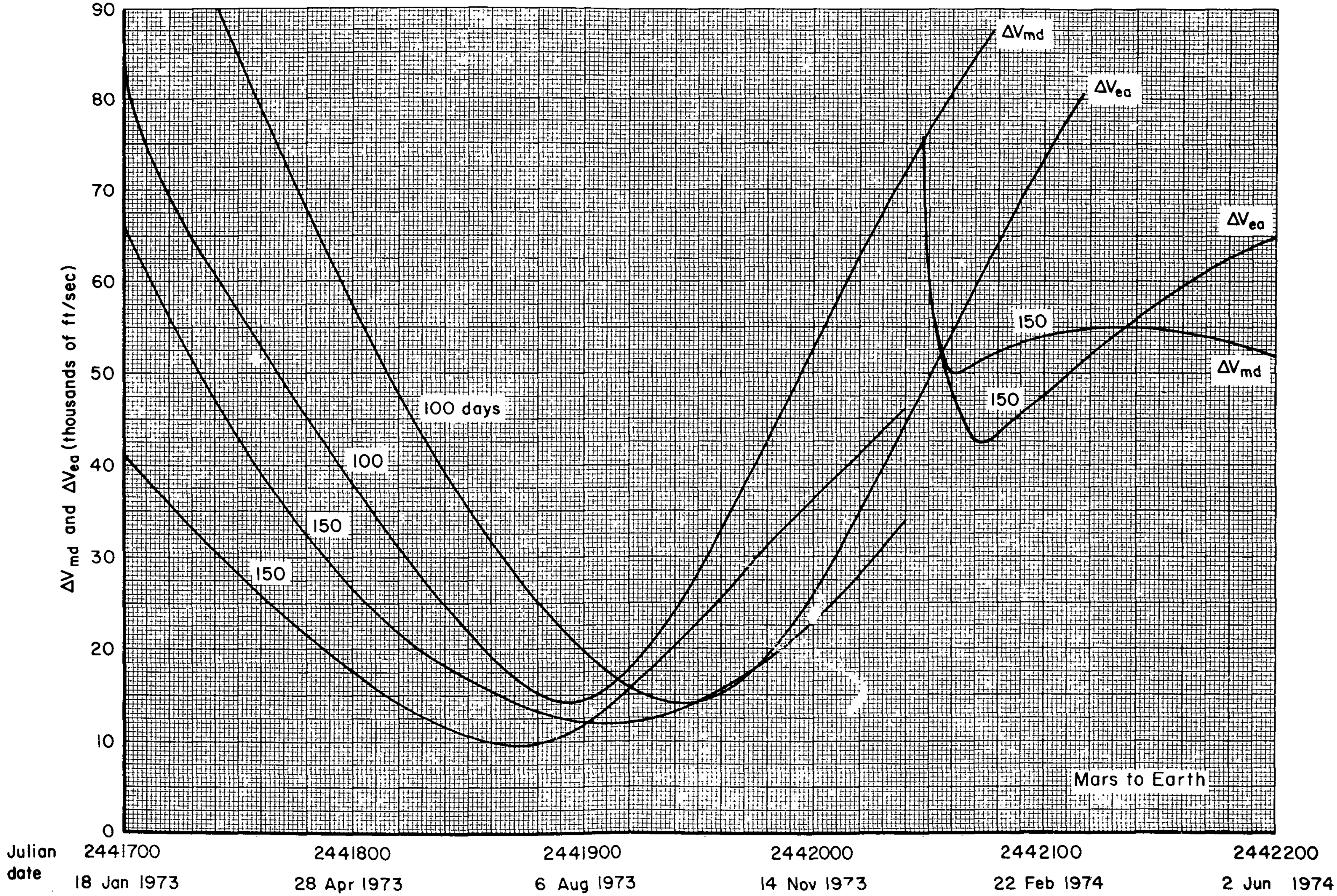

Fig. 5b—Mars departure date versus ΔV_{md} and ΔV_{ea} for constant transfer times (100, 150 days)

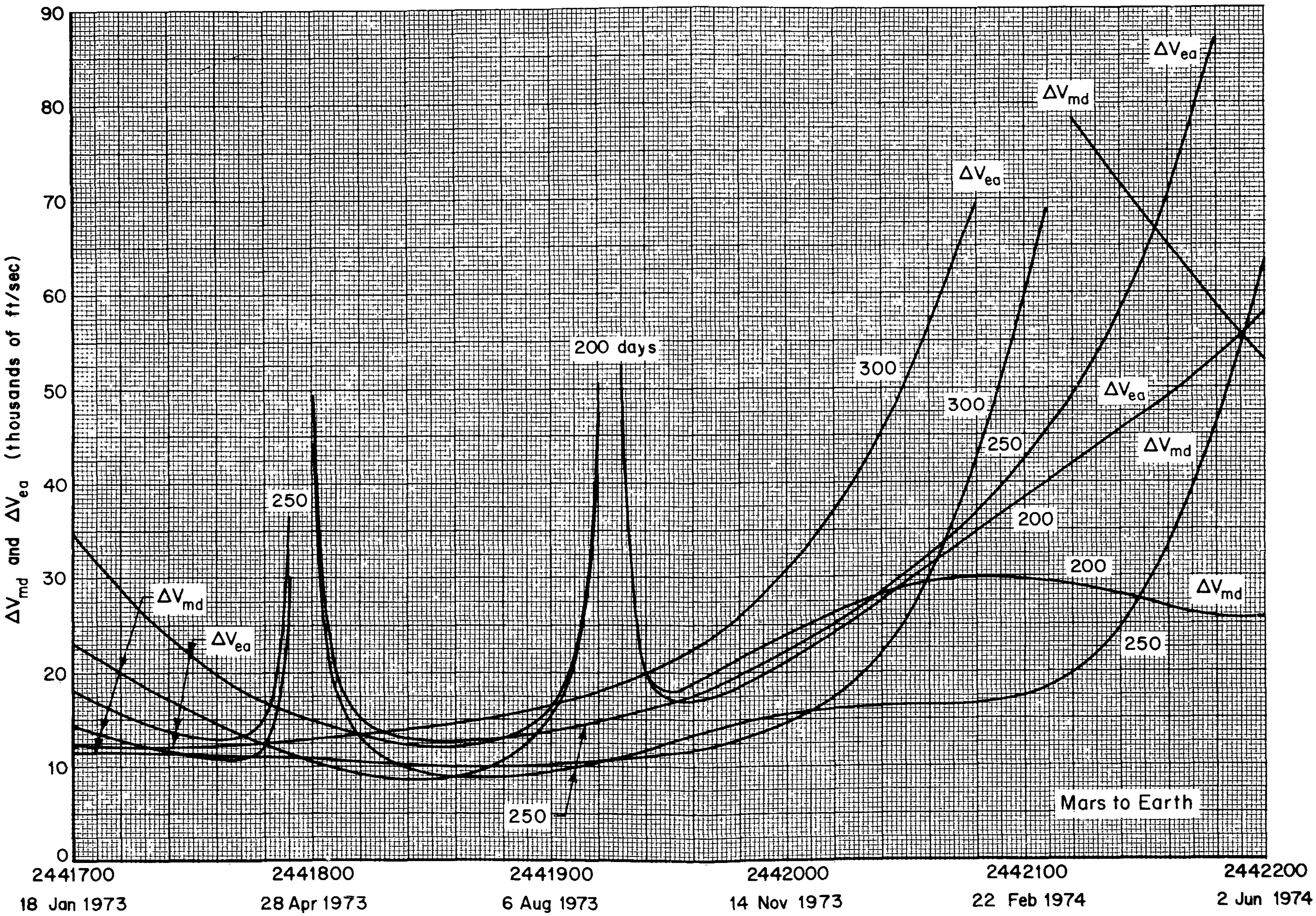

Fig. 5c—Mars departure date versus ΔV_{md} and ΔV_{ea} for constant transfer times (200, 250, 300 days)

