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BALLISTIC MODE MERCURY ORBITER MISSION OPPORTUNITY HANDBOOK EXTENSION

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16. Abstract

Interplanetary trajectory characteristics are presented, for Venus swingbys to Mercury, where multiple revolutions about the Sun are permitted. Additional consideration is given to the use of multiple Venus swingbys and/or to midcourse, near perihelion, propulsive manuvers to improve the performance of the mission as measured in terms of payload in Mercury orbit. Missions in 1980, 1983, 1985 and 1988 were analyzed with navigation results also developed. An exploratory investigation established the availability of low energy mission opportunities in 1991, 1994, 1996 and 1999.

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FOREWORD

Prior effort under study contract NAS2-7268 included preparation of "Ballistic Mode Mercury Orbiter Mission Opportunity Handbook," NASA CR-2298. This was primarily devoted to detailed analyses of interplanetary trajectory characteristics for four baseline mission opportunities corresponding to launch in 1977, 1980, 1985 and 1988. Also reported in the Handbook were results of preliminary investigations to assess the performance improvement potential of two alternate flight techniques: midcourse maneuvers and multiple Venus swingby. It was determined that modest midcourse maneuvers could produce significant performance improvements for the 1977 and 1985 opportunities. Also, two new mission opportunities predicated on multiple Venus swingby and corresponding to launch in 1983 and 1988 were identified and partially optimized.

As a result of these findings, a contract extension was awarded to complete performance and navigation analyses for the 1985 mission opportunity with optimized midcourse maneuvers and for the 1983 and 1988 multiple Venus swingby opportunities. In addition, identification and confirmation of high-performance opportunities through the 1990's was undertaken to provide a general assessment of ballistic mode potential for advanced Mercury missions. Investigation of midcourse maneuvers to further improve the high-performance 1980, 1983 and 1988 mission opportunities completed the scope of the study extension.

This document reports results of the foregoing analyses and investigations. Data are presented in a format consistent with the previously published "Ballistic Mode Mercury Mission Opportunity Handbook."

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I. INTRODUCTION AND SUMMARY

Four baseline Mercury orbiter mission opportunities were previously analyzed in detail and results documented in "Ballistic Mode Mercury Orbiter Mission Opportunity Handbook," NASA CR-2298. Feasibility of implementing these missions was confirmed by assessment of navigation requirements and Mercury encounter dispersions. Also reported in the Handbook were investigations of the performance potential of two alternate flight techniques: midcourse maneuvers and multiple Venus swingby. Positive findings from these exploratory analyses resulted in award of an extension of the study contract to provide detailed data for three specific missions to a level commensurate with the four baseline cases. In addition, the search for ballistic mode opportunities was extended through the 1990's and further performance improvement investigations were undertaken.

The technique of applying modest midcourse maneuvers (200-400 m/s) near perihelion of the Earth-to-Venus transfer trajectory was found to compensate for the relatively poor planetary alignments characterizing the 1977 and 1985 mission opportunities. While the 1977 case is probably academic due to timing, the 1985 opportunity represents a potential follow-up to an initial Mercury orbiter mission launched in the early 1980's. Accordingly, complete optimization of performance parameters and assessment of navigation requirements were performed for the 1985 opportunity with midcourse maneuvers.

Parametric performance data and flight characteristics for the 1985 mission with midcourse maneuvers are presented in Section IV. Analysis of navigation maneuver requirements showed that modifications to critical tracking geometries resulted in significant reduction in micourse correction requirements from the baseline ballistic version of the 1985 opportunity.

Further optimization of performance parameters for the 1983 and 1988 multiple Venus swingby missions produced some improvement from previously quoted values. Moreover, navigation requirements for these cases also benefited from advantageous tracking geometries. As a net result, the performance potential of multiple Venus swingby has been further demonstrated to compensate for the disadvantages of increased complexity and generally longer flight times. Sections III and V present detailed data for the 1983 and 1988 missions respectively.

Previous search for mission opportunities during the 1990's had produced negative results for the single Venus swingby flight technique. However, with the additional planetary geometry options applicable to multiple Venus swingby, several such opportunties were identified. High performance cases were confirmed for launch in 1991, 1994, 1996, and 1999. Partially optimized performance parameters for these cases are presented in Section VII.

Application of midcourse maneuvers had proven effective for two of the four baseline mission opportunities. To further assess the potential of this flight technique, investigations were conducted to evaluate performance improvement potential for the 1980 baseline mission and for the 1983 and 1988 multiple Venus swingby cases. These analyses indicated only marginal effectiveness for improving planetary geometries, apparently because they were already near-ideal for the cases studied.

Peculiarites in the Venus arrival/departure characteristics for the 1980 mission prevent ballistic matches for Earth launch dates late in the launch period. Previous investigation had confirmed limited effectiveness of modest velocity maneuvers in the vicinity of Venus to accomplish non-ballistic matches. Application of midcourse maneuvers was assessed as an alternate method of modifying conditions at Venus in lieu of powered Venus swingby. Results of these analyses are presented in Section II-A and indicate only slight advantage over the powered Venus swingby technique.

Performance improvement potential of midcourse maneuvers for the 1983 and 1988 multiple Venus swingby missions was evaluated analytically by inspection of Venus arrival/departure conditions. These assessments are discussed in Appendix 2. It was concluded that some improvement could be expected but of insufficient magnitude to warrant detailed computer analysis.

While maneuvers in the vicinity of Earth-to-Venus transfer orbit perihelion have not proved effective for well-aligned multiple Venus swingby mission cases, a variation of the technique may yet prove effective. For multiple Venus swingby missions, the ideal Venus-to-Mercury transfer is close to 180 degrees. Of the cases studied, some missions have optimized with a Type I transfer and others, due to subtle differences in geometry, have optimized with a Type II transfer. For this reason, it is possible that a broken-plane maneuver on the Venus-to-Mercury trajectory may exhibit advantages. Investigation of this latter class of midcourse maneuvers was not included in the study scope and has not been performed.

A summary of the study results is presented in Figure I-1 in the context of the original baseline mission opportunities. Qualifications include the tabulated maneuver requirements for navigation corrections. Cases for which precise navigation analyses have not been conducted are based on a nominal allowance of 250 m/s.

The missions corresponding to launch in the 1990's are all predicated on the multiple Venus swingby flight technique. These cases represent confirmed high-performance opportunities and do not constitute the entire spectrum of options available for mission planning purposes. Preliminary search has indicated that non-optimum opportunities at the performance level of the 1980 baseline mission occur in abundance and could be defined for any time period of particular interest.

Also shown on Figure I-1 is an alternate 1980 mission utilizing multiple Venus swingby. This mission was not anticipated in the study scope due to the apparent adequacy of the baseline 1980 opportunity and the focus on long term perspective. It is presented to illustrate the potential expansion of mission options possible with concentration on a specific time period. Also, since 1980 represents a strong candidate for initial launch of a Mercury orbiter spacecraft, the option for increased performance at the expense of proportional increase in flight time could be advantageous. In particular, the ability to accommodate an orbited weight of over 600 kg could be especially significant to the prospects of a Mariner class spacecraft design. Preliminary data for the alternate 1980 mission is presented in Section II-B. Further definition of this opportunity is recommended for future consideration.

CONDITIONS

Titan IIIE/Centaur Launch Vehicle
15-Day Launch Period
Minimum Venus Swingby Altitude = 250 km
Mercury Orbit Periapsis Altitude = 500 km
Mercury Orbit Eccentricity = 0.8
Mercury Orbit Insertion Propulsion: Single Stage Solid
Specific Impulse = 290 sec.
Propellant Fraction = 0.93
Auxiliary Propulsion: Hydrazine Monopropellant
Specific Impulse = 235 sec.
Inert Weight Not Deducted from Orbited Weight

LEGEND	LAUNCH YEAR	TOTAL AUXILIARY PROPULSION MANEUVERS (MPS)
——— Baseline Opportunities (Single Venus Swingby, No Midcourse Maneuvers)	1977	227
	1980	266 (Including 100 at Venus)
	1985	242
	1988	282 (Including 75 at Venus)
- - - With Midcourse Maneuvers	1977	627 (Including 400 Midcourse)
	1985	535 (Including 400 Midcourse)
— — With Multiple Venus Swingby	1980	250 (Estimated)
	1983	166
	1988	320 (Including 200 at Venus)
	1991	250 (Estimated)
	1994	250 (Estimated)
	1996	250 (Estimated)
	1999	250 (Estimated)

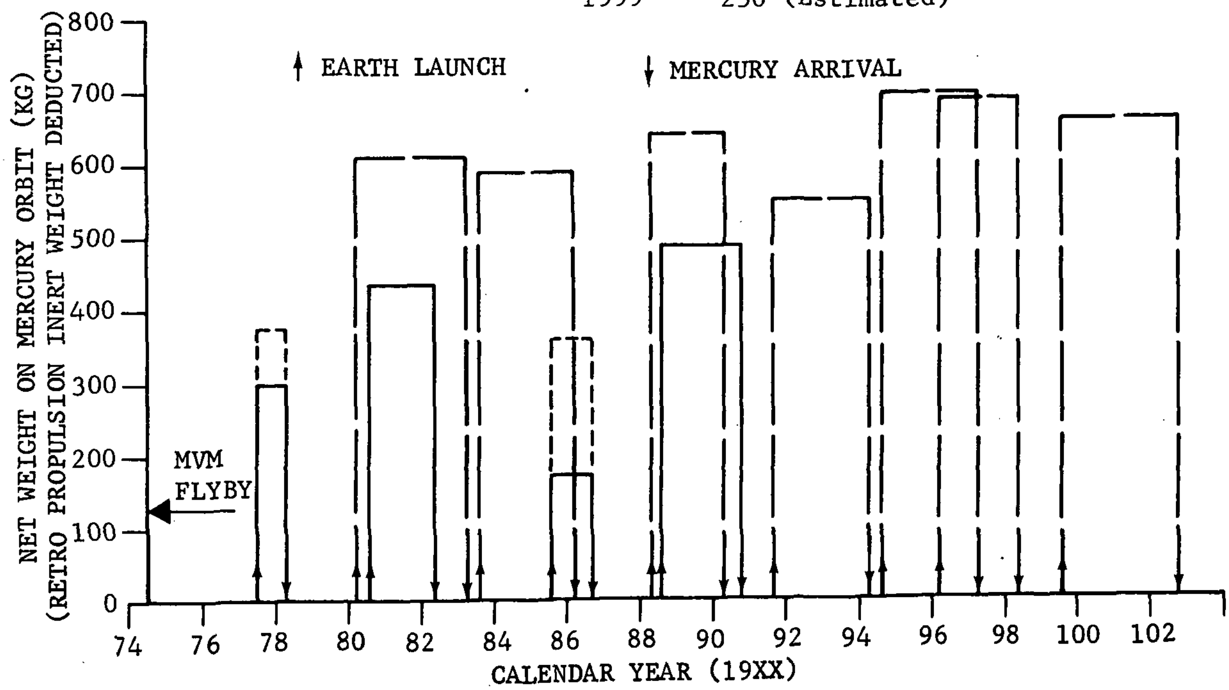

Figure I-1 Mission Opportunity Summary

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II. 1980 MISSION OPPORTUNITIES

II. 1980 MISSION OPPORTUNITIES

This section presents results of applying midcourse maneuvers to the later launch dates in the 1980 baseline mission launch period. Evaluation of effectiveness is discussed in the context of powered maneuvers at Venus swingby which have been previously shown to be advantageous.

Also presented are characteristics and partially optimized performance parameters for the recently identified alternate 1980 mission. This opportunity is predicated on triple Venus swingby and involves a flight time of 36.7 months. In view of the significance of 1980 launch and the performance advantage over the baseline 1980 opportunity, preliminary data have been included in this study report.

A. BASELINE OPPORTUNITY WITH MIDCOURSE MANEUVERS

1. Performance Parameters - Investigation of the potential performance improvement provided by a midcourse velocity maneuver on the Earth-Venus trajectory segment is presented for late launch dates of the 1980 baseline mission. Due to the Venus arrival/departure characteristics for this mission, small maneuvers at Venus were effective in improving Mercury arrival conditions. Midcourse maneuvers were examined as an alternative means of modifying Venus conditions for late Earth launch dates, which display abrupt performance degradation. A midcourse maneuver executed near perihelion of the Earth-Venus leg reduces Mercury arrival velocity for the late launches by delaying Venus encounter. Time of the maneuver is optimized as described in detail in Section III-A. Briefly, the targeting criteria involves a ballistic trajectory from Earth to Venus. For a fixed maneuver time, this initial Venus trajectory is adjusted to match actual Venus arrival and departure velocity magnitudes. For a desired actual Venus date, the time of the maneuver is then varied to minimize the midcourse maneuver requirement.

Decreases in relative velocity at Mercury as a function of midcourse velocity maneuver are presented in Figure II-1. For a typical late Earth launch date (7-5-80), Mercury arrival is shown parametrically (4-13-82 to 4-15-82) along with Venus swingby altitude effects. No ballistic solutions occur for that launch date, and a 200 m/s velocity maneuver at Venus yields a V_{HM} greater than 7 km/sec (250 km swingby altitude). For a Mercury arrival on