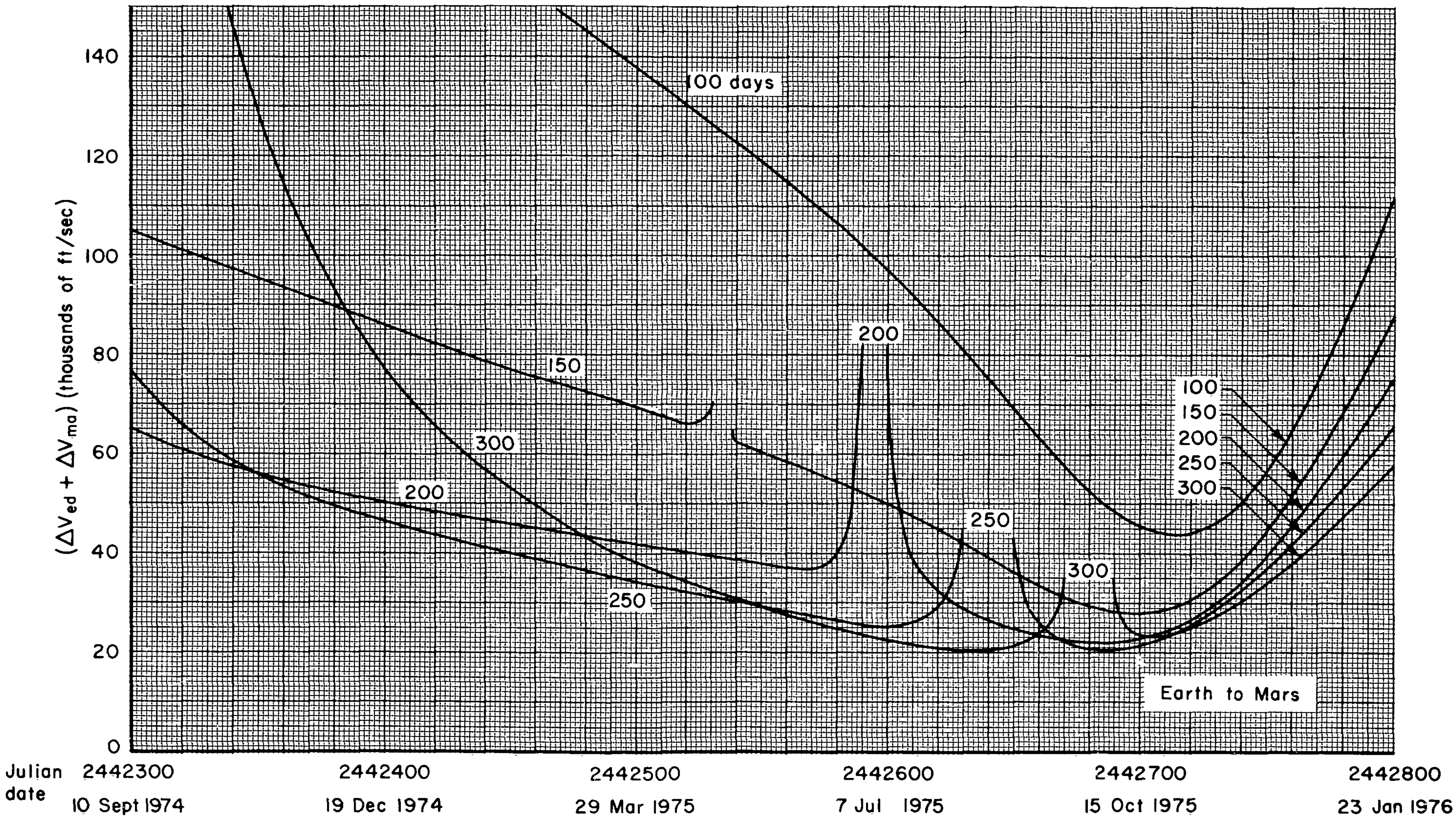

Fig. 6a— Earth departure date versus ($\Delta V_{ed} + \Delta V_{ma}$) for constant transfer times (10 Sept 1974 – 23 Jan 1976)

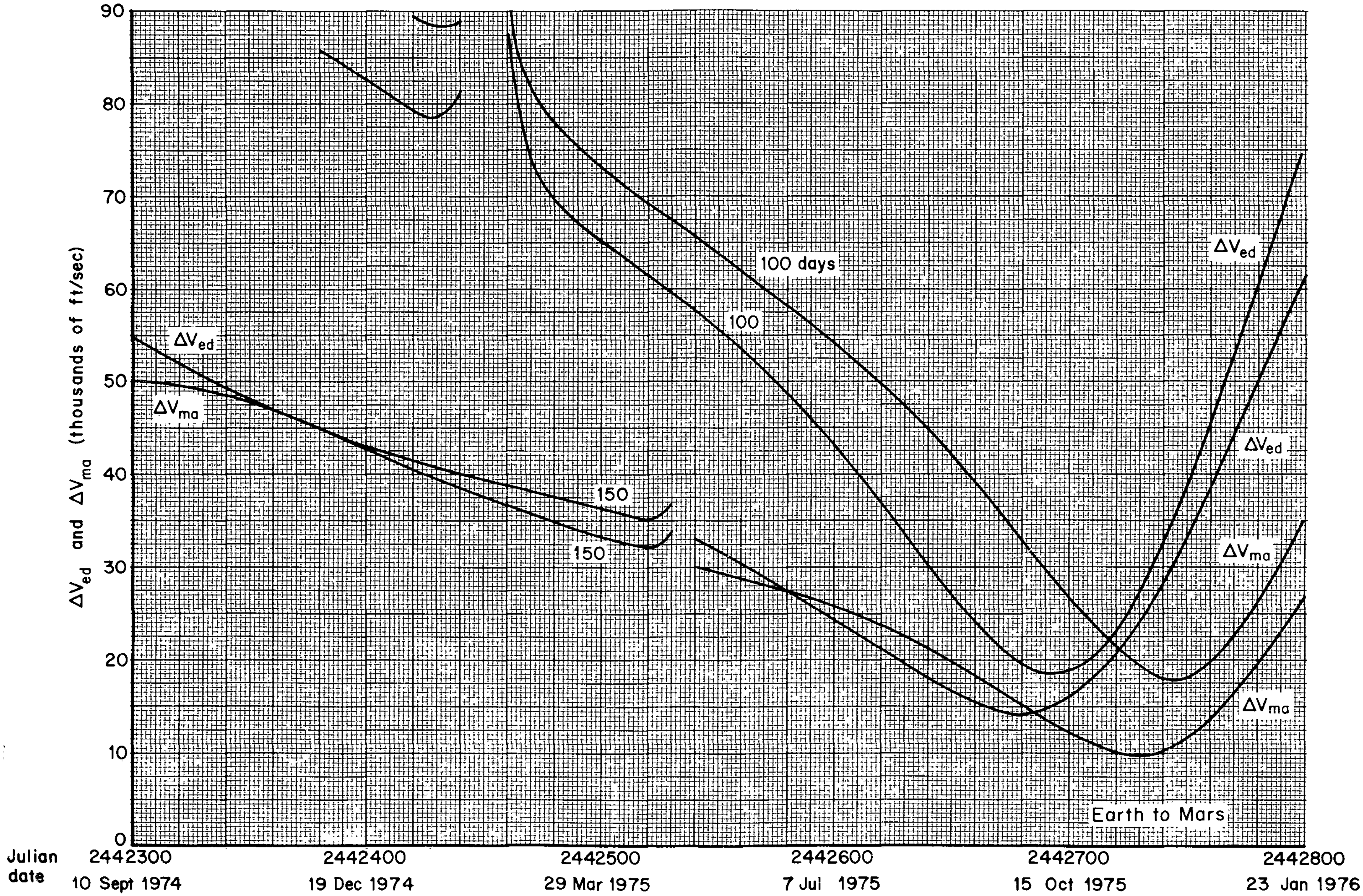

Fig. 6b—Earth departure date versus ΔV_{ed} and ΔV_{ma} for constant transfer times

(100, 150 days)

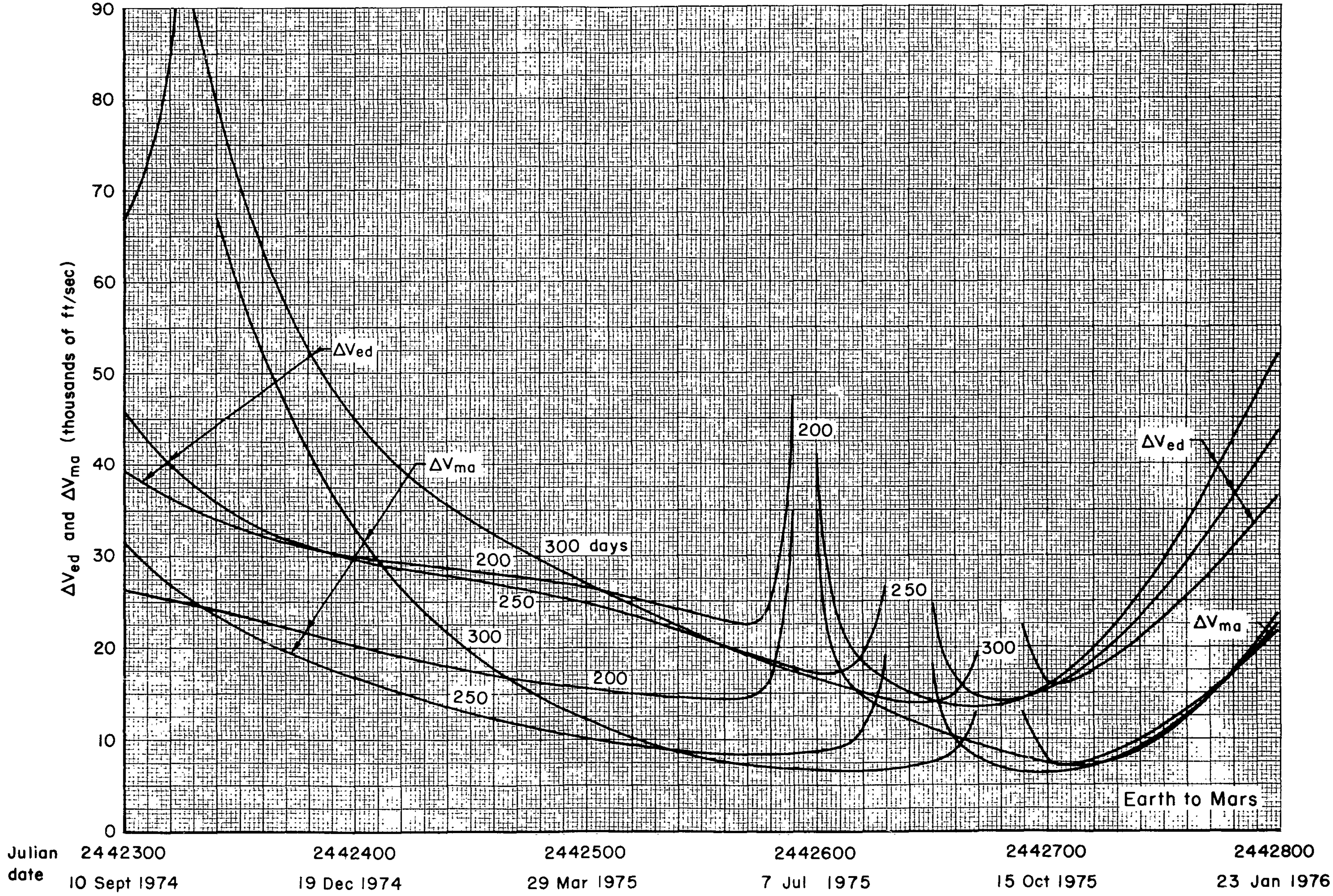

Fig. 6c — Earth departure time versus ΔV_{ed} and ΔV_{ma} for constant transfer times (200, 250, 300 days)

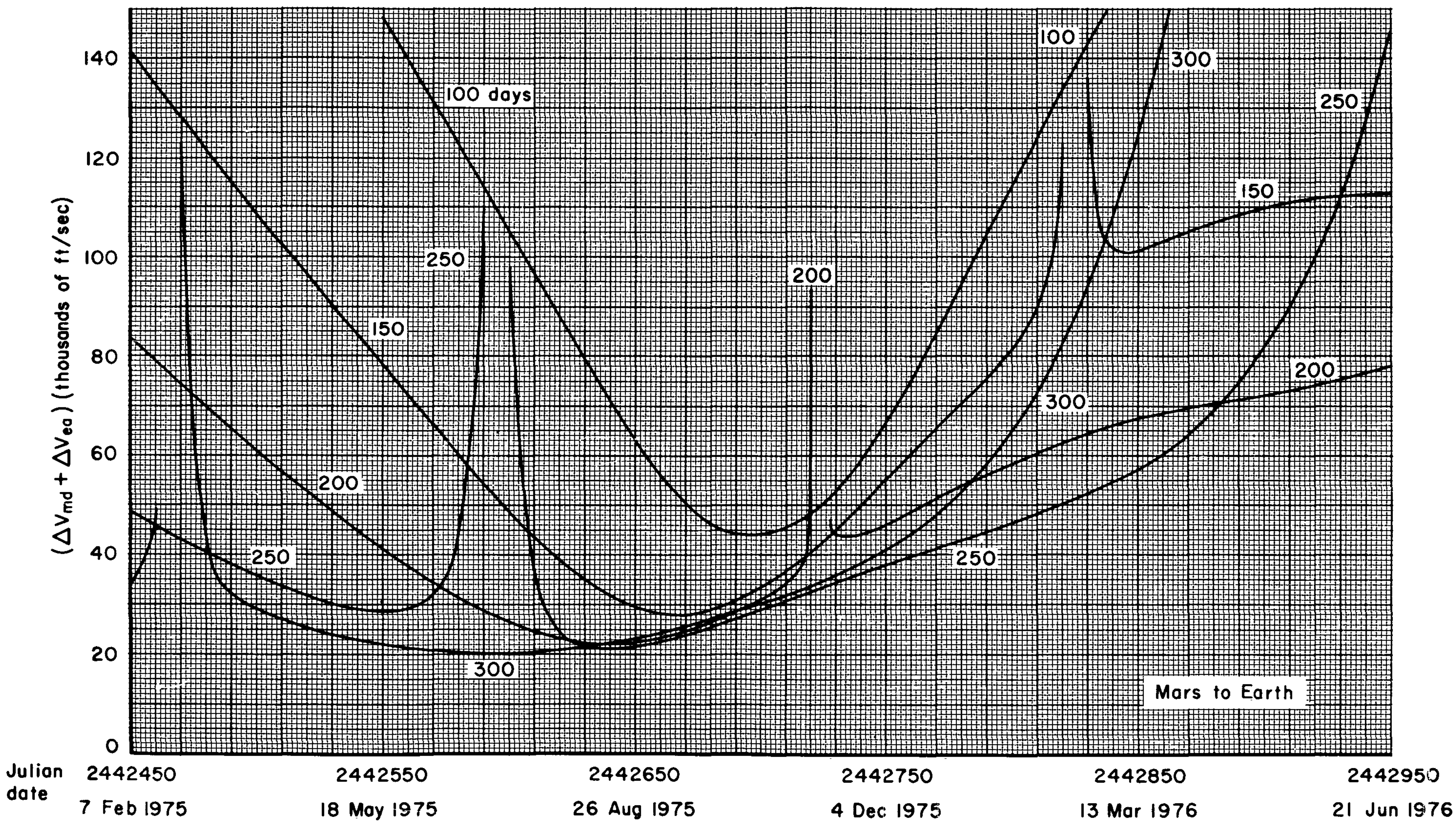

Fig. 7a— Mars departure date versus ($\Delta V_{md} + \Delta V_{ea}$) for constant transfer times (7 Feb 1975 - 21 Jun 1976)

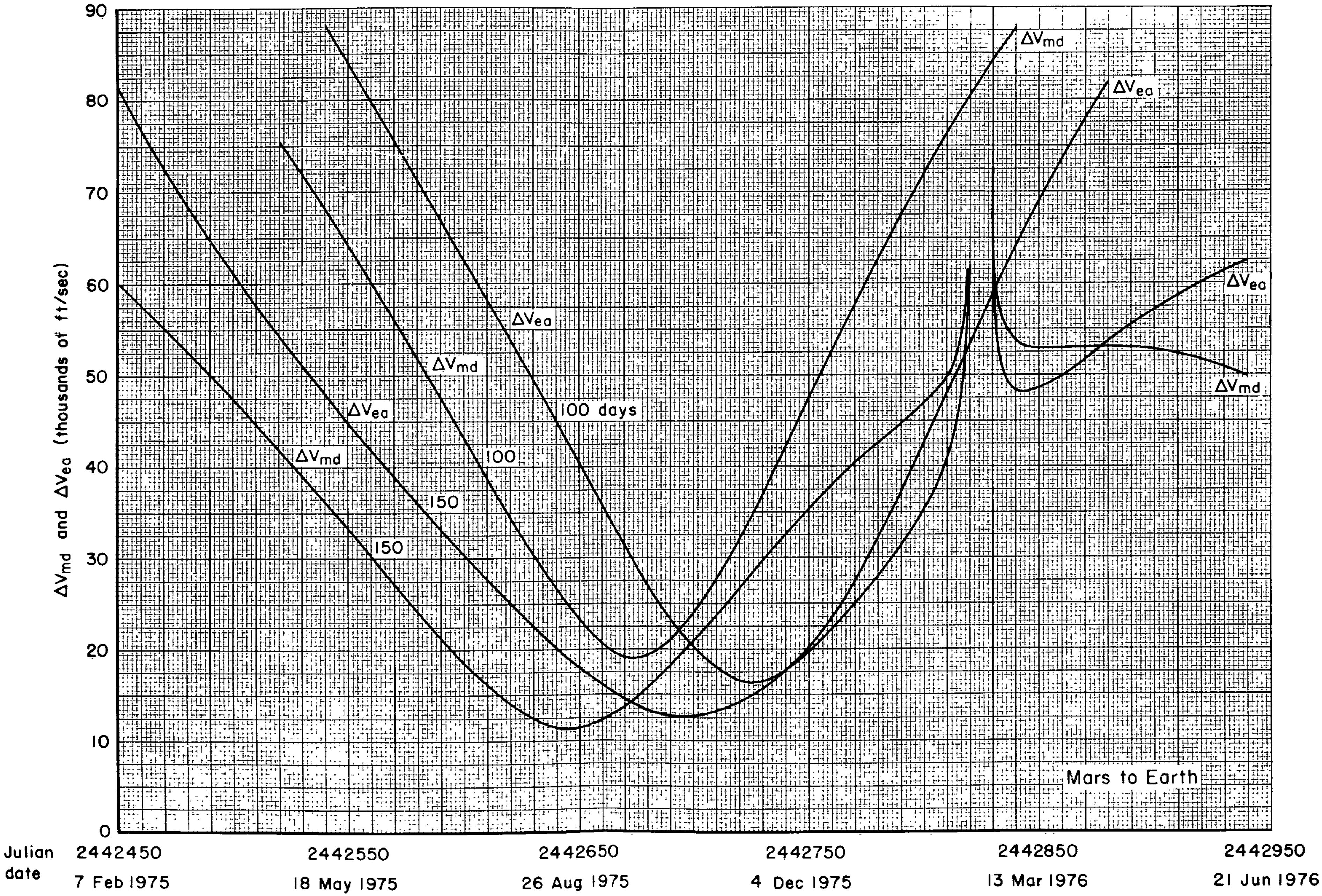

Fig. 7b—Mars departure date versus ΔV_{md} and ΔV_{ea} for constant transfer times (100, 150 days)