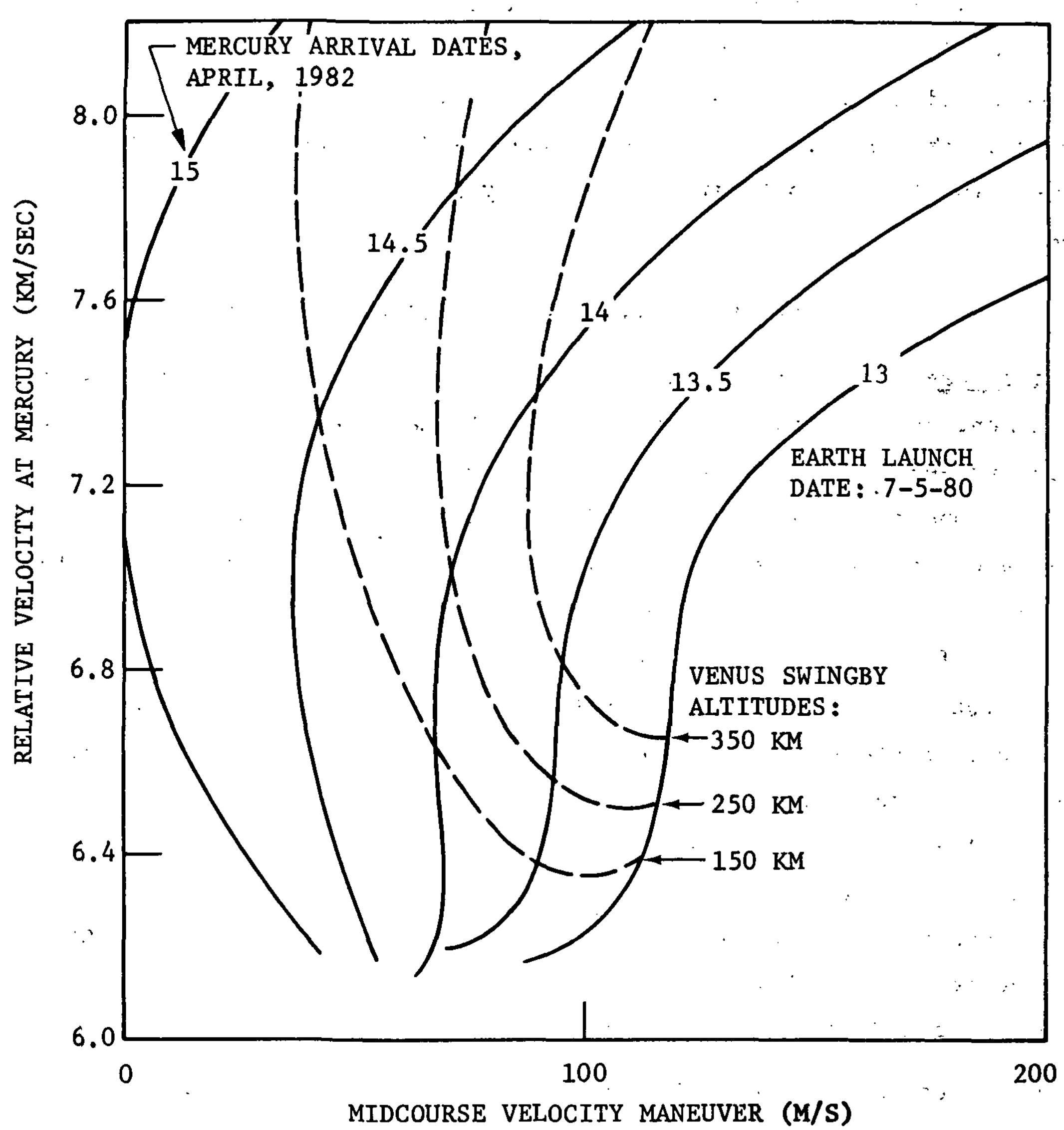
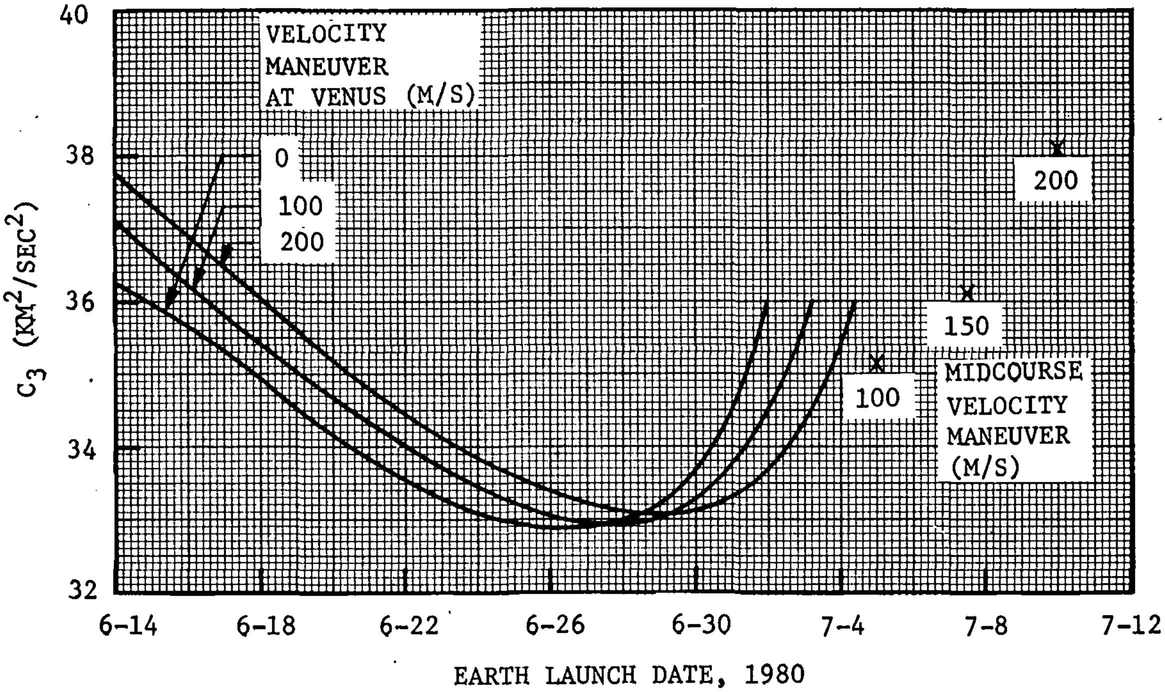


Figure II-1 Relative Velocity at Mercury vs Midcourse Velocity Maneuvers, 1980 Baseline Opportunity

4-13-82, a midcourse maneuver of 107 m/s accomplished near perihelion of the Earth-Venus trajectory will result in a V_{HM} of 6.50. These data are translated onto Figure II-2, which shows ballistic trajectories, effects of maneuvers at Venus, and effectiveness of midcourse maneuvers for three late launch dates. Launch energy requirements are shown to increase with the later launches, while V_{HM} is improved. Although the trajectories with velocity maneuvers at Venus are labeled 100 m/s and 200 m/s, navigation analyses showed that combination with the large post-Venus navigation correction (207 m/s) reduced the 100 m/s to 26 m/s net cost, and similar effects would reduce the actual cost of a 200 m/s maneuver. No such vector bargain can be achieved with a midcourse velocity maneuver. Therefore, the performance improvement potential of midcourse maneuvers is not significantly greater than for maneuvers at Venus, and further optimization was not pursued.



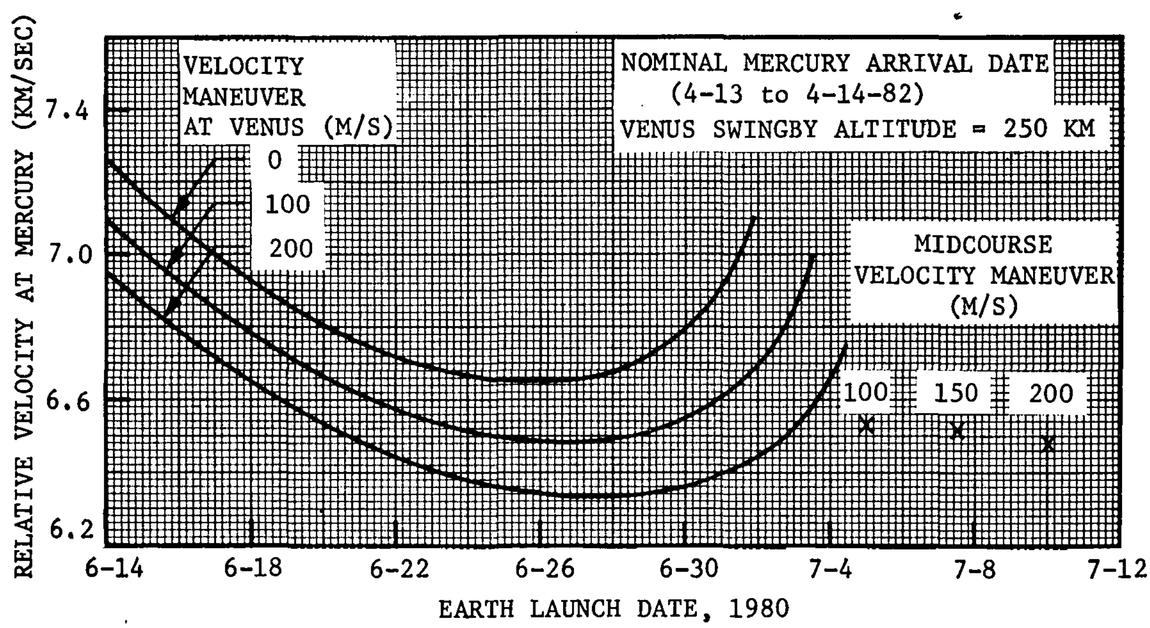


Figure II-2 Potential of Midcourse Maneuvers, 1980 Baseline Opportunity

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2. <u>Trajectory Data</u> - Tabulated results for a typical reference trajectory with a late launch from the 1980 baseline opportunity which utilizes a midcourse velocity maneuver appear in Table II-1. Mercury encounter date was selected to minimize Mercury approach velocity within an altitude constraint of 250 km at Venus and a midcourse maneuver magnitude of 100 m/s. The print key which defines each listed parameter is located in Section 1 of the Appendix.

```
JD=2444425.500   C3=  35.265  FLT TIM= 351.633   JUL  5 1980   0, 0, 0.
ECLIPTIC           X                 Y                 Z                 TOTAL
R EARTH     3.2559930E+07    -1.4857275E+08     1.0067988E+04     1.5209869E+08
V EARTH     2.8610932E+01     6.2748116E+00    -6.3122519E-04     2.9290932E+01
VEL S/C     2.2798060E+01     6.6214643E+00    -1.1736088E+00     2.3769154E+01
VHE        -5.8128718E+00     3.4665269E-01    -1.1729776E+00     5.9401619E+00
RAA=176.587 DECA=-11.339       SEVHE=105.456
EQUATORIAL         X                 Y                 Z                 TOTAL
R EARTH     3.2559930E+07    -1.3631483E+08    -5.8997469E+07     1.5209869E+08
V EARTH     2.8610932E+01     5.7571934E+00     2.5803934E+00     2.9290932E+01
VEL S/C     2.2798060E+01     6.5418566E+00     1.6248978E+00     2.3769154E+01
VHE        -5.8128718E+00     7.8466323E-01    -9.5549561E-01     5.9401619E+00
RAA=172.312 DECA= -9.252 RP= 72198111.90 APO=152717109.43
A=112457610.67 E= .35800 I=  2.836 NODE=282.438 W=186.847
TH1= 186.9   TH2= 361.7   DTH= 174.8    TYPE   IV     I

JD=2444777.13     DEL V=    .100    JUN 21 1981 15 12 8.417
ECLIPTIC           X                 Y                 Z                 TOTAL
RADIUS     -2.1915746E+07     6.9239390E+07     3.2147402E+05     7.2625728E+07
V S/C B    -4.8127216E+01    -1.2341172E+01     2.4600466E+00     4.9745203E+01
V S/C A    -4.8044522E+01    -1.2288307E+01     2.4429227E+00     4.9651249E+01
DEL VEL     8.2693243E-02     5.2864692E-02    -1.7125912E-02     9.9630040E-02
A=111574670.2 E=     .353043 I=    2.82 NODE= 102.41 W=    5.16
RP= 72183995.3 APO=150965345.1 TH1=  12.40 TH2= 105.66 DTH=  93.26 TYPE=  I

JD=2444815.700 VHA= 12.465 VHD= 12.465  JUL 30 1981   4, 47, 59.999
ECLIPTIC           X                 Y                 Z                 TOTAL
R VENUS    -1.0077039E+08    -3.8359454E+07     5.2572043E+06     1.0795257E+08
V VENUS     1.2213036E+01    -3.2887671E+01    -1.1706800E+00     3.5103764E+01
V S/C A     1.5995117E-01    -3.5624533E+01     3.6988531E-01     3.5626795E+01
VHA        -1.2063075E+01    -2.7368623E+00     1.5405653E+00     1.2465213E+01
V S/C D     1.7366138E-01    -2.9668450E+01    -1.3916774E+00     2.9701609E+01
VHD        -1.2040355E+01     3.2192209E+00    -2.2099745E-01     1.2465246E+01
RCA=  6301.1    BTH=195.3     B*T=     -7841     B*R=     -2138     HCA=    251.1
RAA= 192.8 DECA=    7.1 SPA= 170.9 EPA= 143.0 CPA=   96.5    TYPE IV     I
RAE= 336.1 DECE=  -1.4 RAS=  20.8 DECS=  -2.8
AH=      2090.7 EH=  4.01381 I= 163.2 NODE= 348.4 W= 140.2 TAU=  75.6
A= 84179971.4 E=     .436559 I=    4.8 NODE= 416.4 W= 356.7 TURN=  28.9
TH1= 147.7 THF= 336.9 DTH= 189.3 FLT TIM= 257.175
PERIHELION= 47430418.6  APHELION=120929524.1
```

TABLE II-1 TRAJECTORY PRINTOUT 7-5-80 LAUNCH

```
JD=2445072.875     VHP=  6.524    APR 13 1982  9, 0, 0.
ECLIPTIC            X                    Y                    Z                   TOTAL
R MERCURY   4.2026449E+07      2.4363910E+07     -1.8036141E+06      4.8611475E+07
V MERCURY  -3.3927330E+01      4.4404234E+01      6.7523642E+00      5.6288490E+01
V S/C      -3.7315053E+01      4.3669077E+01      4.9160107E+00      6.2318517E+01
VHP        -3.3877230E+00      5.2648426E+00     -1.8363535E+00      6.5243719E+00
RAA= 122.8    DECA= -16.3     SPA=  88.1    EPA=  81.9    CPA=  60.3
RAE= 204.2    DECE=     .5    RAS=-149.9    DECS=    2.1
EQUATORIAL          X                    Y                    Z                   TOTAL
R MERCURY  -4.7319991E+07     -1.1130768E+07     -7.4505806E-09      4.8611475E+07
V MERCURY   1.9911031E+01     -5.2649264E+01      0.                 5.6288490E+01
V S/C       2.1500256E+01     -5.8436142E+01     -2.5600463E+00      6.2318517E+01
VHP         1.5392254E+00     -5.7868778E+00     -2.5600463E+00      6.5243719E+00
RAA= 285.4  DECA= -23.1  RAS=  13.2  DECS=      .0  RAE=    7.6  DECE=  -2.3
MERCURY OP          X                    Y                    Z                   TOTAL
R MERCURY   4.6419361E+07     -1.4433176E+07     -7.4505806E-09      4.8611475E+07
V MERCURY   9.5740318E+00      5.5468238E+01      0.                 5.6288490E+01
V S/C       1.1142652E+01      6.1260795E+01     -2.5600463E+00      6.2318517E+01
VHP         1.5688204E+00      5.7924970E+00     -2.5600463E+00      6.5243719E+00
RAA=  74.8  DECA= -23.1  RAS= 162.7  DECS=      .0  RAE=  157.1  DECE=  -2.3
```

TABLE II-1 TRAJECTORY PRINTOUT 7-5-80 LAUNCH (Continued)