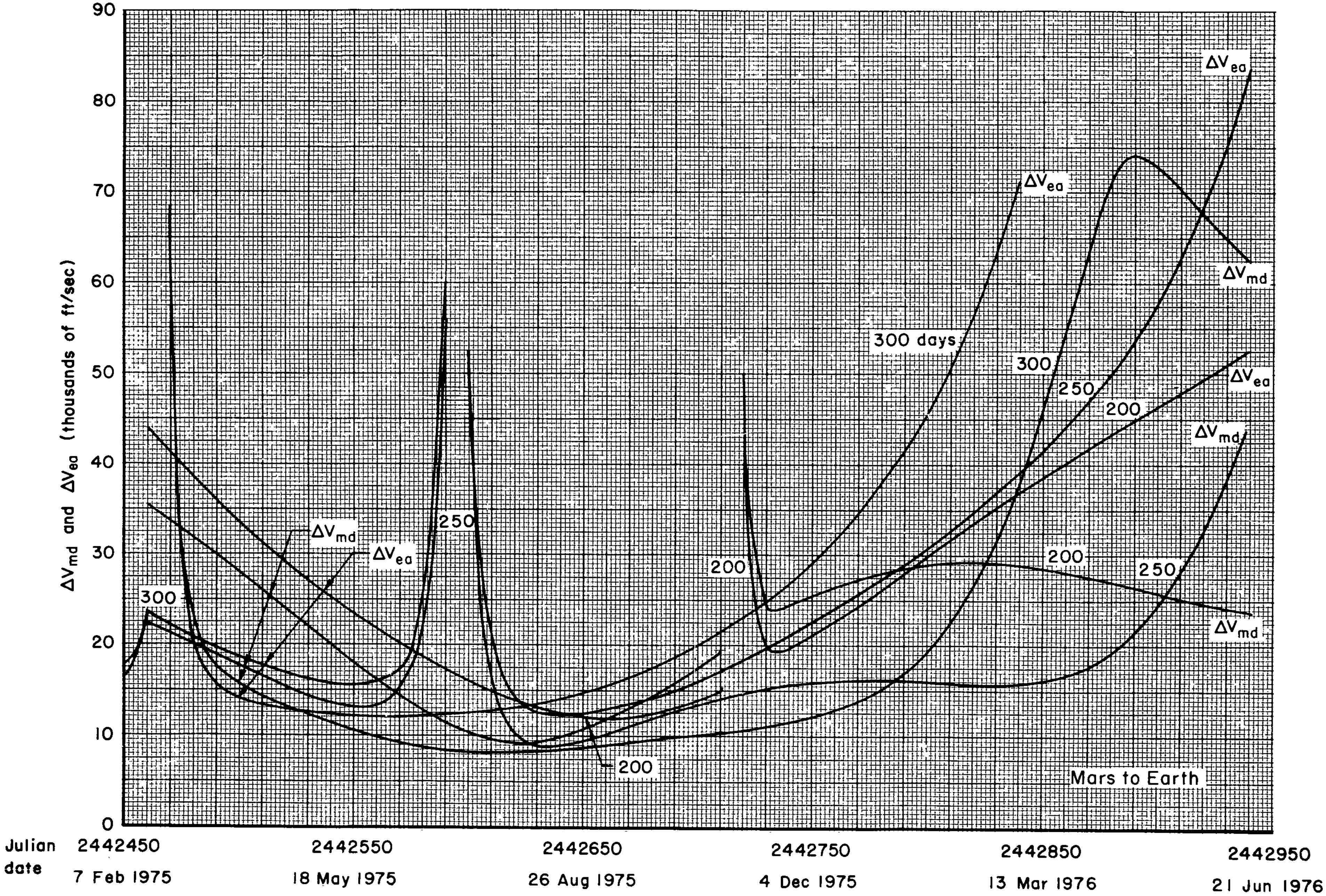

Fig. 7c — Mars departure date versus ΔV_{md} and ΔV_{ea} for constant transfer times (200, 250, 300 days)

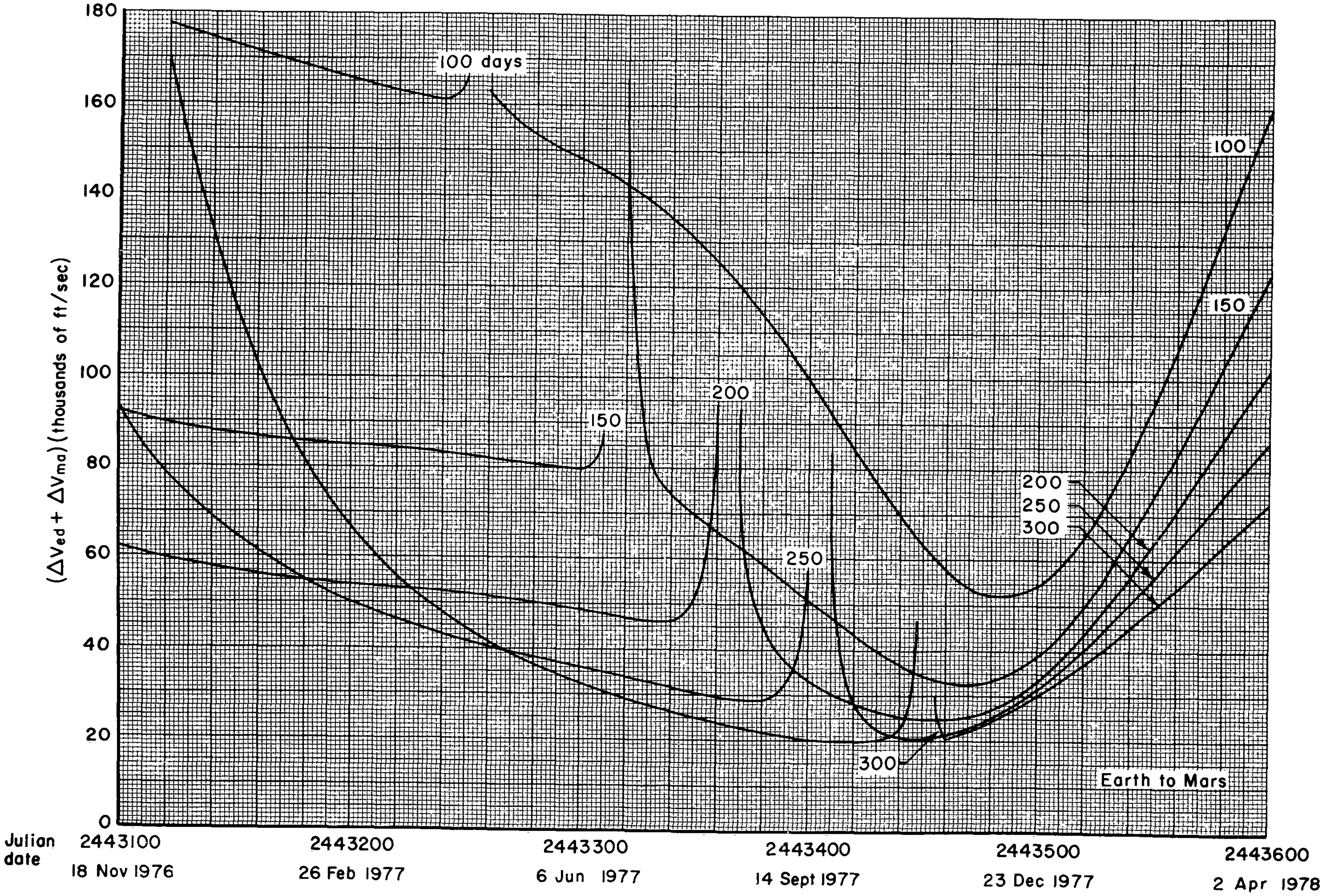

Fig. 8a — Earth departure date versus ($\Delta V_{ed} + \Delta V_{ma}$) for constant transfer times (18 Nov 1976–2 Apr 1978)

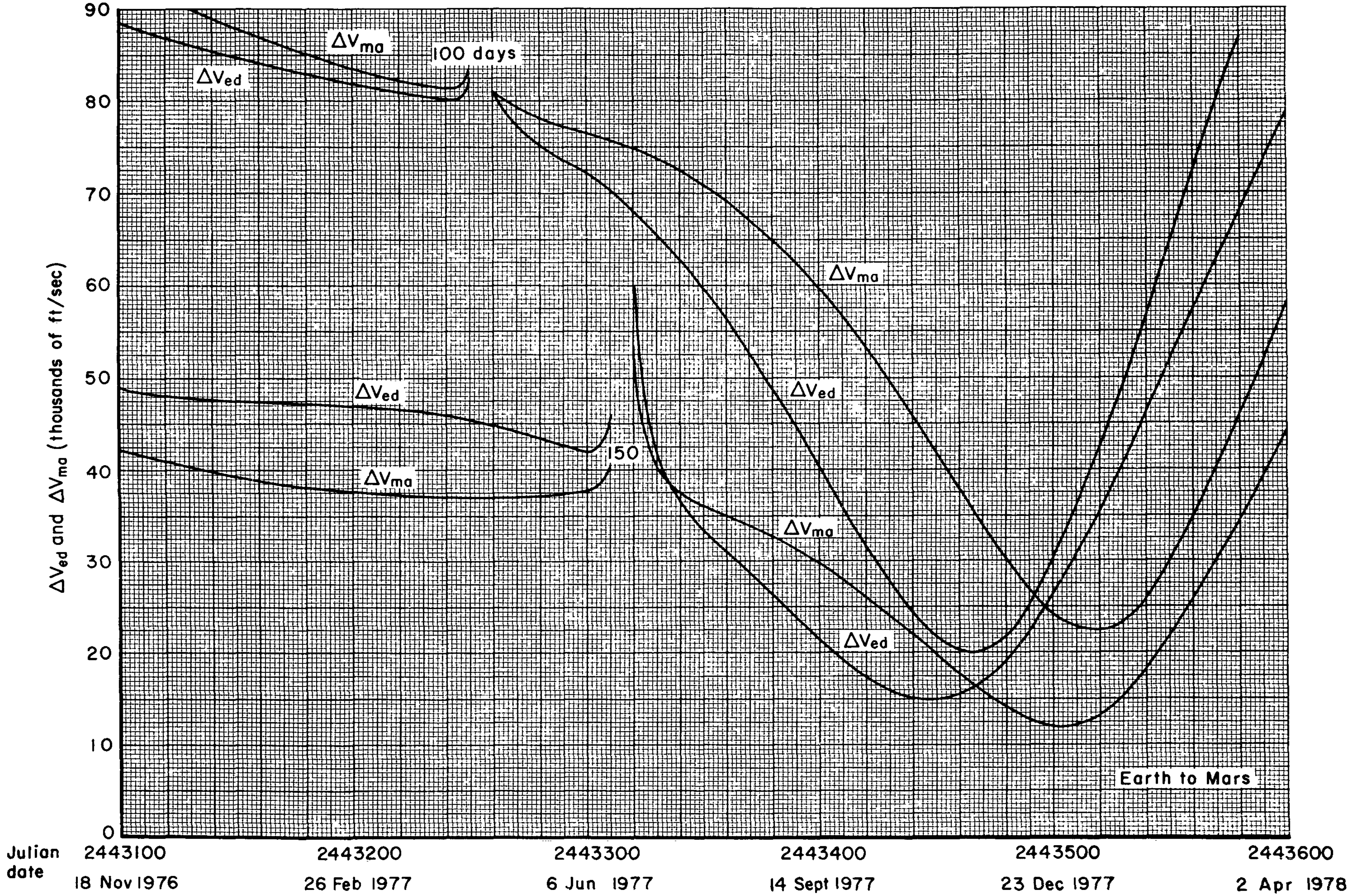

Fig. 8b — Earth departure date versus ΔV_{ed} and ΔV_{ma} for constant transfer times (100, 150 days)