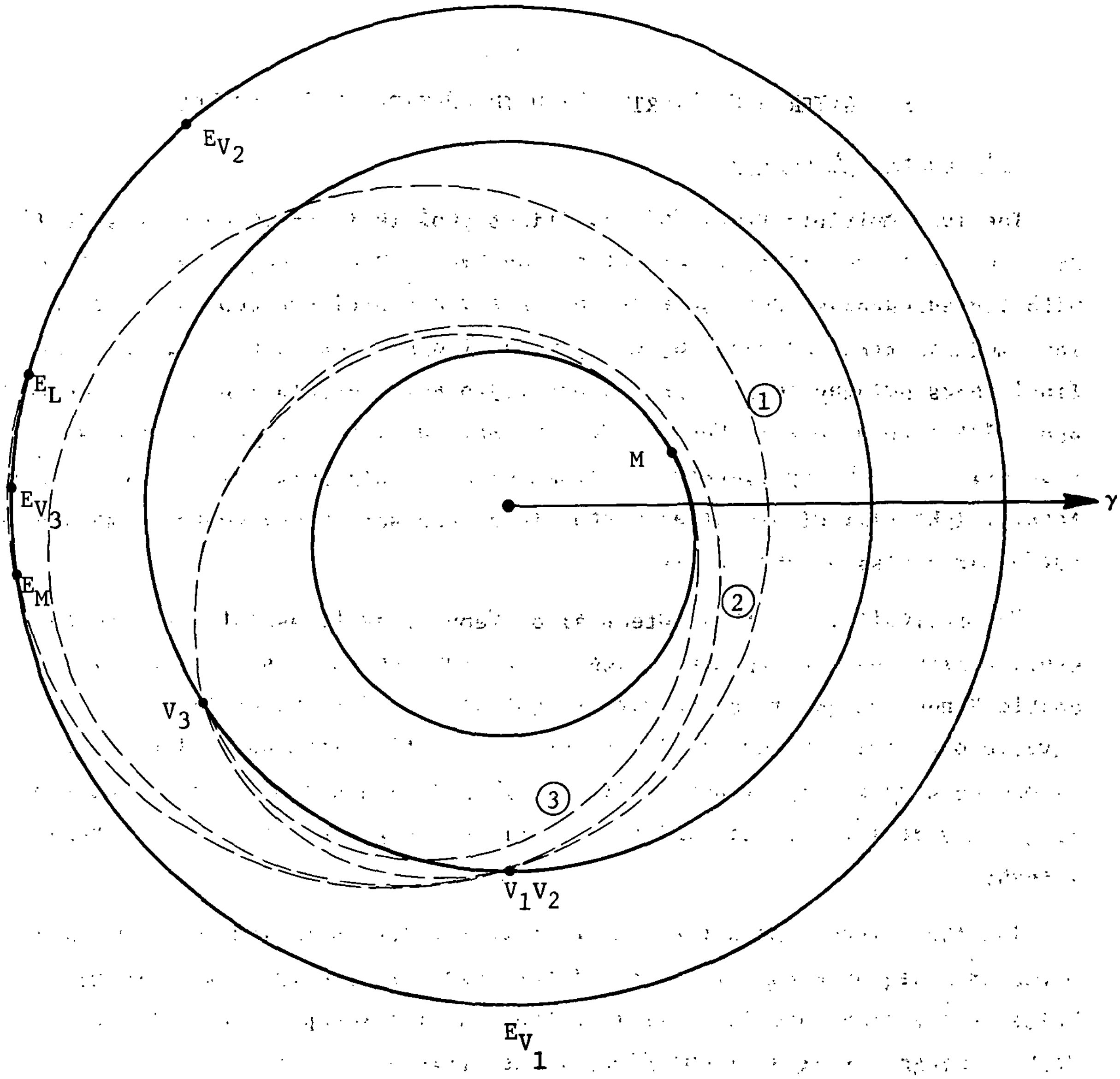
B. ALTERNATE OPPORTUNITY WITH MULTIPLE VENUS SWINGBY

1. Heliocentric Geometry

The 1980 multiple Venus Swingby flight profile is depicted on Figure II-3 as an ecliptic projection. As shown, the Venus swingby sequence is initiated with two successive encounters at the same Venus position separated by an intermediate transfer orbit with a period of one Venus year. The third and final Venus swingby occurs after about 2 5/6 solar revolutions of the spacecraft and 1 5/6 revolutions of Venus. Mercury encounter is delayed by two extra solar revolutions of the spacecraft to accommodate Mercury phasing. The resultant total flight time of almost 37 months is a necessary consequence of this high-performance mission opportunity.

Theoretically, the full potential of Venus gravity-assist for Mercury orbiter missions corresponds to two close Venus encounters. In practice, double Venus swingby missions with flight time of 3 years or less involve one close encounter with Venus (frequently altitude-limited) and a second swingby at high Venus altitude. This disproportionate distribution of gravity assist effects limits the performance potential of double Venus swingby.

The three Venus encounters inherent to the alternate 1980 mission geometry occur in a sequence that improves distribution of effects between swingbys. While net performance is still less than optimum (comparable to the best double swingby missions identified) Venus altitudes are relaxed to about 15,000 km, 2300 km,and 19,000 km respectively for the three successive encounters.



E_L: EARTH AT LAUNCH, 3-6-80

E_{V_1}: EARTH AT FIRST VENUS SWINGBY (V_1), 6-19-80

E_{V_2}: EARTH AT SECOND VENUS SWINGBY (V_2), 1-29-81

E_{V_3}: EARTH AT THIRD VENUS SWINGBY (V_3), 3-19-82

E_M: EARTH AT MERCURY ENCOUNTER (M), 3-29-83

① ONE COMPLETE SOLAR REVOLUTION BETWEEN FIRST AND SECOND VENUS SWINGBYS

② TWO COMPLETE SOLAR REVOLUTIONS BETWEEN SECOND AND THIRD VENUS SWINGBYS

③ TWO COMPLETE SOLAR REVOLUTIONS BEFORE MERCURY ENCOUNTER

Figure II-3 Heliocentric Geometry, 1980 Multiple Venus Swingby Opportunity

2. <u>Performance Parameters</u>

Optimization of Mercury arrival date has not been completed. However, the data presented on Figure II-4 are sufficient to confirm high performance potential for the mission opportunity. Due to the opposite trends displayed by Mercury approach velocity and launch energy, determination of best performance involves significant interactions between launch vehicle characteristics, type of propulsion employed for Mercury orbit insertion and desired length of launch period. For the Titan IIIE/Centaur launch vehicle, single stage solid rocket motor for orbit insertion and 15-day launch period, calculations show best performance to correspond to the left-hand portion of the Figure II-4 data. The earliest launch dates lose compatibility with ballistic matches at the second Venus encounter indicating possible further improvements by application of midcourse maneuvers and/or powered Venus swingby maneuvers.

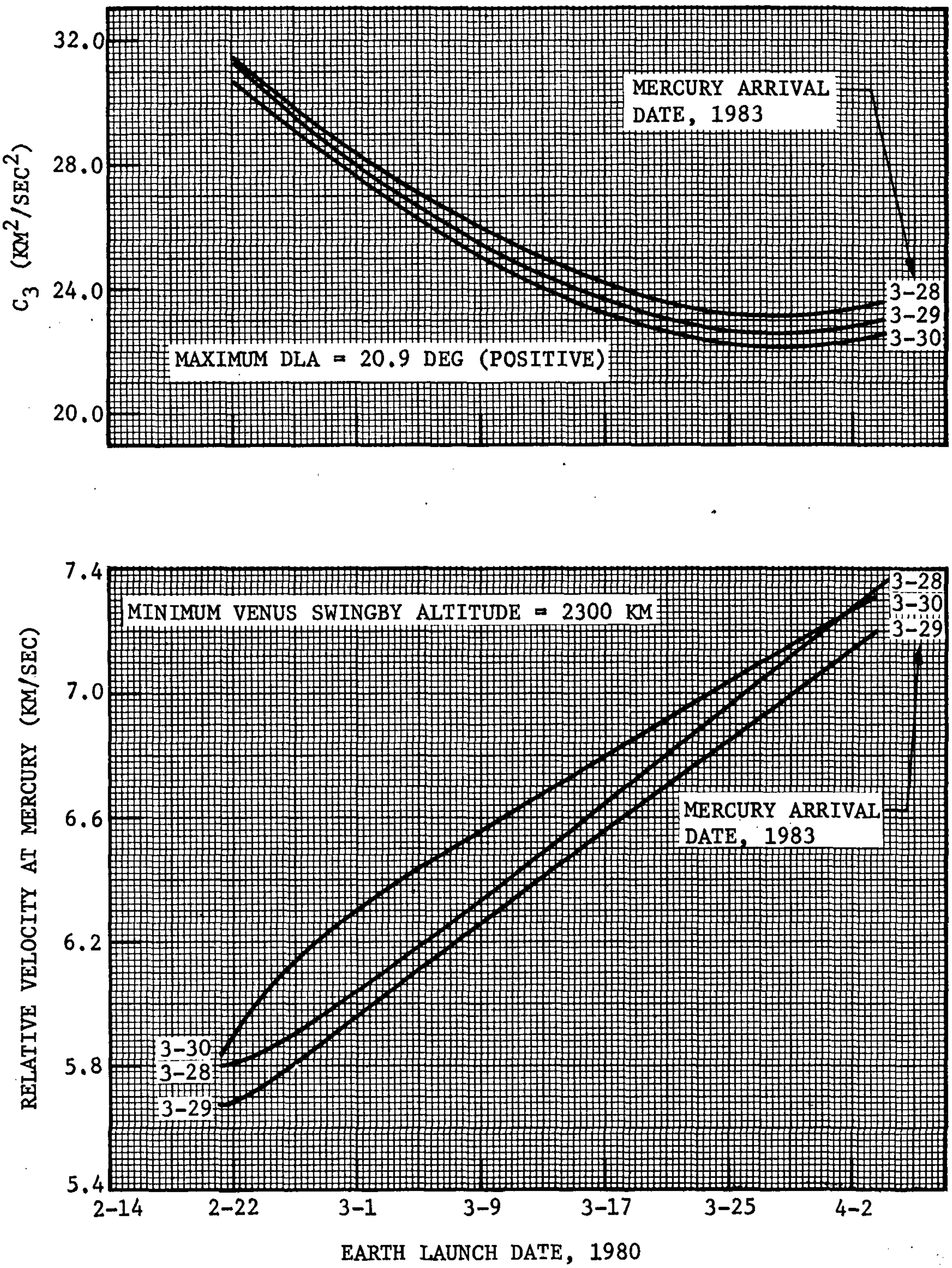


Figure II-4 Relative Velocity at Mercury and C_3 vs Launch/Arrival Date, 1980 Multiple Venus Swingby Opportunity

3. Trajectory Data

Tabular data for a representative Earth launch date (2-26-80) and Mercury arrival date (3-29-83) are listed in Table II-1. Conditions at Earth launch, each of the three Venus encounters and Mercury approach are displayed in detail together with the general characteristics of the heliocentric transfer orbits. A print key for interpretation of Table II-1 is provided in Appendix 1 of this document.

```
JD=2444295.500   C3=  29.364  FLT TIM= 111.716   FEB 26 1980  0, 0, 0.
ECLIPTIC          X                   Y                    Z                 TOTAL
R EARTH    -1.3507498E+08    6.0730014E+07   -3.2406789E+03    1.4809924E+08
V EARTH    -1.2702729E+01   -2.7271338E+01    1.3533042E-03    3.0084634E+01
VEL S/C    -1.3694273E+01   -2.1951512E+01   -2.8204761E-01    2.5874342E+01
VHE        -9.9154423E-01    5.3198256E+00   -2.8400092E-01    5.4188893E+00
RAA=100.558 DECA= -3.004        SEVHE= 55.288
EQUATORIAL        X                   Y                    Z                 TOTAL
R EARTH    -1.3507498E+08    5.5719141E+07    2.3760158E+07    1.4809924E+08
V EARTH    -1.2702729E+01   -2.5021360E+01   -1.0884169E+01    3.0084634E+01
VEL S/C    -1.3694273E+01   -2.0027611E+01   -9.0313672E+00    2.5874342E+01
VHE        -9.9154423E-01    4.9937486E+00    1.8528015E+00    5.4188893E+00
RAA=101.230 DECA= 19.997 RP= 84569218.86 APO=151841387.36
A=118205303.11 E= .28456 I=    .630 NODE=335.677 W= 20.647
TH1= 159.5    TH2= 269.8    DTH= 110.4    TYPE     I

JD=2444407.216 VHA= 10.343 VHD= 10.343  JUN 16 1980 17, 11,  1.810
ECLIPTIC          X                   Y                    Z                 TOTAL
R VENUS    -7.2981836E+06   -1.0847705E+08   -1.1202799E+06    1.0872805E+08
V VENUS     3.4705124E+01   -2.4813809E+00   -2.0334922E+00    3.4853092E+01
V S/C A     3.5510313E+01    7.5772811E+00    2.3681110E-01    3.6310516E+01
VHA         8.0518833E-01    1.0058662E+01    2.2703033E+00    1.0343079E+01
V S/C D     3.3912334E+01    7.8294612E+00   -1.8414191E+00    3.4853092E+01
VHD        -7.9279034E-01    1.0310862E+01    1.9207308E-01    1.0343079E+01
RCA= 20814.9   BTH=308.1    B*T=     14608    B*R=    -18609    HCA= 14764.9
RAA=  85.4 DECA=  12.7 SPA=  12.1 EPA= 165.4 CPA=  89.2    TYPE  I
RAF= 261.8 DFCE=    1.5 RAS=  86.2 DECS=     .6
AH=       3036.7 EH=  7.85452 I=  53.0 NODE= 275.2 W= 156.7 TAU=  82.7
A=108209145.7 E=     .288927 I=    3.4 NODE= 436.1 W= 297.7 TURN=  14.6
THI= 252.3 THF= 252.3 DTH= 360.  FLT TIM= 224.702
PERIHELION= 76944561.7  APHELION=139473729.6

JD=2444631.918 VHA= 10.343 VHD= 10.343  JAN 27 1981 10,  1, 20.035
ECLIPTIC          X                   Y                    Z                 TOTAL
R VENUS    -7.2981836E+06   -1.0847705E+08   -1.1202799E+06    1.0872805E+08
V VENUS     3.4705124E+01   -2.4813809E+00   -2.0334922E+00    3.4853092E+01
V S/C A     3.3912334E+01    7.8294812E+00   -1.8414191E+00    3.4853092E+01
VHA        -7.9279034E-01    1.0310662E+01    1.9207308E-01    1.0343079E+01
V S/C D     2.8742287E+01    5.9569420E+00   -1.5702085E+00    2.9395063E+01
VHD        -5.9628377E+00    8.4383229E+00    4.6328368E-01    1.0342889E+01
RCA=  8373.3    BTH=  3.2     B*T=     10981    B*R=         619    HCA=  2323.3
RAA=  94.4 DECA=    1.1 SPA=    8.3 EPA=  15.2 CPA=  77.1    TYPE VI    I
RAE= 109.6 DFCE=     .3 PAS=  86.2 DECS=     .6
AH=       3036.7 EH=  3.75740 I=    3.4 NODE=  76.2 W=    2.8 TAU=  74.6
A= 84149030.8 E=     .388140 I=    3.4 NODE= 436.1 W= 342.0 TURN=  30.9
THI= 208.0 THF= 510.7 DTH= 302.7 FLT TIM= 413.505
PERIHELION= 51487416.1  APHELION=116810645.5
```