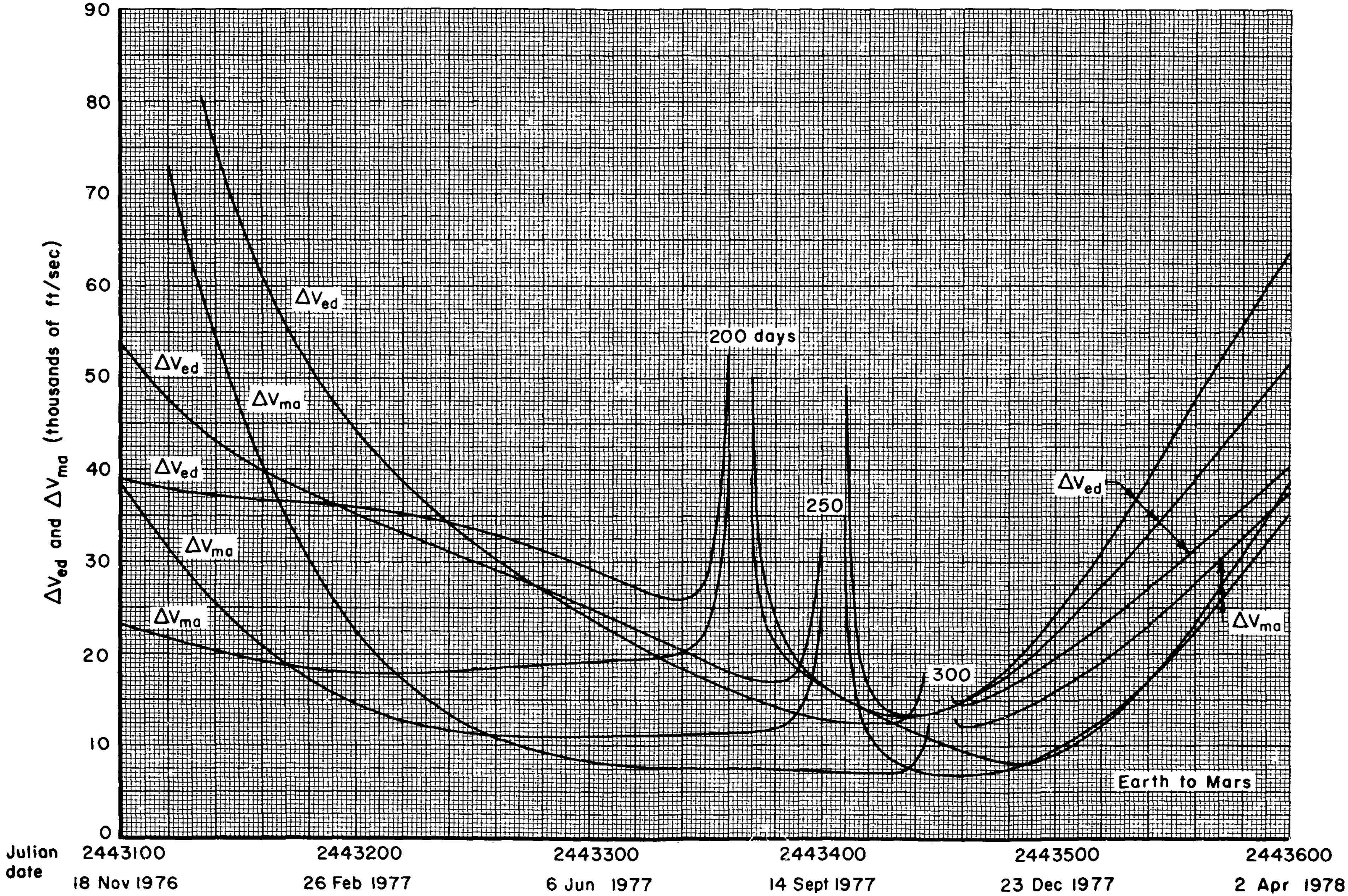

Fig. 8c — Earth departure date versus ΔV_{ed} and ΔV_{ma} for constant transfer times (200, 250, 300 days)

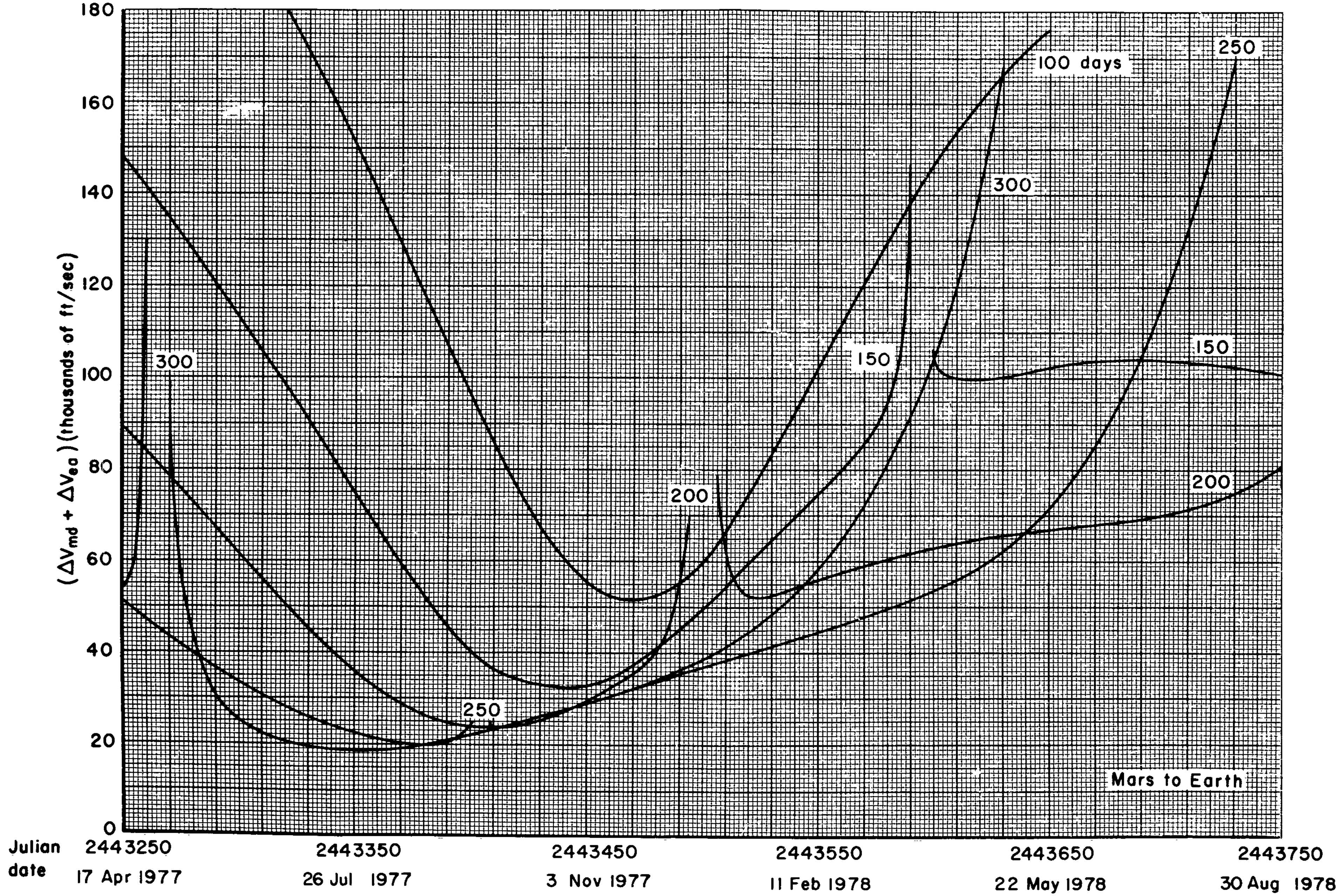

Fig. 9a — Mars departure date versus ($\Delta V_{md} + \Delta V_{ea}$) for constant transfer times (17 Apr 1977–30 Aug 1978)

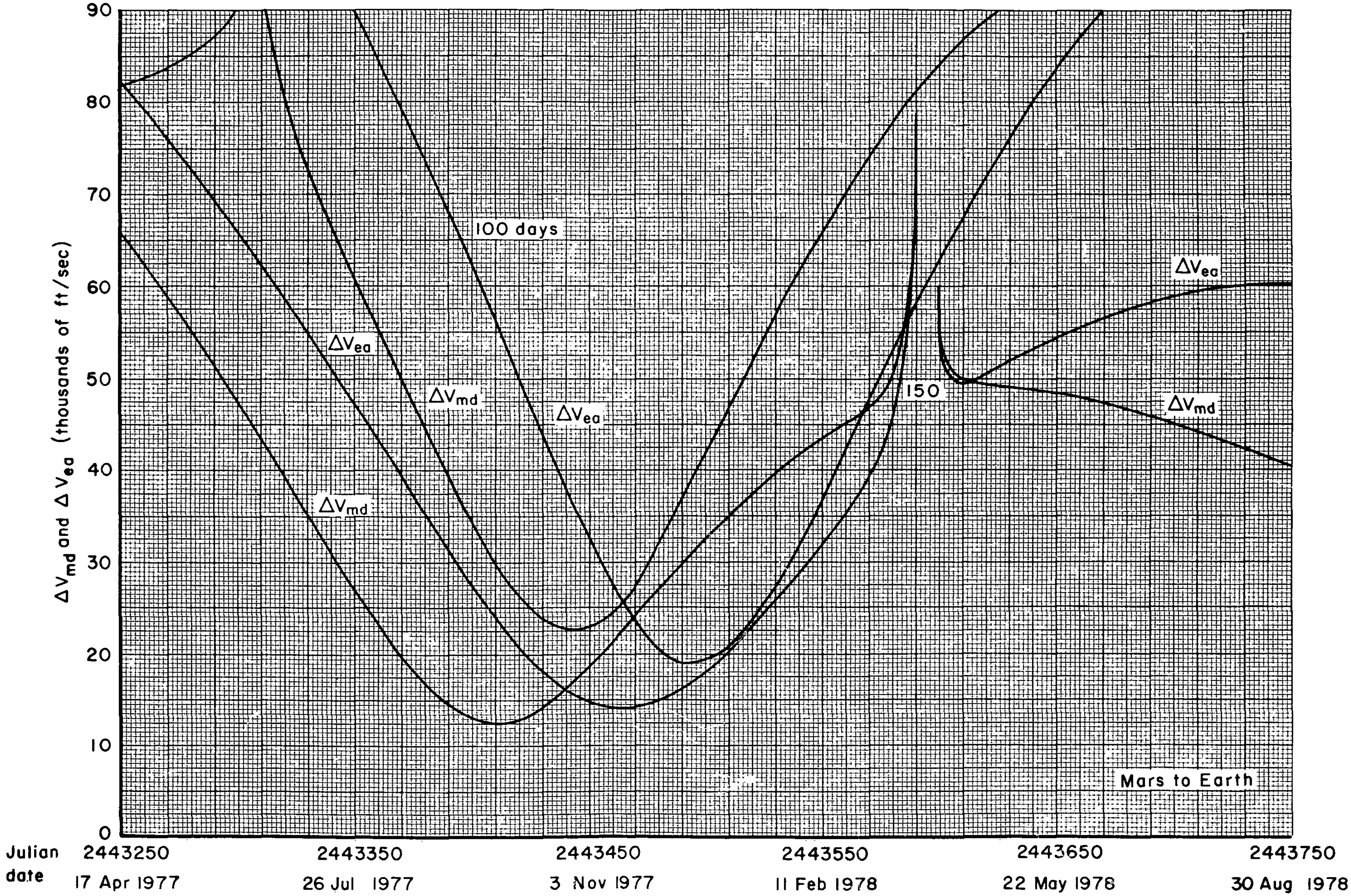

Fig. 9b — Mars departure date versus ΔV_{md} and ΔV_{ea} for constant transfer times (100, 150 days)

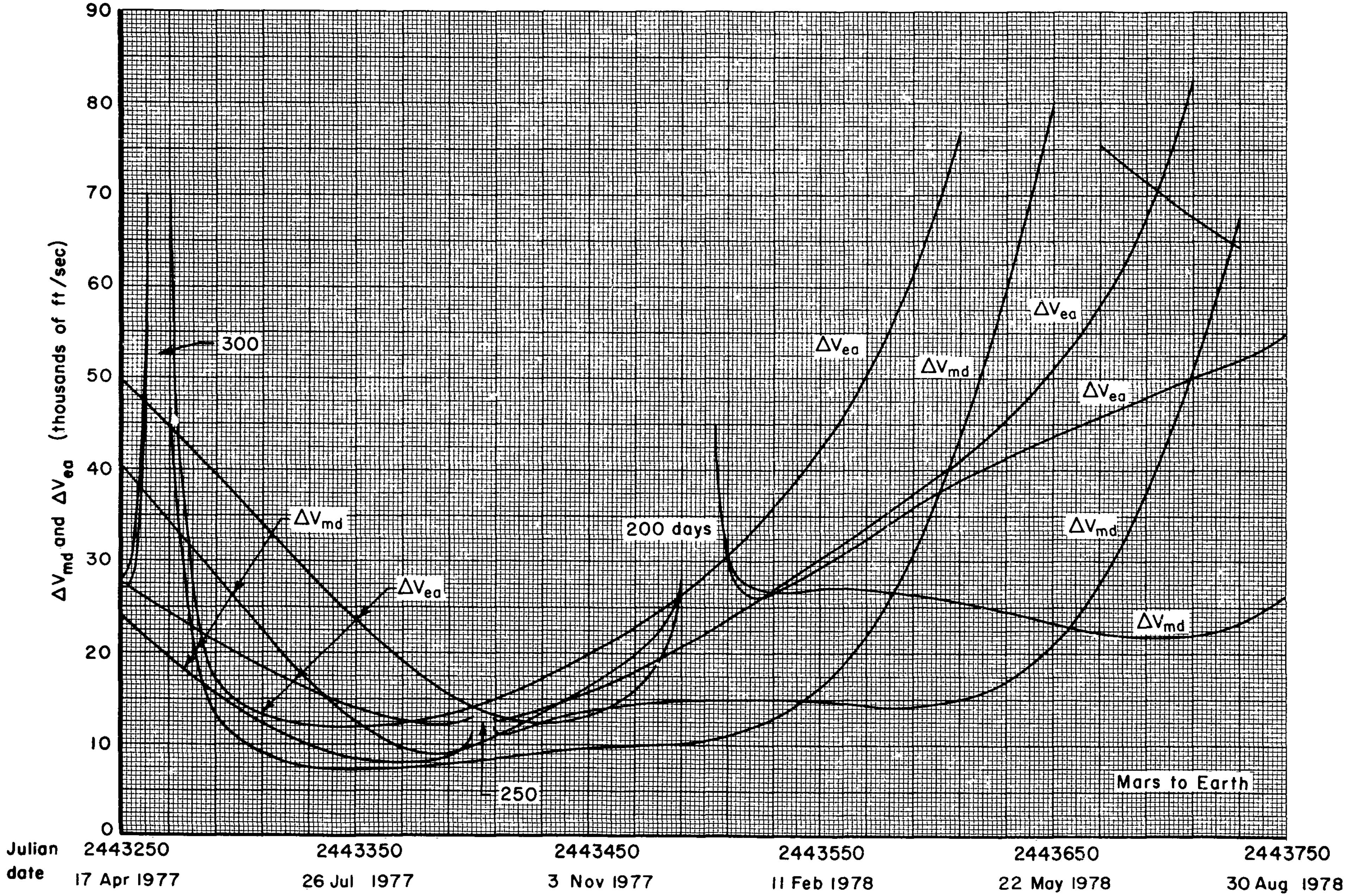

Fig. 9c — Mars departure date versus ΔV_{md} and ΔV_{ea} for constant transfer times (200, 250, 300 days)

Departure dates from Earth are near the Hohmann departure dates of April 1971 and April 1975.

By using Figs. 2, 3, 6, and 7 and trial and error, the Earth departure dates for minimum total velocity can be found. The departure dates and other pertinent data are shown in Table 1.

If the required total velocity increment is to be minimized, the exact departure dates can be determined from the figures or, for these particular cases, from Table 2. Table 3 can be used to convert Julian dates to calendar dates for the period of interest.

Table 1

DEPARTURE DATES FOR MINIMUM TOTAL VELOCITY INCREMENTS (EXAMPLE 1)

Item	Date	Velocity Increment (ft/sec)	Date	Velocity Increment (ft/sec)
Mission 1[a]				
Earth departure	4-29-71	12,600	4-18-75	34,600
Mars arrival	9-26-71	13,000	9-15-75	31,900
Mars departure	9-26-71	18,900	9-15-75	13,000
Earth arrival	4-13-72	20,100	4-2-76	11,700
Total velocity increment, ΔV_T	--	64,600	--	91,200
Mission 2[b]				
Earth departure	12-10-70	20,700	3-1-75	27,800
Mars arrival	6-28-71	21,500	9-15-75	16,600
Mars departure	6-28-71	12,500	9-15-75	13,600
Earth arrival	11-25-71	13,200	2-12-76	14,500
Total velocity increment, ΔV_T	--	67,900	--	72,500

[a] Earth-to-Mars transfer time = 150 days; return time = 200 days.
[b] Earth-to-Mars transfer time = 200 days; return time = 150 days.

Table 2

DATA FOR ROUND-TRIP MISSIONS TO MARS WITH ZERO STAY TIME IN THE MARS PARKING ORBIT

			Departure from Earth 1971				Departure from Earth 1975			
Time Going (days)	Time Return (days)	Mission Time (days)	Depart Earth (Julian Date)	$\Delta V_{ed} + \Delta V_{ma}$ (ft/sec)	$\Delta V_{md} + \Delta V_{ea}$ (ft/sec)	ΔV_T (ft/sec)	Depart Earth (Julian Date)	$\Delta V_{ed} + \Delta V_{ma}$ (ft/sec)	$\Delta V_{md} + \Delta V_{ea}$ (ft/sec)	ΔV_T (ft/sec)
100	100	200	2441080	43,800	48,300	92,100	2442630	80,800	53,000	133,800
100	150	250	1100	35,200	46,000	81,200	2670	57,800	65,400	123,200
100	200	300	1120	30,000	38,900	68,900	2700	45,600	58,100	103,700
100	250	350	1120	30,000	33,500	63,500	2700	45,600	46,500	92,100
100	300	400	1110	32,100	44,600	76,700	2680	52,700	52,500	105,200
150	100	250	1010	44,000	39,000	83,000	2560	58,900	45,400	104,300
150	150	300	1030	36,900	38,800	75,700	2540	62,900	30,800	93,700
150	200	350	1070	25,600	39,000	64,600	2520	66,500	24,700	91,200
150	250	400	1090	22,200	36,100	58,300	2670	31,500	50,000	81,500
150	300	450	1060	28,000	44,500	72,500	2570	56,800	33,500	90,300
200	100	300	0940	40,200	32,100	72,300	2500	42,100	43,900	86,000
200	150	350	0930	42,200	25,600	67,800	2470	44,400	28,100	72,500
200	200	400	1060	20,700	47,500	68,200	2460	45,100	23,300	68,400
200	250	450	1060	20,700	39,300	60,000	2450	46,000	21,800	67,800
200	300	500	0960	36,800	36,500	73,300	2440	46,900	22,300	69,200
250	100	350	0880	35,600	30,100	65,700	2450	40,000	44,000	84,000
250	150	400	0870	37,100	23,900	61,000	2430	42,400	29,000	71,400
250	200	450	0840	42,000	21,400	63,400	2420	43,600	24,700	68,300
250	250	500	0940	27,900	30,100	58,000	2410	45,000	22,600	67,600
250	300	550	0920	30,000	37,800	67,800	2420	43,600	25,700	69,300
300	100	400	0860	39,100	36,500	75,600	2430	61,100	53,000	114,100
300	150	450	0850	41,500	30,100	71,600	2430	61,200	45,000	106,200
300	200	500	0800	34,000	34,000	68,000	2530	32,600	64,000	96,600
300	250	550	0890	34,000	30,100	64,100	2520	34,500	50,000	84,500
300	300	600	0900	33,000	42,400	75,400	2460	49,900	44,000	93,900