TABLE II-2   TRAJECTORY PRINTOUT 2-26-80 LAUNCH

```
JD=2445045.422 VHA= 10.311 VHD= 10.311  MAR 16 1982 22, 8,  7.747
ECLIPTIC          X                  Y                  Z                 TOTAL
R VENUS   -9.4488681E+07    -5.2200999E+07     4.6987729E+06     1.0805153E+08
V VENUS    1.6688688E+01    -3.0814833E+01    -1.3986313E+00     3.5071675E+01
V S/C A    6.5744611E+00    -2.8905157E+01    -7.8899371E-01     2.9653906E+01
VH A      -1.0114227E+01     1.9096765E+00     6.0963757E-01     1.0310970E+01
V S/C D    6.9354627E+00    -2.7600855E+01    -2.3260447E+00     2.8553780E+01
VHD       -9.7532251E+00     3.2139781E+00    -9.2741341E-01     1.0310924E+01
RCA= 27713.1  BTH=228.6    B*T=    -20262    B*R=    -22953    HCA= 21663.1
RAA= 169.3 DECA=   3.4 SPA= 140.4 EPA=  40.1 CPA=  87.4    TYPE  V    I
RAE= 129.8 DECE=  -3.2 PAS=  28.9 DECS=  -2.5
AH=     3055.6 EH= 10.06959 I= 131.3 NODE= 346.3 W= 169.8 TAU=  84.3
A= 80865628.1 E=    .411000 I=   6.0 NODE= 413.3 W= 358.6 TURN=  11.4
THI= 156.9 THF= 325.7 DTH= 168.8 FLT TIM= 377.078
PERIHELION= 47629842.1  APHELION=114101414.2

JD=2445422.500     VHP=  5.813    MAR 29 1983  0, 0, 0.
ECLIPTIC          X                  Y                  Z                 TOTAL
R MERCURY  4.7693820E+07     1.5268541E+07    -3.0701179E+06     5.0172248E+07
V MERCURY -2.4271956E+01     4.8688856E+01     6.2294687E+00     5.4758915E+01
V S/C     -2.7571874E+01     5.3445586E+01     5.6998083E+00     6.0408002E+01
VHP       -3.2999179E+00     4.7567304E+00    -5.2966041E-01     5.8134742E+00
RAA= 124.8   DECA=  -5.2    SPA=  73.4   EPA=  65.1    CPA=  71.5
RAE= 189.6   DECE=    .9    RAS=-162.2   DECS=   3.5
EQUATORIAL        X                  Y                  Z                 TOTAL
R MERCURY -4.8338397E+07    -1.3440754E+07     0.                   5.0172248E+07
V MERCURY  2.2807208E+01    -4.9783231E+01     2.8421709E-14     5.4758915E+01
V S/C      2.5860525E+01    -5.4579185E+01    -1.2134918E+00     6.0408002E+01
VHP        3.0533174E+00    -4.7959538E+00    -1.2134918E+00     5.8134742E+00
RAA= 302.5  DECA= -12.0  RAS=  15.5  DECS=  -0.    RAE=   7.7  DECE=  -3.4
MERCURY OP        X                  Y                  Z                 TOTAL
R MERCURY  4.3594322E+07    -2.4835248E+07     0.                   5.0172248E+07
V MERCURY  1.9261688E+01     5.1259401E+01     2.8421709E-14     5.4758915E+01
V S/C      2.0514118E+01     5.6805151E+01    -1.2134918E+00     6.0408002E+01
VHP        1.2524300E+00     5.5457497E+00    -1.2134918E+00     5.8134742E+00
RAA=  77.3  DECA= -12.0  RAS= 150.3  DECS=  -0.    RAE= 142.5  DECE=  -3.4
```

TABLE II-2 TRAJECTORY PRINTOUT 2-26-80 LAUNCH (Continued)

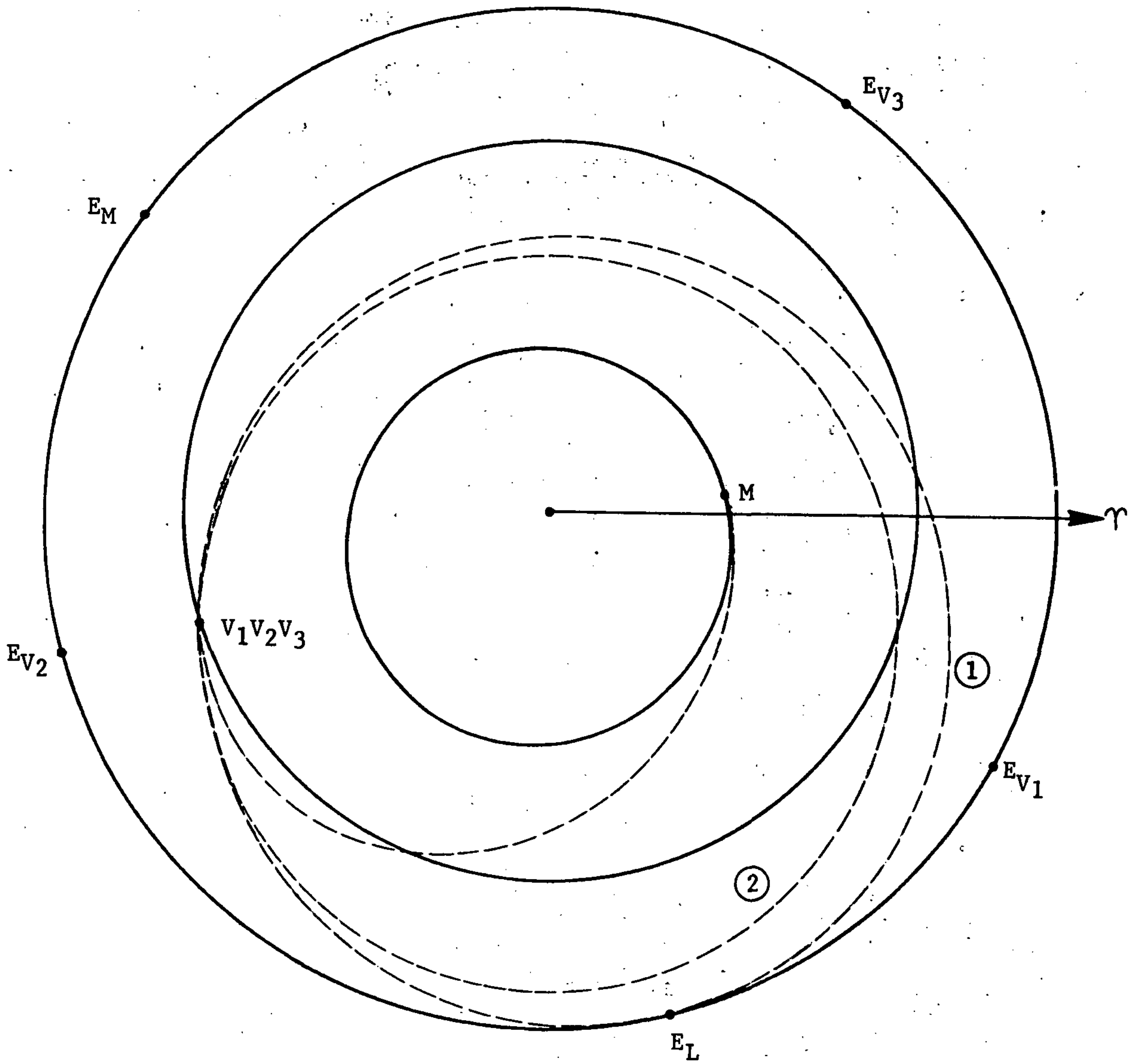
III. 1983 MULTIPLE VENUS SWINGBY OPPORTUNITY

III. 1983 MULTIPLE VENUS SWINGBY OPPORTUNITY

A. HELIOCENTRIC GEOMETRY

Figure III-1 shows the flight profile for the 31-month 1983 multiple Venus swingby opportunity. The heliocentric geometry for this triple Venus swingby opportunity includes one extra phasing orbit from launch to initial Venus swingby. The first swingby establishes a spacecraft orbit period equal to the Venus orbit period, assuring second and third Venus encounters, without changing spacecraft inclination. Then the second swingby establishes the required final spacecraft orbit plane, leaving only in-plane effects for the third gravity-assist. No extra phasing orbits are required between final Venus swingby and and Mercury encounter.

The use of triple Venus gravity assist represents an increase in required navigation analysis over that associated with single Venus swingby. The significance of multiple Venus swingby to tracking and navigation requirements is discussed in Subsection III-E.



E_L: EARTH AT LAUNCH, 7-8-83

E_{V_1}: EARTH AT FIRST VENUS SWINGBY (V_1), 8-25-84

E_{V_2}: EARTH AT SECOND VENUS SWINGBY (V_2), 4-6-85

E_{V_3}: EARTH AT THIRD VENUS SWINGBY (V_3), 11-17-85

E_M: EARTH AT MERCURY ENCOUNTER (M), 2-14-86

1 ONE COMPLETE SOLAR REVOLUTION BEFORE FIRST VENUS SWINGBY

2 ONE COMPLETE SOLAR REVOLUTION BETWEEN FIRST AND SECOND VENUS SWINGBYS
ONE COMPLETE SOLAR REVOLUTION BETWEEN SECOND AND THIRD VENUS SWINGBYS

Figure III-1 Heliocentric Geometry, 1983 Multiple Venus Swingby Opportunity

B. PERFORMANCE PARAMETERS

Performance parameters for the 1983 multiple Venus swingby opportunity are presented in Figure III-2. Relative arrival velocities for each launch date shown have been optimized with respect to Mercury arrival date. Launch energies corresponding to minimum relative arrival velocities are shown in the upper portion of the figure. As shown, the Mercury arrival velocities are comparable to those of the best single Venus baseline cases, while the corresponding launch energies are considerably lower than those for the single Venus swingby missions. As a result, the mission performance shows a significant improvement over the performance of the baseline cases (fig. I-1), demonstrating the usefulness of the multiple swingby flight technique.

Slight mismatches of the ballistic Venus arrival/departure characteristics for this multiple Venus opportunity prevent mission performance from reaching maximum potential. The performance improvement potential of using a midcourse velocity maneuver to correct the inherent ballistic mismatches was investigated. Results of this investigation are discussed in Section 2 of the Appendix.

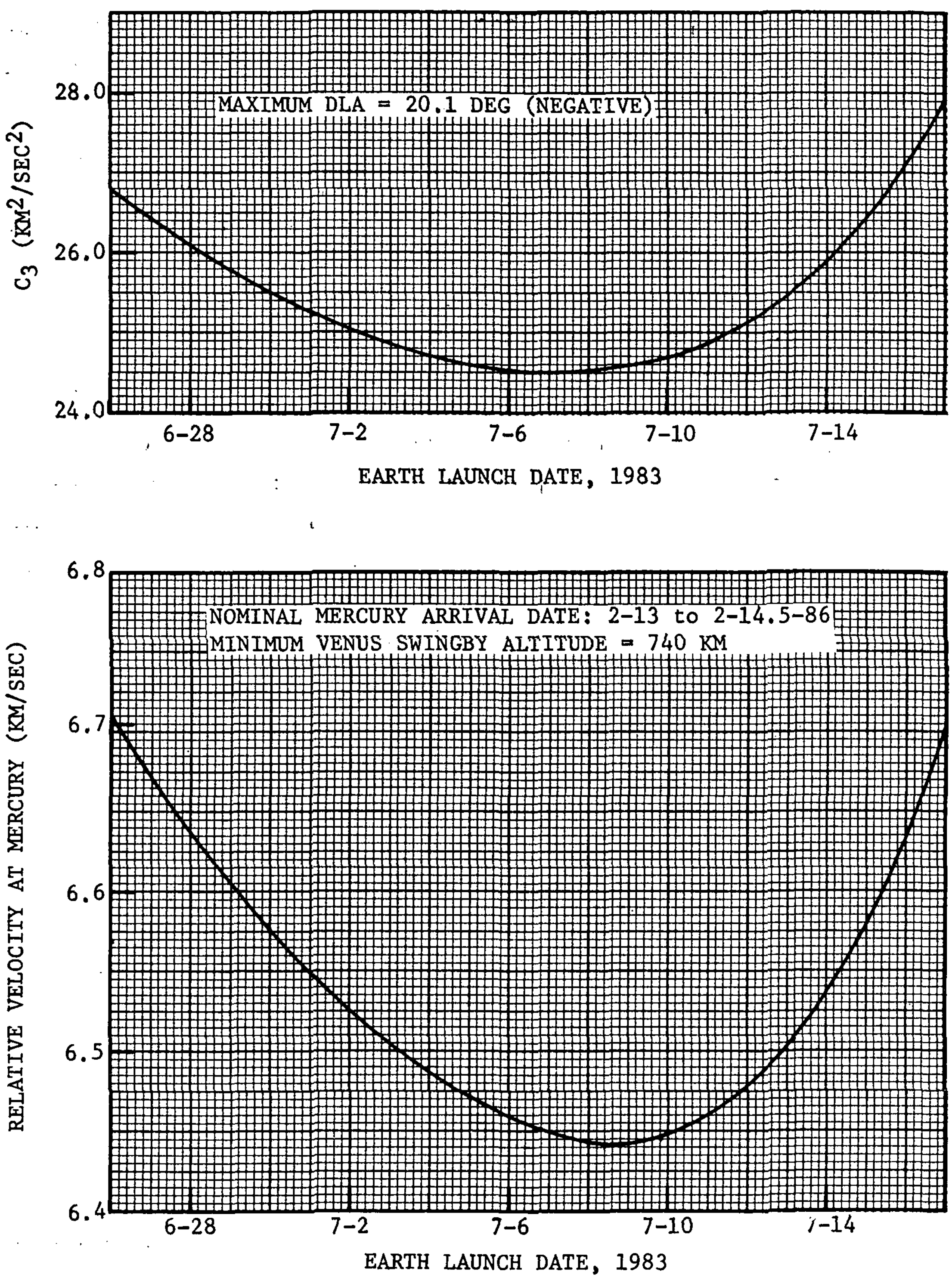


Figure III-2 Minimum Relative Velocity at Mercury and Corresponding C_3 vs Launch Date, 1983 Multiple Venus Swingby Opportunity