Table 3

JULIAN DAY NUMBER AND CORRESPONDING GREGORIAN CALENDAR DATE

Julian	Calendar	Julian	Calendar	Julian	Calendar
1970		1973		1976	
2440600	Jan 14	2441720	Feb 7	2442800	Jan 23
0640	Feb 23	1760	Mar 19	2840	Mar 3
0680	Apr 4	1800	Apr 28	2880	Apr 12
0720	May 14	1840	Jun 7	2920	May 22
0760	Jun 23	1880	Jul 17	2960	Jul 1
0800	Aug 2	1920	Aug 26	3000	Aug 10
0840	Sep 11	1960	Oct 5	3040	Sep 19
0880	Oct 21	2000	Nov 14	3080	Oct 29
0920	Nov 30	2040	Dec 24	3120	Dec 8
1971		1974		1977	
2440960	Jan 9	2442080	Feb 2	2443160	Jan 17
1000	Feb 18	2120	Mar 14	3200	Feb 26
1040	Mar 30	2160	Apr 23	3240	Apr 7
1080	May 9	2200	Jun 2	3280	May 17
1120	Jun 18	2240	Jul 12	3320	Jun 26
1160	Jul 28	2280	Aug 21	3360	Aug 5
1200	Sep 6	2320	Sep 30	3400	Sep 14
1240	Oct 16	2360	Nov 9	3440	Oct 24
1280	Nov 25	2400	Dec 19	3480	Dec 3
1972		1975		1978	
2441320	Jan 4	2442440	Jan 28	2443520	Jan 12
1360	Feb 13	2480	Mar 9	3560	Feb 21
1400	Mar 24	2520	Apr 18	3600	Apr 2
1440	May 3	2560	May 28	3640	May 12
1480	Jun 12	2600	Jul 7	3680	Jun 21
1520	Jul 22	2640	Aug 16	3720	Jul 31
1560	Aug 31	2680	Sep 25	3760	Sep 9
1600	Oct 10	2720	Nov 4		
1640	Nov 19	2760	Dec 14		
1680	Dec 29				

It is interesting to note that for the 1971 departure, a reversal of the transfer times essentially reverses the total velocity increments required for each leg of the journey, while the sum of the four velocity increments does not change significantly.

For the 1975 departure date, the total velocity is significantly higher than for the 1971 departure. A reversal of the transfer times in 1975, however, does not reverse the order of the velocity increment for each leg of the journey, and the sum of the four velocity increments is decreased significantly.

A study of Table 2 shows that with only one exception the total velocity increment for missions starting in 1975 is higher than for those starting in 1971. Also, Table 2 shows that many of the missions having constant transfer time have a nearly constant total velocity increment.

Example 2

Assume that the following hypothetical mission is desired:

Minimum velocity for the outbound trip
Zero stay time in the Mars parking orbit
Total velocity increment for the return trip = 20,000 ft/sec

Again using Figs. 2, 3, 6, and 7 we can find the data shown in Table 4.

Table 4

DEPARTURE DATES AND MINIMUM TOTAL VELOCITY INCREMENTS (EXAMPLE 2)

Item	Date	Velocity Increment (ft/sec)	Date	Velocity Increment (ft/sec)
Earth departure	9-1-70	27,500	12-9-74	30,400
Mars arrival	5-9-71	16,400	6-27-75	20,900
Mars departure	5-9-71	7,200	6-27-75	8,300
Earth arrival	11-25-71	12,800	4-22-76	11,700
Total velocity increment, ΔV_T	--	63,900	--	71,300

The later departure results in a mission time of 500 days, 50 days longer than the earlier mission, and requires an additional 7400 ft/sec velocity increment on the outbound trip. The additional velocity is necessary primarily because the heliocentric latitude of Mars and the distance of Mars from the Sun at arrival are larger.

Figures 10 and 11 show data for a constant total velocity increment of 30,000 ft/sec for the trip from Mars to Earth for the 1971 and 1975 departure dates and zero stay time in the Mars parking orbit. The data points in Figs. 10 and 11 appear to define smooth curves except for the points for the 200-day transfer in Fig. 8. The deviation of these points is caused by the discontinuity in the 200-day transfer curve in Fig. 2. Because the motion is assumed to be Keplerian between Earth and Mars, the inclination of the heliocentric orbit plane will increase rapidly as the heliocentric transfer angle approaches 180 deg. The large inclination angles result in large velocity increments. This is indicated by the discontinuities in the curves of Figs. 2 through 9. If a mid-course plane change of two or three degrees is allowed, the vehicle can travel in the ecliptic plane to some point, say to the Mars line of nodes, and then travel in the Mars orbit plane or in a nearby plane. The velocity increments for this type of orbital transfer can be obtained approximately by carefully sketching a smooth curve across the discontinuities in the curves of Figs. 2 through 9. Except for the discontinuities, the curves obtained for transfers with a mid-course plane change will not differ significantly from those of Figs. 2 through 9.[3]

In all of the examples a stay time in the Mars parking orbit of zero was arbitrarily chosen. Because of the location of the minima and the slopes of the velocity-increment curves in Figs. 2 through 9, it is clear that for a minimum velocity increment, increased stay time at Mars requires earlier departure dates from Earth and results in an increased total velocity increment for the mission. This is illustrated by using the mission of Example 1, the curves in Figs. 2 through 9, and by letting the stay time at Mars increase from zero to 100 days. The results are shown in Fig. 12. The curves show an approximately linear increase in the total velocity increment with stay time at Mars for