C. TRAJECTORY DATA

Tabulated details for three representative ballistic trajectories for the 1983 multiple Venus opportunity are listed in Tables III-1 through III-3. The Earth launch dates (7-1, 7-8, 7-15) are centered approximately on the best performance 15-day ballistic launch period. Corresponding Mercury arrival dates are chosen to provide minimum relative velocity at Mercury arrival. The print key which defines each listed parameter appears in Section 1 of the Appendix.

```
JD=2445516.500   C3=  25.314  FLT TIM= 420.438   JUL  1 1983  0, 0, 0.
ECLIPTIC            X                    Y                    Z                  TOTAL
R EARTH      2.0591208E+07   -1.5069189E+08    1.1304608E+04    1.5209222E+08
V EARTH      2.9027219E+01    3.9310922E+00   -5.1818575E-04    2.9292199E+01
VEL S/C      2.4354193E+01    2.5558816E+00   -1.2598763E+00    2.4520329E+01
VHE         -4.6730264E+00   -1.3752105E+00   -1.2593581E+00    5.0313380E+00
RAA=196.398 DECA=-14.495          SEVHE= 81.660
EQUATORIAL          X                    Y                    Z                  TOTAL
R EARTH      2.0591208E+07   -1.3826010E+08   -5.9867565E+07    1.5209222E+08
V EARTH      2.9027219E+01    3.6068734E+00    1.6577744E+00    2.9292199E+01
VEL S/C      2.4354193E+01    2.8461291E+00   -5.9909856E-02    2.4520329E+01
VHE         -4.6730264E+00   -7.6074429E-01   -1.7176843E+00    5.0313380E+00
RAA=189.246 DECA=-19.941 RP= 79776983.26 APO=152255778.79
A=116016381.03 E= .31236 I=  2.947 NODE=277.864 W=175.974
TH1= 176.1   TH2= 455.5   DTH= 279.4   TYPE   IV   I

JD=2445936.938 VHA= 10.896 VHD= 10.896  AUG 24 1984 10, 30, 14.371
ECLIPTIC            X                    Y                    Z                  TOTAL
R VENUS     -1.0294753E+08   -3.1880189E+07    5.4740555E+06    1.0790971E+08
V VENUS      1.0123865E+01   -3.3610020E+01   -1.0605647E+00    3.5117671E+01
V S/C A     -3.5743901E-01   -3.6270936E+01    2.7367660E-01    3.6273730E+01
VHA         -1.0481304E+01   -2.6609164E+00    1.3342413E+00    1.0895797E+01
V S/C D     -5.8472891E-01   -3.5111710E+01    2.7710240E-01    3.5117671E+01
VHD         -1.0708593E+01   -1.5016901E+00    1.3376671E+00    1.0895797E+01
RCA= 47742.0    BTH=179.4     B*T=    -50402    B*R=        485    HCA= 41692.0
RAA= 194.2 DECA=    7.0 SPA= 174.9 EPA= 154.9 CPA=  96.8   TYPE  I
RAE= 349.7 DECE=  -1.3 RAS=  17.2 DECS=  -2.9
AH=      2736.4 EH= 18.44707 I= 172.9 NODE= 279.8 W=  82.4 TAU=  86.9
A=108209149.6 E=     .311680 I=   2.9 NODE=  97.9 W= 351.7 TURN=   6.2
THI= 107.7 THF= 107.7 DTH= 360.  FLT TIM= 224.713
PERIHELION= 74482518.9  APHELION=141935780.4

JD=2446161.651 VHA= 10.896 VHD= 10.896  APR  6 1985  3, 37, 25.031
ECLIPTIC            X                    Y                    Z                  TOTAL
R VENUS     -1.0294753E+08   -3.1880189E+07    5.4740555E+06    1.0790971E+08
V VENUS      1.0123865E+01   -3.3610020E+01   -1.0605647E+00    3.5117671E+01
V S/C A     -5.8472891E-01   -3.5111710E+01    2.7710240E-01    3.5117671E+01
VHA         -1.0708593E+01   -1.5016901E+00    1.3376671E+00    1.0895797E+01
V S/C D     -1.5998218E-01   -3.4834733E+01   -4.4459708E+00    3.5117671E+01
VHD         -1.0283847E+01   -1.2247130E+00   -3.3854061E+00    1.0895797E+01
RCA=  9816.8    BTH=257.3     B*T=      -569    B*R=     -12238    HCA=  3766.8
RAA= 188.0 DECA=    7.1 SPA= 169.9 EPA=  14.7 CPA=  95.3   TYPE  I
RAE= 190.8 DECE=  -7.4 RAS=  17.2 DECS=  -2.9
AH=      2736.4 EH=  4.58750 I=  92.6 NODE=   7.7 W= 160.3 TAU=  77.4
A=108209149.6 E=     .290990 I=   9.0 NODE= 395.9 W= 251.1 TURN=  25.2
THI= 106.4 THF= 106.4 DTH= 360.  FLT TIM= 224.702
PERIHELION= 76721421.2  APHELION=139696878.1
```

TABLE III-1 TRAJECTORY PRINTOUT   7-1-83 LAUNCH

```
JD=2446386.353 VHA= 10.896 VHD= 10.893  NOV 16 1985 20, 27, 44.333
ECLIPTIC          X                  Y                  Z                  TOTAL
R VENUS    -1.0294753E+08    -3.1880189E+07     5.4740555E+06     1.0790971E+08
V VENUS     1.0123865E+01    -3.3610020E+01    -1.0605647E+00     3.5117671E+01
V S/C A    -1.5998218E-01    -3.4834733E+01    -4.4459708E+00     3.5117671E+01
VHA        -1.0283847E+01    -1.2247130E+00    -3.3854061E+00     1.0895797E+01
V S/C D     7.6017128E-01    -2.8736429E+01    -3.7504591E+00     2.8990105E+01
VHD        -9.3636933E+00     4.8735903E+00    -2.6898944E+00     1.0893400E+01
RCA=  6870.4   BTH=178.5    B*T=     -9206    B*R=        237    HCA=   820.4
RAA= 186.8 DECA= -18.1  SPA= 156.6 EPA= 143.4 CPA=  70.6   TYPE  I
RAE=  38.3 DECE=  -1.3  RAS=  17.2 DECS=  -2.9
AH=      2736.4 EH=  3.51075 I= 161.8 NODE= 101.5 W= 258.0 TAU=  73.5
A= 81958277.4 E=    .402095 I=   9.0 NODE= 395.9 W=    6.4 TURN=  33.1
THI= 154.6 THF= 319.8 DTH= 165.2 FLT TIM=  88.786
PERIHELION= 49003291.2  APHELION=114913263.6

JD=2446475.139    VHP=  6.550    FEB 13 1986 15,19,44.413
ECLIPTIC          X                  Y                  Z                  TOTAL
R MERCURY  5.2309349E+07     2.3070975E+06    -4.5603911E+06     5.2558423E+07
V MERCURY -1.1525108E+01     5.0969207E+01     5.2602144E+00     5.2520073E+01
V S/C     -1.3205787E+01     5.6435645E+01     8.4528454E+00     5.8573248E+01
VHP       -1.6806792E+00     5.4664378E+00     3.1926311E+00     6.5497724E+00
RAA= 107.1   DECA=  29.2   SPA=  74.9   EPA=  52.2   CPA= 105.0
RAE= 153.6   DECE=   1.4   RAS=-177.5   DECS=   5.0
EQUATORIAL        X                  Y                  Z                  TOTAL
R MERCURY -4.8957182E+07    -1.9120203E+07    -2.9802322E-08     5.2558423E+07
V MERCURY  2.7803925E+01    -4.4556703E+01     5.6843419E-14     5.2520073E+01
V S/C      3.1498283E+01    -4.9316173E+01     2.5687907E+00     5.8573248E+01
VHP        3.6943572E+00    -4.7594702E+00     2.5687907E+00     6.5497724E+00
RAA= 307.8  DECA=  23.1  RAS=  21.3  DECS=    .0  RAE= 352.7  DECE=  -5.4
MERCURY OP        X                  Y                  Z                  TOTAL
R MERCURY  3.7241482E+07    -3.7087192E+07    -2.9802322E-08     5.2558423E+07
V MERCURY  2.9558183E+01     4.3412807E+01     5.6843419E-14     5.2520073E+01
V S/C      3.2423377E+01     4.8712948E+01     2.5687907E+00     5.8573248E+01
VHP        2.8651941E+00     5.3001411E+00     2.5687907E+00     6.5497724E+00
RAA=  61.6  DECA=  23.1  RAS= 135.1  DECS=    .0  RAE= 106.5  DECE=  -5.4
```

TABLE III-1 TRAJECTORY PRINTOUT 7-1-83 LAUNCH (Continued)

```
JD=2445523.500   C3=  24.532  FLT TIM= 414.127    JUL  8 1983  0, 0, 0.
ECLIPTIC            X                   Y                  Z              TOTAL
R EARTH     3.7964099E+07    -1.4728163E+08     1.0920290E+04     1.5209586E+08
V EARTH     2.8358592E+01     7.3335837E+00    -7.7233880E-04     2.9291487E+01
VEL S/C     2.3659640E+01     6.3666863E+00    -1.2325971E+00     2.4532276E+01
VHE        -4.6989519E+00    -9.6689737E-01    -1.2318247E+00     4.9530225E+00
RAA=191.627 DECA=-14.401          SEVHE= 92.739
EQUATORIAL          X                   Y                  Z              TOTAL
R EARTH     3.7964099E+07    -1.3513113E+08    -5.8454702E+07     1.5209586E+08
V EARTH     2.8358592E+01     6.7286655E+00     3.0089223E+00     2.9291487E+01
VEL S/C     2.3659640E+01     6.3315843E+00     1.4788321E+00     2.4532276E+01
VHE        -4.6989519E+00    -3.9708125E-01    -1.5300902E+00     4.9530225E+00
RAA=184.830 DECA=-17.977 RP= 80045377.90 APO=152114794.01
A=116080085.95 E= .31043 I=  2.880 NODE=284.536 W=181.266
TH1= 181.3   TH2= 455.2   DTH= 273.8    TYPE   IV    I

JD=2445937.627 VHA= 10.836 VHD= 10.836  AUG 25 1984  3,  2, 14.359
ECLIPTIC            X                   Y                  Z              TOTAL
R VENUS    -1.0233663E+08    -3.3840782E+07     5.4110173E+06     1.0792248E+08
V VENUS     1.0758044E+01    -3.3406990E+01    -1.0941919E+00     3.5113526E+01
V S/C A     4.2108887E-01    -3.6273287E+01     4.3751969E-01     3.6278370E+01
VHA        -1.0336955E+01    -2.8662977E+00     1.5317115E+00     1.0835795E+01
V S/C D     1.6683859E-01    -3.5110433E+01     4.3521798E-01     3.5113526E+01
VHD        -1.0591206E+01    -1.7034429E+00     1.5294098E+00     1.0835795E+01
RCA= 47606.4    BTH=179.7      B*T=     -50296      B*R=       297     HCA= 41556.4
RAA= 195.5 DECA=    8.1  SPA= 174.1 EPA= 154.3 CPA=   98.2    TYPE  I
RAE= 350.6 DECE=   -1.3  RAS=   18.3 DECS=  -2.9
AH=      2766.8 EH= 18.20641 I= 171.9 NODE= 283.1 W=   84.5 TAU=   86.9
A=108209149.6 E=     .309664 I=    2.9 NODE= 104.5 W= 346.2 TURN=    6.3
THI= 107.6 THF= 107.6 DTH= 360.  FLT TIM= 224.702
PERIHELION= 74700649.2  APHELION=141717650.0

JD=2446162.328 VHA= 10.836 VHD= 10.836  APR  6 1985 19, 52, 33.645
ECLIPTIC            X                   Y                  Z              TOTAL
R VENUS    -1.0233663E+08    -3.3840782E+07     5.4110173E+06     1.0792248E+08
V VENUS     1.0758044E+01    -3.3406990E+01    -1.0941919E+00     3.5113526E+01
V S/C A     1.6683859E-01    -3.5110433E+01     4.3521798E-01     3.5113526E+01
VHA        -1.0591206E+01    -1.7034429E+00     1.5294098E+00     1.0835795E+01
V S/C D     5.5190409E-01    -3.4826557E+01    -4.4459051E+00     3.5113526E+01
VHD        -1.0206140E+01    -1.4195671E+00    -3.3517133E+00     1.0835795E+01
RCA=  9458.8    BTH=267.4      B*T=       -546      B*R=    -11896     HCA=  3408.8
RAA= 189.1 DECA=    8.1  SPA= 169.5 FPA=  15.5 CPA=   96.6    TYPE  I
RAE= 190.4 DECE=   -7.3  RAS=   18.3 DECS=  -2.9
AH=      2766.8 EH=  4.41871 I=   92.6 NODE=    8.8 W= 158.8 TAU=   76.9
A=108209149.6 E=     .289762 I=    9.0 NODE= 396.9 W= 251.2 TURN=   26.2
THI= 106.3 THF= 106.3 DTH= 360.  FLT TIM= 224.702
PERIHELION= 76854287.8  APHELION=139564011.4
```

TABLE III-2 TRAJECTORY PRINTOUT 7-8-83 LAUNCH

```
JD=2446387.030 VHA= 10.836 VHD= 10.836  NOV 17 1985 12, 42, 52.930
ECLIPTIC            X                     Y                      Z                   TOTAL
R VENUS     -1.0233663E+08     -3.3840782E+07      5.4110173E+06      1.0792248E+08
V VENUS      1.0758044E+01     -3.3406990E+01     -1.0941919E+00      3.5113526E+01
V S/C A      5.5190409E-01     -3.4826557E+01     -4.4459051E+00      3.5113526E+01
VHA         -1.0206140E+01     -1.4195671E+00     -3.3517133E+00      1.0835795E+01
V S/C D      1.3856275E+00     -2.8660435E+01     -3.7468552E+00      2.8937509E+01
VHD         -9.3724166E+00      4.7465549E+00     -2.6526634E+00      1.0835525E+01
RCA=  6809.4    BTH=178.6      B*T=      -9165     B*R=          224     HCA=    759.4
RAA= 187.9 DECA= -18.0 SPA= 156.7 EPA= 143.7 CPA=   71.0    TYPE  I
RAE=  39.2 DECE=  -1.3 RAS=   18.3 DECS=  -2.9
AH=       2766.8 EH=  3.46111 I= 161.9 NODE= 102.4 W= 257.5 TAU=  73.2
A= 81819039.1 E=     .402348 I=    9.0 NODE= 396.9 W=    6.2 TURN=  33.6
THI= 155.0 THF= 321.5 OTH= 166.5 FLT TIM=  88.604
PERIHELION= 48899337.1   APHELION=114738741.0

JD=2446475.633      VHP=   6.447    FEB 14 1986  3,12, 4.642
ECLIPTIC            X                     Y                      Z                   TOTAL
R MERCURY  5.1772890E+07      4.4829775E+06     -4.3317946E+06      5.2146847E+07
V MERCURY -1.3582686E+01      5.0834803E+01      5.4359877E+00      5.2898171E+01
V S/C      -1.5245986E+01      5.6237067E+01      8.5370036E+00      5.8889118E+01
VHP        -1.6633000E+00      5.4022642E+00      3.1010159E+00      6.4472727E+00
RAA= 107.1    DECA=  28.7     SPA=  77.1    EPA=  52.8    CPA= 104.6
RAE= 154.5    DECE=    1.3    RAS=-175.1    DECS=   4.8
EQUATORIAL          X                     Y                      Z                   TOTAL
R MERCURY -4.8773427E+07     -1.8451192E+07     -2.9802322E-08      5.2146847E+07
V MERCURY  2.7356188E+01     -4.5275330E+01      8.5265128E-14      5.2898171E+01
V S/C      3.0749323E+01     -5.0162074E+01      2.4846909E+00      5.8889118E+01
VHP        3.3931354E+00     -4.8867441E+00      2.4846909E+00      6.4472727E+00
RAA= 304.8   DECA=  22.7  RAS=  20.7  DECS=      .0  PAE= 350.6   DECE=  -5.4
MERCURY OP          X                     Y                      Z                   TOTAL
R MERCURY  3.8473128E+07     -3.5201025E+07     -2.9802322E-08      5.2146847E+07
V MERCURY  2.8061256E+01      4.4841749E+01      8.5265128E-14      5.2898171E+01
V S/C      3.0891272E+01      5.0074783E+01      2.4846909E+00      5.8889118E+01
VHP        2.8300162E+00      5.2330340E+00      2.4846909E+00      6.4472727E+00
RAA=  61.6   DECA=  22.7  RAS= 137.5  DECS=      .0  RAE= 107.4   DECE=  -5.4
```

TABLE III-2 TRAJECTORY PRINTOUT 7-8-83 LAUNCH (Continued)

```
JD=2445530.500   C3=  26.453  FLT TIM= 407.081    JUL 15 1983  0, 0, 0.
ECLIPTIC           X                  Y                  Z                  TOTAL
R EARTH     5.4813795E+07   -1.4184167E+08    1.0384943E+04     1.5206450E+08
V EARTH     2.7298873E+01    1.0635915E+01   -1.0161989E-03     2.9297630E+01
VEL S/C     2.2319861E+01    1.0255864E+01   -1.2332303E+00     2.4594304E+01
VHE        -4.9790120E+00   -3.8005054E-01   -1.2322141E+00     5.1432821E+00
RAA=184.365 DECA=-13.862          SEVHE=106.263
EQUATORIAL         X                  Y                  Z                  TOTAL
R EARTH     5.4813795E+07   -1.3013990E+08   -5.6236210E+07     1.5206450E+08
V EARTH     2.7298873E+01    9.7585594E+00    4.3189589E+00     2.9297630E+01
VEL S/C     2.2319861E+01    9.9000486E+00    3.0210368E+00     2.4594304E+01
VHE        -4.9790120E+00    1.4148916E-01   -1.2979221E+00     5.1432821E+00
RAA=178.372 DECA=-14.605 RP= 79991933.20 APO=152715216.41
A=116353574.80 E= .31251 I=  2.879 NODE=291.206 W=187.790
TH1= 187.9   TH2= 455.0   DTH= 267.1   TYPE   IV    I


JD=2445937.581 VHA= 10.927 VHD= 10.927  AUG 25 1984  1, 56, 39.530
ECLIPTIC           X                  Y                  Z                  TOTAL
R VENUS    -1.0236803E+08   -3.3743102E+07    5.4142137E+06     1.0792184E+08
V VENUS     1.0726452E+01   -3.3417420E+01   -1.0925212E+00     3.5113734E+01
V S/C A     3.3300135E-01   -3.6308334E+01    6.4499517E-01     3.6315589E+01
VHA        -1.0393451E+01   -2.8909139E+00    1.7375164E+00     1.0927038E+01
V S/C D     7.0167019E-02   -3.5107913E+01    6.3547909E-01     3.5113734E+01
VHD        -1.0656285E+01   -1.6904934E+00    1.7280003E+00     1.0927038E+01
RCA= 45664.1    BTH=179.9     B*T=    -48308    B*R=          59    HCA= 39614.1
RAA= 195.5 DECA=    9.1 SPA= 173.2 EPA= 153.9 CPA=  99.2   TYPE  I
RAE= 350.5 DECE=  -1.3 RAS=  18.2 DECS=  -2.9
AH=      2720.8 EH= 17.78352 I= 170.9 NODE= 285.1 W=  86.3 TAU=  86.8
A=108209149.6 E=    .311633 I=    2.9 NODE= 111.2 W= 339.3 TURN=   6.4
THI= 107.7 THF= 107.7 DTH= 360.  FLT TIM= 224.713
PERIHELION= 74487579.7  APHELION=141930719.5

JD=2446162.294 VHA= 10.927 VHD= 10.927  APR  6 1985 19,  3, 50.174
ECLIPTIC           X                  Y                  Z                  TOTAL
R VENUS    -1.0236803E+08   -3.3743102E+07    5.4142137E+06     1.0792184E+08
V VENUS     1.0726452E+01   -3.3417420E+01   -1.0925212E+00     3.5113734E+01
V S/C A     7.0167019E-02   -3.5107913E+01    6.3547909E-01     3.5113734E+01
VHA        -1.0656285E+01   -1.6904934E+00    1.7280003E+00     1.0927038E+01
V S/C D     5.0038549E-01   -3.4795777E+01   -4.6880542E+00     3.5113734E+01
VHD        -1.0226067E+01   -1.3783570E+00   -3.5955330E+00     1.0927038E+01
RCA=  8393.2    BTH=267.3     B*T=      -500    B*R=   -10764    HCA=  2343.2
RAA= 189.0 DECA=    9.1 SPA= 168.9 EPA=  16.5 CPA=  97.5   TYPE  I
RAE= 190.4 DECE=  -7.3 RAS=  18.2 DECS=  -2.9
AH=      2720.8 EH=  4.08487 I=  92.6 NODE=   8.6 W= 156.7 TAU=  75.8
A=108209149.6 E=    .289627 I=    9.4 NODE= 396.0 W= 252.0 TURN=  28.3
THI= 106.3 THF= 106.3 DTH= 360.  FLT TIM= 224.702
PERIHELION= 76868820.8  APHELION=139549478.4
```

TABLE III-3 TRAJECTORY PRINTOUT 7-15-83 LAUNCH

```
JD=2446386.396 VHA= 10.927 VHD= 10.924  NOV 17 1985 11, 54,  9.459
ECLIPTIC          X                 Y                 Z                TOTAL
R VENUS    -1.0236803E+08   -3.3743102E+07    5.4142137E+06    1.0792184E+08
V VENUS     1.0726452E+01   -3.3417420E+01   -1.0925212E+00    3.5113734E+01
V S/C A     5.0038548E-01   -3.4795777E+01   -4.6880542E+00    3.5113734E+01
VHA        -1.0226067E+01   -1.3783570E+00   -3.5955330E+00    1.0927038E+01
V S/C D     1.3256050E+00   -2.8642441E+01   -3.9474966E+00    2.8943555E+01
VHD        -9.4008472E+00    4.7749788E+00   -2.8549754E+00    1.0923701E+01
RCA=  6787.7   BTH=178.5    B*T=     -9108    B*R=        243    HCA=    737.7
RAA= 187.7 DECA= -19.2 SPA= 155.6 EPA= 142.9 CPA=  69.8   TYPE  I
RAE=  39.1 DECE=  -1.3 RAS=  18.2 DECS=  -2.9
AH=      2720.8 EH=  3.49476 I= 160.7 NODE= 102.3 W= 257.7 TAU=  73.4
A= 81835960.0 E=    .402405 I=   9.4 NODE= 396.0 W=   7.1 TURN=  33.3
THI= 154.9 THF= 323.4 DTH= 168.4 FLT TIM=  89.004
PERIHELION= 48904744.6  APHELION=114767175.4

JD=2446476.000     VHP=  6.576   FEB 14 1986 12, 0, 6.004
ECLIPTIC          X                 Y                 Z                TOTAL
R MERCURY   5.1318275E+07    6.0908162E+06   -4.1575894E+06    5.1845433E+07
V MERCURY  -1.5124224E+01    5.0676620E+01    5.5629249E+00    5.3177139E+01
V S/C      -1.6589675E+01    5.6037653E+01    9.0785086E+00    5.9142668E+01
VHP        -1.4654512E+00    5.3610331E+00    3.5155838E+00    6.5762871E+00
RAA= 105.3  DECA=  32.3   SPA=  80.3   EPA=  56.2   CPA= 108.1
RAE= 155.2  DECE=   1.3   RAS=-173.2   DECS=   4.6
EQUATORIAL        X                 Y                 Z                TOTAL
R MERCURY  -4.8627292E+07   -1.7981528E+07   -2.9802322E-08    5.1845433E+07
V MERCURY   2.7024680E+01   -4.5798196E+01    5.6843419E-14    5.3177139E+01
V S/C       3.0066930E+01   -5.0846079E+01    2.9173863E+00    5.9142668E+01
VHP         3.0422498E+00   -5.0478833E+00    2.9173863E+00    6.5762871E+00
RAA= 301.1  DECA=  26.3  RAS=  20.3  DECS=     .0  RAE= 349.0  DECE=  -5.4
MERCURY OP        X                 Y                 Z                TOTAL
R MERCURY   3.9343679E+07   -3.3764239E+07   -2.9802322E-08    5.1845433E+07
V MERCURY   2.6897585E+01    4.5872955E+01    5.6843419E-14    5.3177139E+01
V S/C       2.9831345E+01    5.0984654E+01    2.9173863E+00    5.9142668E+01
VHP         2.9337598E+00    5.1116987E+00    2.9173863E+00    6.5762871E+00
RAA=  60.1  DECA=  26.3  RAS= 139.4  DECS=     .0  RAE= 108.0  DECE=  -5.4
```

TABLE III-3 TRAJECTORY PRINTOUT 7-15-83 LAUNCH (Continued)

D. FLIGHT CHARACTERISTICS

Four significant geometry parameters are presented in time history format in Figure III-3. Included are spacecraft range from Sun, spacecraft range from Earth, Sun-Earth-spacecraft angle and spacecraft geocentric equatorial declination for the second reference trajectory (Table III-2) of this opportunity. Earth-spacecraft range is large (>200 Mkm) for all critical tracking arcs with the exception of the one prior to second swingby. Solar interference, as shown by a near-zero Sun-Earth-spacecraft angle before Mercury encounter, necessitates an early pre-Mercury maneuver executed at M-19.