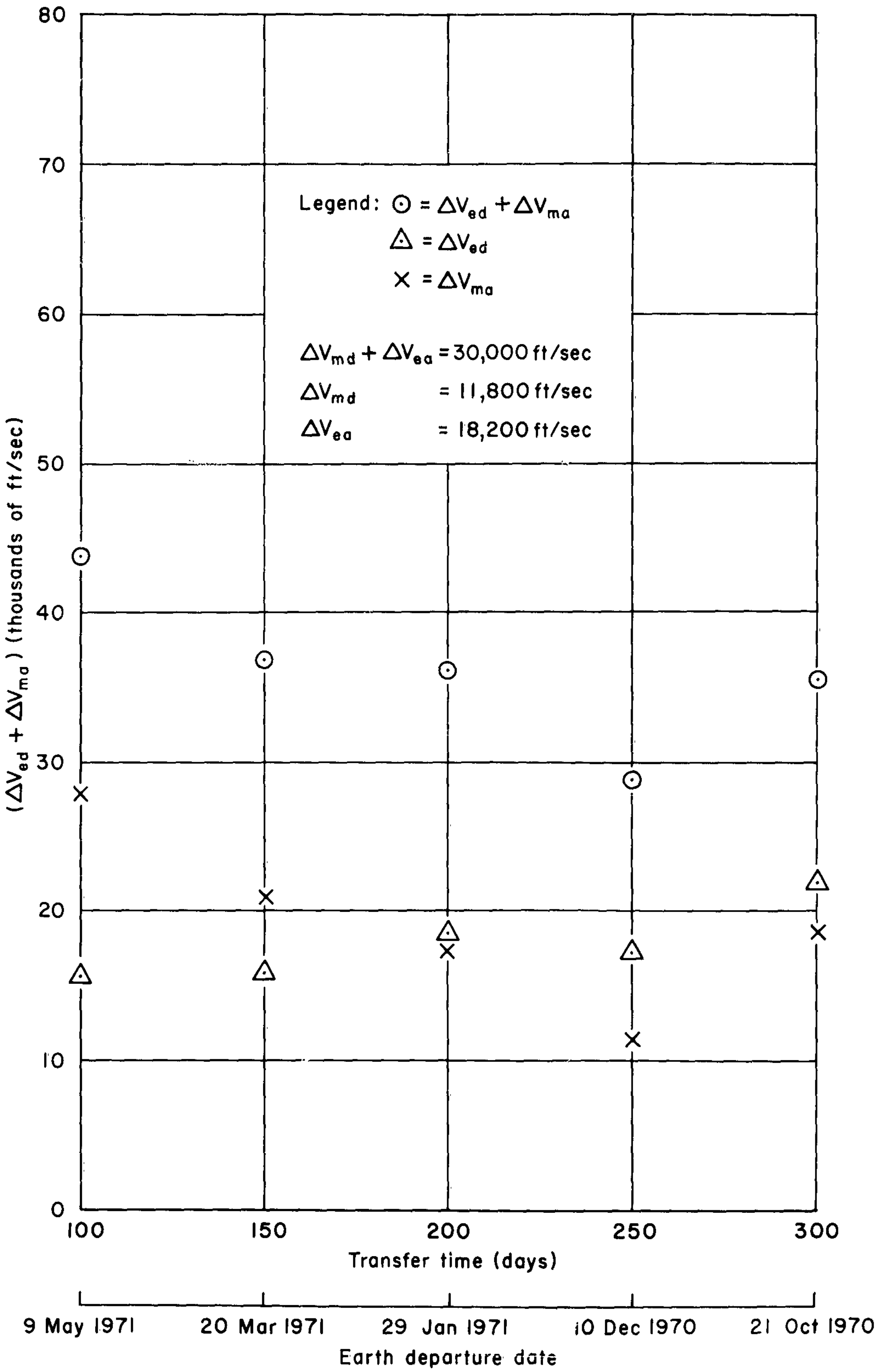

Fig. 10—Earth-to-Mars round trip with constant return-velocity increment

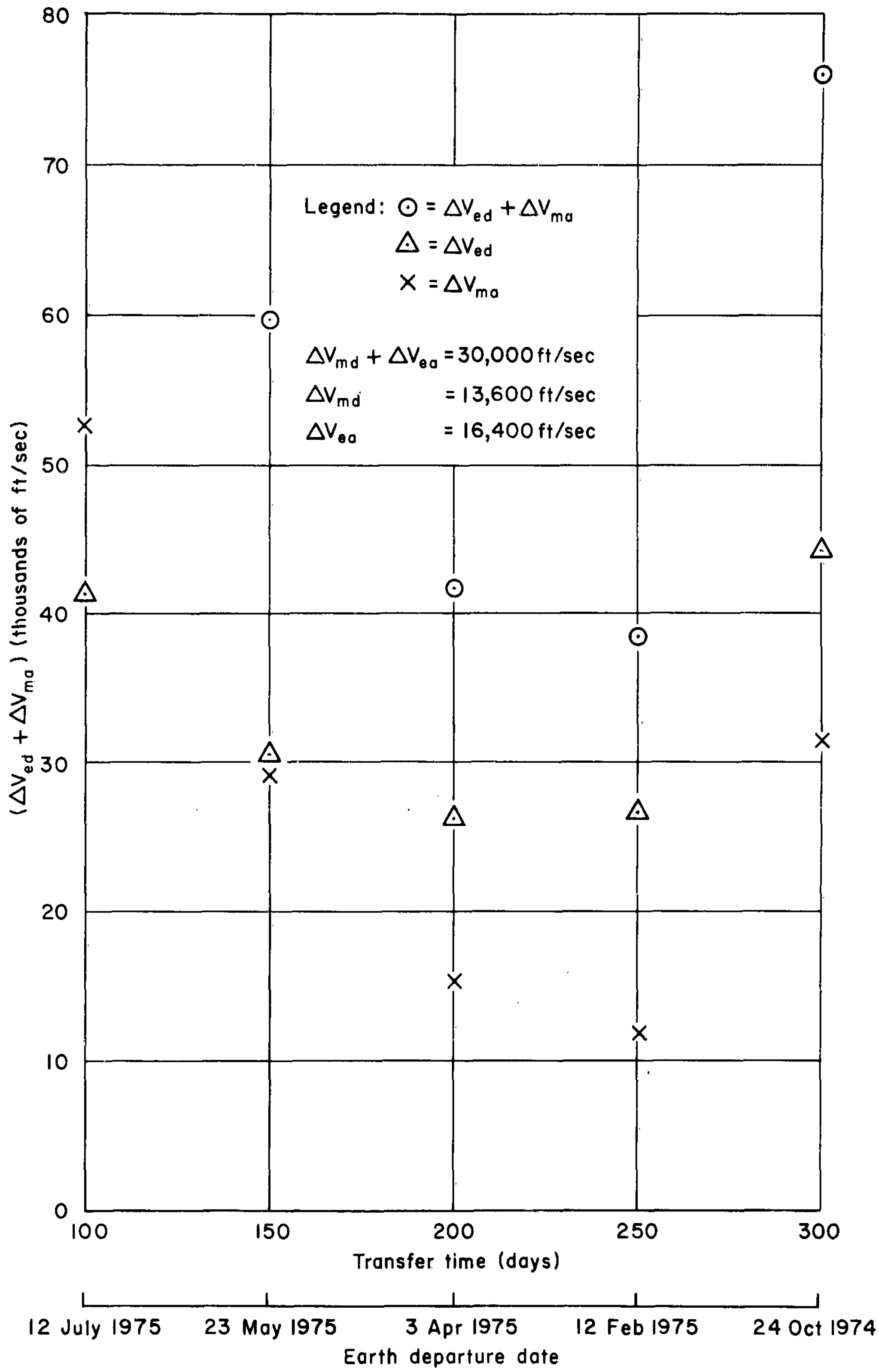

Fig. 11—Earth-to-Mars round trip with constant return-velocity increment

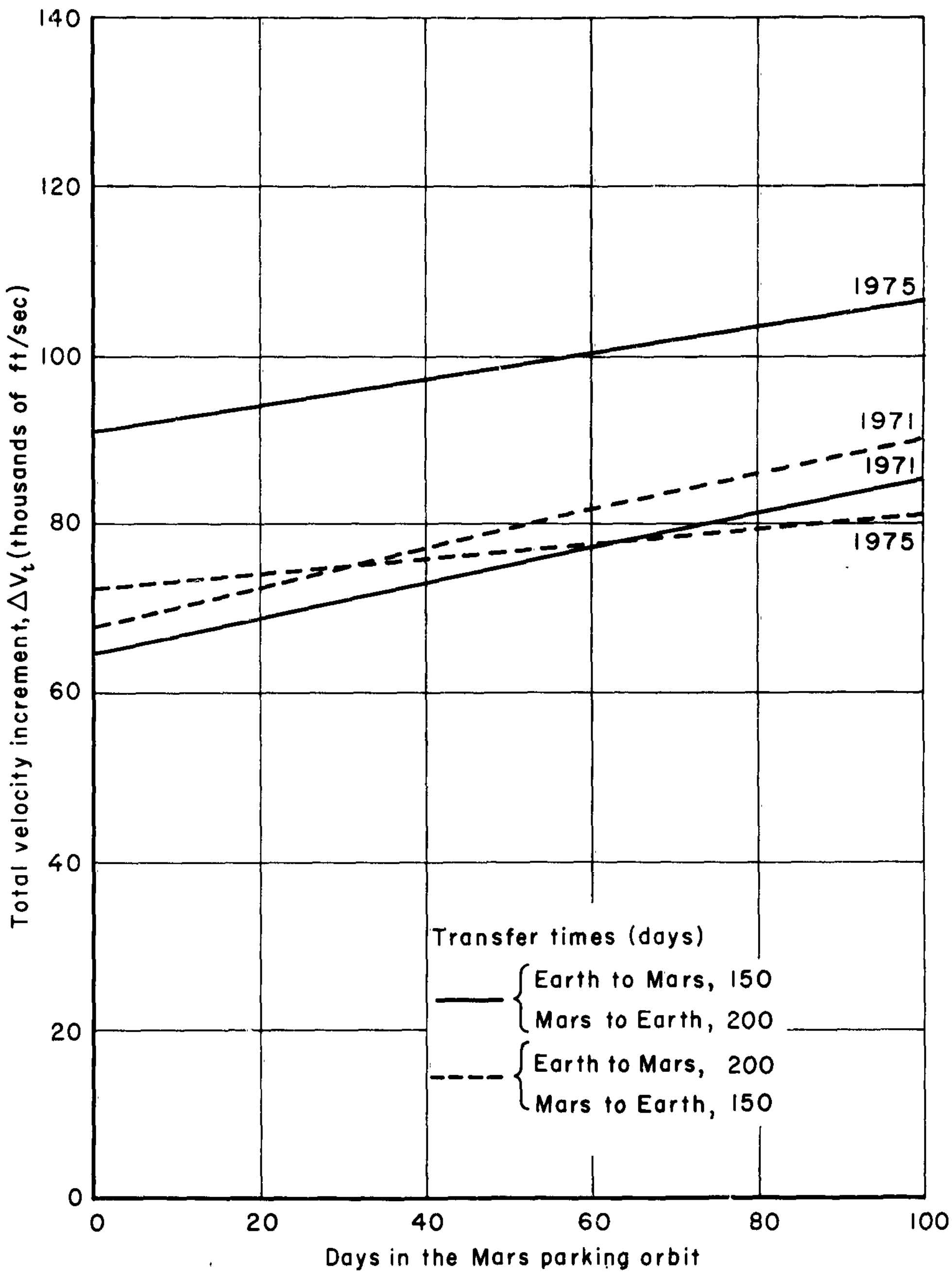

Fig. 12 — Total velocity increment versus stay time at Mars

minimum-energy missions. The average velocity penalties for stay time at Mars are about 210 and 155 ft/sec/day for 1971 and 1975 departures, respectively. For a reversal of the transfer times the average velocity penalties become 223 and 90 ft/sec/day for 1971 and 1975 departures, respectively.

DEPARTURE WINDOWS

For interplanetary missions, two departure windows exist. One, the heliocentric window, is determined by the relative motion of the departure and destination planets. The other, the geocentric window, is determined by the orbital elements of the parking orbit. Because the angular rate of the vehicle in the parking orbit is much greater than the rate of change of the angular orientation of Earth and Mars, a delay of minutes in the departure from the parking orbit on a given departure date may require as much additional velocity increment as a delay of several days if the time of departure from the parking orbit is correct for the delayed-departure date.

Only the size of the heliocentric departure window is discussed. By using Figs. 2 through 9, missions requiring a minimum total velocity increment for several favorable orientations of Earth and Mars are obtained.

Table 5 gives the departure dates and total velocity increments for several minimum-energy missions, all of which assume zero stay time at Mars. As indicated by the first column, ΔT represents the number of days before and after the minimum-energy mission.

CONCLUSIONS

Single-plane heliocentric orbits require excessively large velocity increments when the transfer angle is near 180 deg.

The minimum required velocity increment for an Earth-Mars round-trip mission increases significantly as the departure date increases beyond December 1970.

In general, an increase in the stay time at Mars will require an increase in the required velocity increment.

Table 5

VELOCITY INCREMENT FOR MINIMUM-ENERGY ROUND-TRIP MISSIONS TO MARS WITH ZERO STAY TIME AT MARS

ΔT (days)	Date	ΔV_T (ft/sec)	Date	ΔV_T (ft/sec)	Date	ΔV_T (ft/sec)	Date	ΔV_T (ft/sec)
-100	9-1-70	63,500	8-21-72	78,200	10-30-74	76,000	10-19-76	110,100
- 80	9-21-70	61,400	9-10-72	71,100	11-19-74	72,200	11-08-76	94,300
- 60	10-1-70	61,100	10-30-72	65,300	12-9-74	68,900	11-28-76	82,700
- 40	10-31-70	60,000	10-20-72	62,000	12-29-74	67,500	12-18-76	77,800
- 20	11-20-70	58,200	11-19-72	60,200	1-18-75	67,700	1-7-77	75,600
0	12-10-70	57,800	11-29-72	59,100	2-7-75	67,500	1-27-77	74,800
20	12-30-70	57,900	12-19-72	59,200	2-27-75	70,300	2-16-77	75,300
40	1-19-71	58,500	1-8-73	60,400	3-19-75	71,300	3-8-77	77,100
60	2-8-71	60,000	1-28-73	61,800	4-8-75	72,100	3-28-77	78,000
80	2-28-71	61,900	2-17-73	63,700	4-28-75	73,300	4-17-77	78,300
100	3-20-71	64,300	3-9-73	65,400	5-18-75	74,700	5-7-77	79,400

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