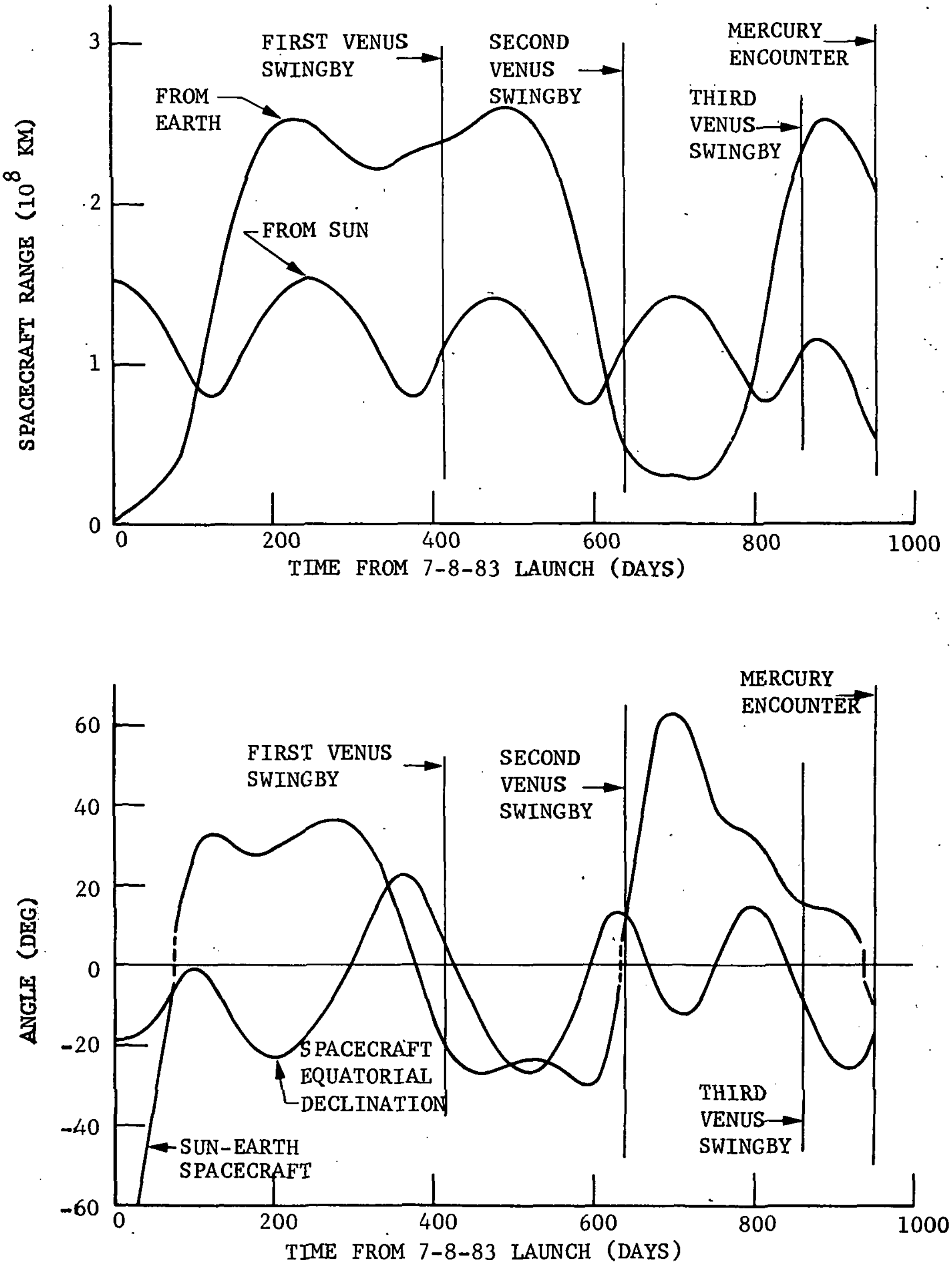


Figure III-3 Typical Time Histories, 1983 Multiple Venus Swingby Opportunity

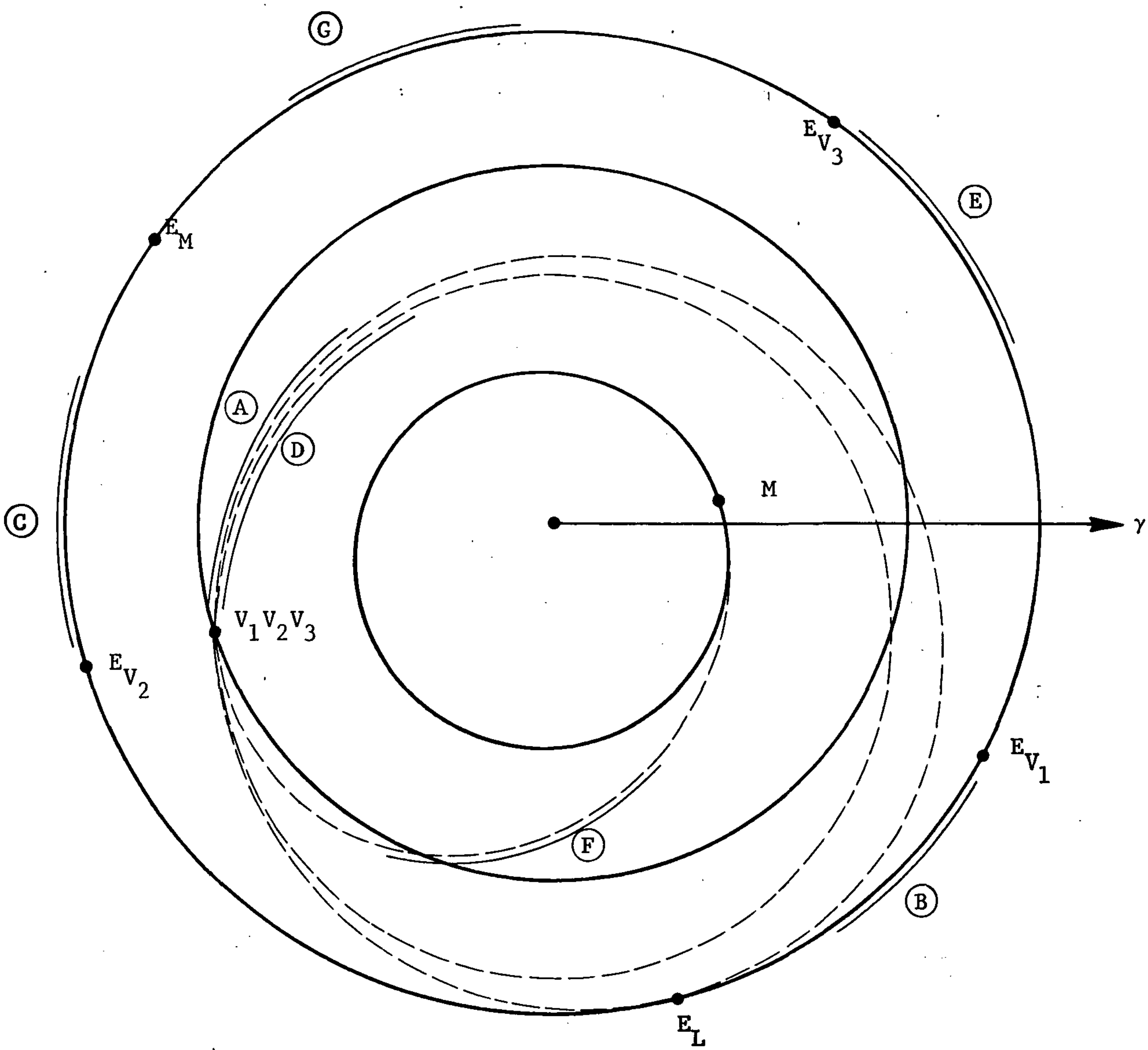
E. NAVIGATION REQUIREMENTS

The four complete heliocentric revolutions with three Venus gravity-assists of the 1983 opportunity require many trajectory correction maneuvers. Their schedule along with mean-plus-three-sigma ΔV requirements for a typical 1983 trajectory are shown below. Geometries for tracking phases prior to each Venus swingby and Mercury encounter appear in Figure III-4. Assumptions and maneuver strategies for the navigation and orbit determination analysis on which these results are based are discussed in the original Handbook (NASA CR-2298) and in Section VI of this report. This maneuver strategy included corrections between successive Venus encounters, but the calculated magnitudes suggest the possibility of eliminating these maneuvers. A less conservative estimate for total corrective ΔV requirements is 127.7 m/s (described in Section VI). The largest post-Venus maneuver corresponds to the closest swingby and requires 104 m/s (mean-plus-three-sigma). However, this third swingby is nominally at 760 km altitude so trajectory dispersions at closest approach are not critical. Analytic determination (Lee-Boain) of this large maneuver yields 103 m/s for .99 cumulative probability level and 130 m/s for .999. The first and second swingbys are at 41,000 km and 3400 km in that order. Post-Venus trajectory corrections require 5.2 m/s and 20.5 m/s (mean-plus-three-sigma).

TABLE III-4

1983 MANEUVER SCHEDULE AND STATISTICAL DESCRIPTION

MANEUVER TIME (days)	MEAN ΔV (m/s)	SIGMA ΔV (m/s)	MEAN PLUS THREE SIGMA (m/s)
E+10	8.58	6.02	26.65
E+200	0.13	0.071	0.34
V_1-3	0.33	0.23	1.03
V_1+2	1.61	1.19	5.16
V_1+112	0.028	0.021	0.092
V_2-3	0.19	0.12	0.55
V_2+2	6.27	4.73	20.47
V_2+112	0.081	0.06	0.26
V_3-3	0.34	0.25	1.10
V_3+2	37.58	22.13	103.97
M-19	2.06	1.52	6.61
		TOTAL	166.23



Ⓐ SPACECRAFT DURING PRE-VENUS$_1$ AND PRE-VENUS$_2$ TRACKING PERIODS

Ⓑ EARTH DURING PRE-VENUS$_1$ TRACKING PERIOD

Ⓒ EARTH DURING PRE-VENUS$_2$ TRACKING PERIOD

Ⓓ SPACECRAFT DURING PRE-VENUS$_3$ TRACKING PERIOD

Ⓔ EARTH DURING PRE-VENUS$_3$ TRACKING PERIOD

Ⓕ SPACECRAFT DURING PRE-MERCURY TRACKING PERIOD

Ⓖ EARTH DURING PRE-MERCURY TRACKING PERIOD

Figure III-4 Critical Tracking Geometries, 1983 Multiple Venus Swingby Opportunity

Mercury approach uncertainties are shown in Figure VI-3. These are dominated by a 60 km Mercury ephemeris error in the T-axis and by the mapping of an out-of-the-ecliptic pre-maneuver knowledge error through a 19-day arc on the R-axis.

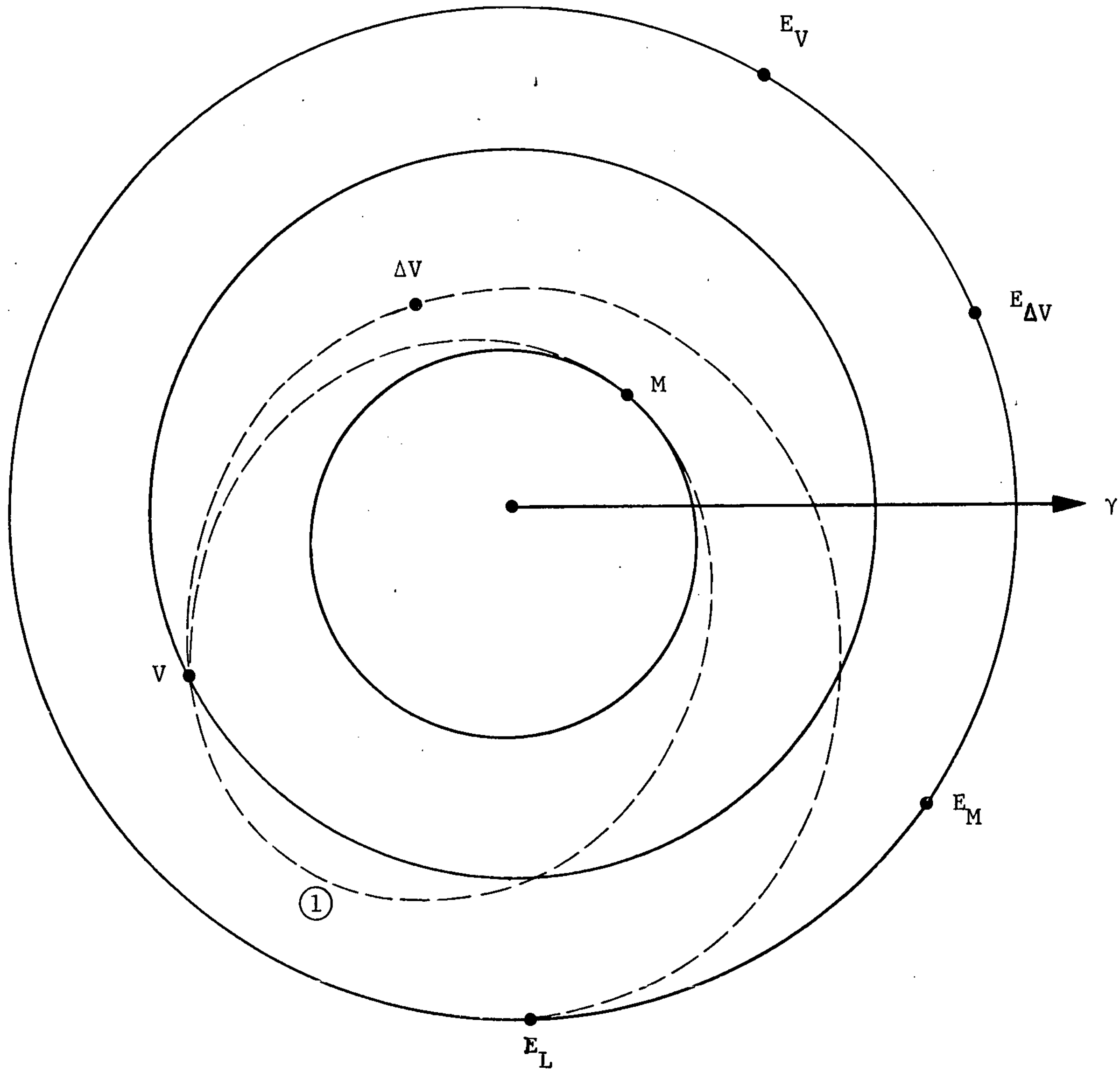
IV. '1985 MISSION OPPORTUNITY WITH MIDCOURSE MANEUVERS

IV. 1985 MISSION OPPORTUNITY WITH MIDCOURSE MANEUVERS

A. HELIOCENTRIC GEOMETRY

As shown in Figure IV-1 , the flight profile for the 14-month 1985 single Venus swingby opportunity incorporating the midcourse velocity maneuver is very similar to the 1985 baseline mission geometry. However, the Venus swingby date is delayed approximately 10 days by the application of a midcourse velocity maneuver near perihelion of the Type II Earth-Venus transfer segment. As in the 1985 single Venus swingby baseline mission, one extra spacecraft phasing revolution is necessary prior to Mercury encounter.

Optimization of Venus swingby date results in a slight shift in Earth position at Venus swingby and Mercury encounter. The implications of these new earth positions to Earth-based tracking and navigation requirements are discussed in Subsection IV-E.



E_L: EARTH AT LAUNCH, 6-24-85

$E_{\Delta V}$: EARTH AT MIDCOURSE VELOCITY MANEUVER, 10-16-85

E_V: EARTH AT VENUS SWINGBY (V), 11-21-85

E_M: EARTH AT MERCURY ENCOUNTER (M), 8-16-86

ΔV: MIDCOURSE VELOCITY MANEUVER (400 M/S)

(1) ONE COMPLETE SOLAR REVOLUTION BEFORE MERCURY ENCOUNTER

Figure IV-1 Heliocentric Geometry, 1985 Opportunity with Midcourse Velocity Maneuver

B. PERFORMANCE PARAMETERS

The use of a midcourse velocity maneuver near perihelion of the Earth-Venus trajectory segment of the 1985 baseline mission opportunity results in a considerable reduction in relative velocity at Mercury and a corresponding increase in mission performance. By allowing proper timing of Venus departure date, the midcourse maneuver is able to alleviate much of the planetary geometry misalignment which is characteristic of the 1985 baseline opportunity. Figure IV-2 shows the minimum relative velocity at Mercury which can be achieved for various constant values of the midcourse maneuver. The corresponding launch energies are presented in Figure IV-3 . The curves shown in Figure IV-2 represent relative arrival velocities which have been optimized with respect to maneuver position as well as Mercury arrival date. The optimization approach used requires some explanation.

For a given Mercury arrival date, choice of a desired Venus swingby date uniquely determines a relative velocity at Mercury and a corresponding relative departure velocity at Venus. A trajectory from Earth to maneuver must then be specified. Although the Earth-maneuver trajectory segment may be chosen as any conic from Earth to some point in space, the Earth-maneuver trajectory segment for this mission is chosen as a portion of an initial trajectory from Earth which encounters Venus at some position ($Venus_i$) near desired swingby position. Thus, rather than being an arbitrary trajectory segment, the Earth-maneuver leg is constrained to be a portion of a true Earth to Venus trajectory. Once a guess for the maneuver position along this Earth-$Venus_i$ trajectory is made, a conic trajectory is patched from maneuver position to desired Venus swingby position, and $Venus_i$ is adjusted to match arrival and departure conditions at desired Venus swingby position. Optimization of the midcourse maneuver (ΔV_{MC}) then consists of finding the combination of $Venus_i$ and maneuver position along the Earth-$Venus_i$ trajectory which results in minimum maneuver magnitude for a given Earth launch date and Mercury arrival date. For this mission, the optimum position of the maneuver in all cases was near perihelion of the Earth-$Venus_i$ trajectory segment with $Venus_i$ being about one day prior to the time of actual Venus swingby. In every case, the maneuver was primarily a retrograde maneuver with a small out-of-the-ecliptic component.

As stated previously, the relative velocities shown in Figure IV-2 are also optimized with respect to Mercury arrival date. In general, the minimum achievable arrival velocity for a given value of ΔV_{MC} varies with Mercury arrival date as shown in Figure IV-4 for a launch date of 7-2-85. For each launch date, determination of optimum Mercury date requires identification of the envelope of minimum arrival velocity vs ΔV_{MC}. The effect of Mercury date upon the arrival velocity vs ΔV_{MC} lines is very pronounced for the later launch dates and is negligible for the early launch dates. Consequently, optimization of Mercury date resulted in greater savings in the late portion of the launch window for each value of ΔV_{MC} in Figure IV-2. The scheme described above for determining optimum position of the midcourse maneuver is used in conjunction with the search for optimum Mercury date to insure that the data shown represents the true minimum relative arrival velocity which can be achieved for a given value of the midcourse maneuver within the constraints outlined earlier.

As seen from Figure IV-2, the relative velocity at Mercury for a 15-day launch period decreases as ΔV_{MC} increases. This decrease, however, is accompanied by an increase in required launch energy. Despite greater required launch energy for higher values of ΔV_{MC}, the lower values of relative arrival velocity result in higher performance for increasing ΔV_{MC}. The mission performance appears to peak near a value of ΔV_{MC}=400 m/s. Consequently, this value was used in the navigation analysis and trajectory printouts for this mission. Optimized performance for the 1985 mission opportunity with midcourse velocity maneuvers is shown in Figure I-1.

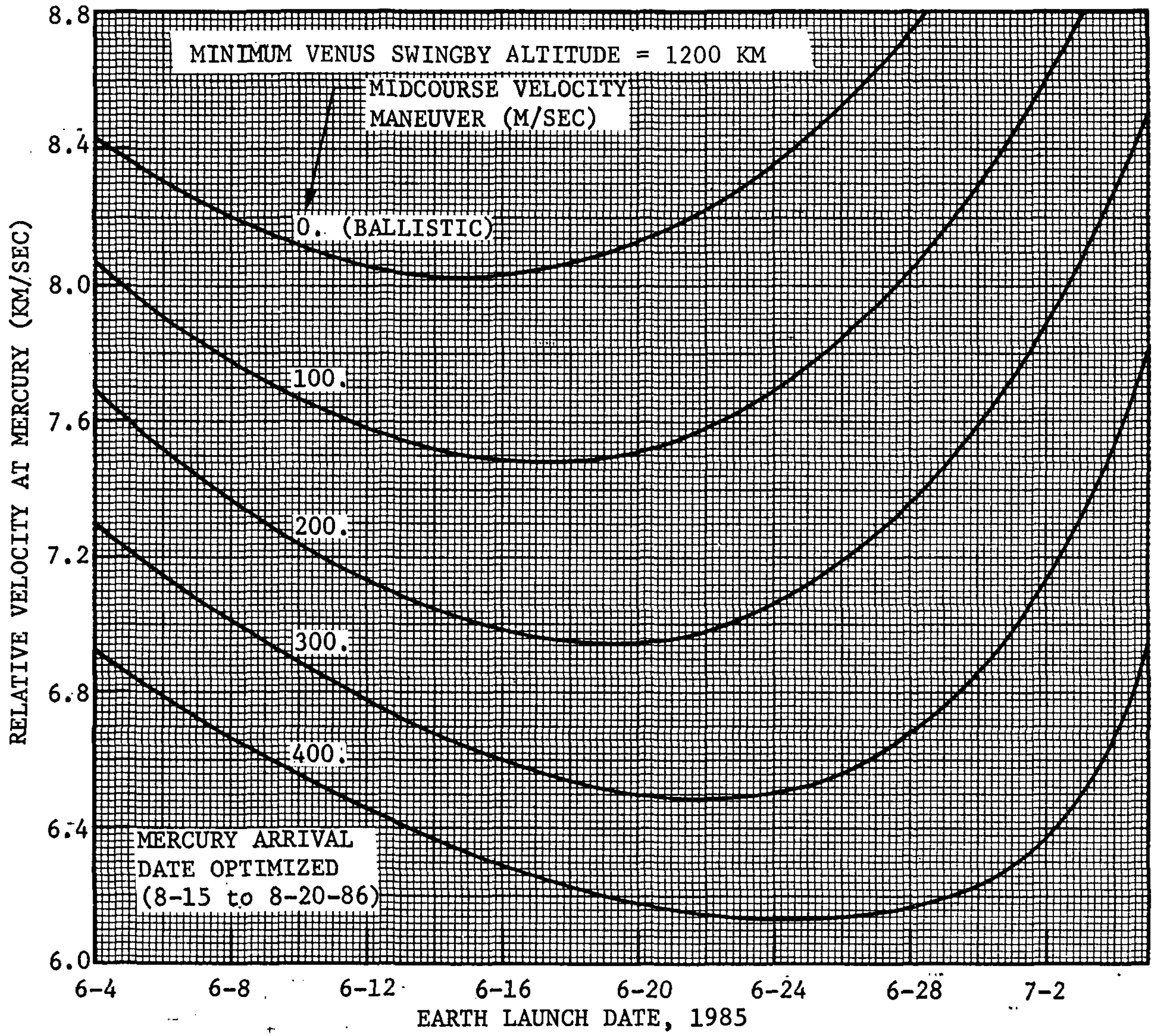


Figure IV-2 Minimum Relative Velocity at Mercury vs Launch Date, 1985 Opportunity with Midcourse Velocity Maneuvers

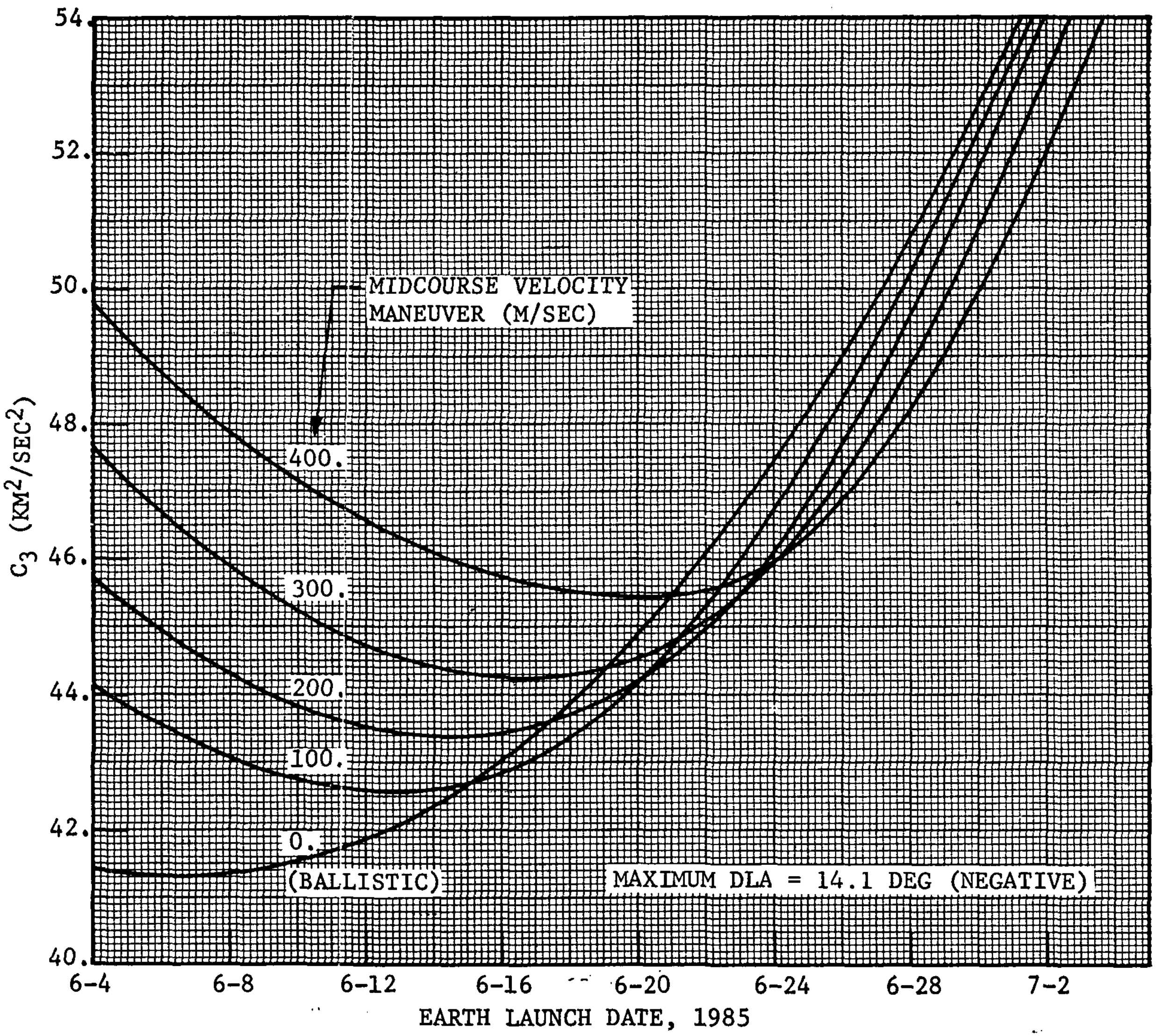


Figure IV-3 C_3 Corresponding to Minimum Relative Velocity vs Launch Date, 1985 Opportunity with Midcourse Velocity Maneuvers

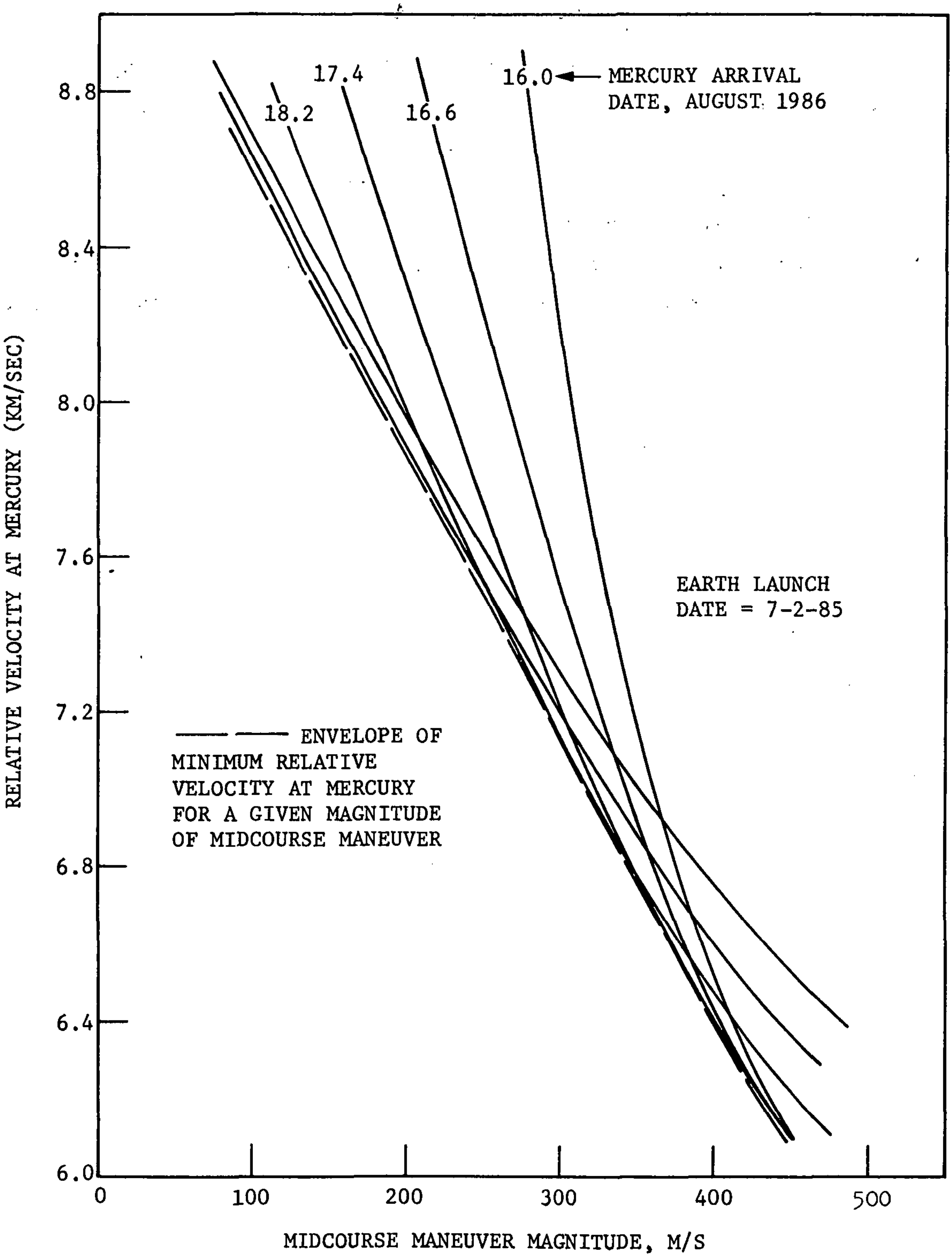


Figure IV-4 Optimization of Mercury Arrival Date, 1985 Mission Opportunity with Midcourse Maneuvers

C. TRAJECTORY DATA

Tabulated details of three reference trajectories for the 1985 opportunity with midcourse velocity maneuvers appear in Tables IV-1 through IV-3. The Earth launch dates (6-17, 6-24, 7-1) are centered approximately on the best performance 15-day launch period. Each reference trajectory includes an optimized 400 m/s maneuver prior to Venus swingby. The Mercury encounter date for each launch date is chosen to minimize Mercury approach velocity. The various parameters are described in the print key in Section 1 of the Appendix.

```
JD=2446233.500    C3=  45.636   FLT TIM= 119.841    JUN 17 1985   0, 0, 0.
ECLIPTIC            X                  Y                  Z                  TOTAL
R EARTH     -1.3593657E+07   -1.5137744E+08    1.2295465E+04     1.5198657E+08
V EARTH      2.9182097E+01   -2.7660929E+00   -1.0818657E-05     2.9312899E+01
VEL S/C      2.2551207E+01   -2.3731924E+00   -1.2301575E+00     2.2709079E+01
VHE         -6.6308907E+00    3.9290050E-01   -1.2301467E+00     6.7554676E+00
RAA=176.609 DECA=-10.492        SEVHE= 88.290
EQUATORIAL          X                  Y                  Z                  TOTAL
R EARTH     -1.3593657E+07   -1.3888982E+08   -6.0252352E+07     1.5198657E+08
V EARTH      2.9182097E+01   -2.5378152E+00   -9.9980243E-01     2.9312899E+01
VEL S/C      2.2551207E+01   -1.6879931E+00   -1.9949758E+00     2.2709079E+01
VHE         -6.6308907E+00    8.4982211E-01   -9.9517338E-01     6.7554676E+00
RAA=172.697 DECA= -8.467 RP= 63663249.74 APO=152012101.51
A=107837675.62 E= .40964 I=  3.106 NODE=264.954 W=178.654
TH1= 178.7   TH2= 331.2   DTH= 152.5   TYPE   II

JD=2446353.34     DEL V=   .400   OCT 14 1985 20 1022.358
ECLIPTIC            X                  Y                  Z                  TOTAL
RADIUS      -2.4971534E+07    6.0675740E+07    1.6392018E+06     6.5633909E+07
V S/C B     -5.1196601E+01   -1.3599992E+01    2.7021368E+00     5.3041053E+01
V S/C A     -5.0842009E+01   -1.3418239E+01    2.6649268E+00     5.2650364E+01
DEL VEL      3.5459174E-01    1.8175375E-01   -3.7209971E-02     4.0019284E-01
A=104336878.9 E=    .390982 I=    3.09 NODE= 444.78 W=  27.63
RP= 63543012.3 APO=145130745.6 TH1=  27.54 TH2= 117.64 DTH=  90.10 TYPE=  I

JD=2446389.660 VHA= 13.625 VHD= 13.625  NOV 20 1985  3, 50, 24.000
ECLIPTIC            X                  Y                  Z                  TOTAL
R VENUS     -9.9613563E+07   -4.1337941E+07    5.1474391E+06     1.0797307E+08
V VENUS      1.3181614E+01   -3.2504796E+01   -1.2210024E+00     3.5097116E+01
V S/C A     -2.6275023E-01   -3.4441215E+01   -1.5500413E-01     3.4442566E+01
VHA         -1.3444364E+01   -1.9364187E+00    1.0659982E+00     1.3624867E+01
V S/C D     -1.9117728E-01   -3.0080342E+01   -2.1843544E+00     3.0160155E+01
VHD         -1.3372791E+01    2.4244535E+00   -9.6335207E-01     1.3624887E+01
PCA=  8163.1   BTH=204.6     B*T=     -8874    B*R=     -4057    HCA=  2113.1
RAA= 188.2 DECA=    4.5 SPA= 165.6 EPA= 145.6 CPA=  92.9   TYPE IV    I
RAE=  42.5 DECE=  -1.2 RAS=  22.5 DECS=  -2.7
AH=      1750.0 EH=  5.66468 I= 155.0 NODE= 358.5 W= 159.1 TAU=  79.8
A= 85697435.2 E=    .453021 I=    6.3 NODE= 408.3 W=   9.5 TURN=  20.3
THI= 144.6 THF= 344.9 DTH= 200.3 FLT TIM= 268.840
PERIHFLION= 46874725.2  APHELION=124520145.3
```

TABLE IV-1 TRAJECTORY PRINTOUT 6-17-85 LAUNCH

```
JD=2446658.500    VHP=  6.256   AUG 16 1986  0, 0, 0.
ECLIPTIC            X                 Y                  Z                 TOTAL
R MERCURY  3.4808005E+07    3.2150176E+07    -5.0371924E+05    4.7386547E+07
V MERCURY -4.2640845E+01    3.7975315E+01     7.0121840E+00    5.7528575E+01
V S/C     -4.6572368E+01    4.2840645E+01     6.9534234E+00    6.3660477E+01
VHP       -3.9315223E+00    4.8653295E+00    -5.8760583E-02    6.2555376E+00
RAA= 128.9   DECA=   -.5   SPA=  93.8   EPA= 175.0   CPA=  76.6
RAE= 303.9   DECE=    .2   RAS=-137.3   DECS=    .6
EQUATORIAL          X                 Y                  Z                 TOTAL
R MERCURY  2.0545981E+07    4.2700673E+07    -3.7252903E-09    4.7386547E+07
V MERCURY -5.4032572E+01    1.9748877E+01     2.8421709E-14    5.7528575E+01
V S/C     -5.9430035E+01    2.2805000E+01    -8.1194461E-01    6.3660477E+01
VHP       -5.3974630E+00    3.0561233E+00    -8.1194461E-01    6.2555376E+00
RAA= 150.5  DECA=  -7.5  RAS=-115.7  DECS=    .0  RAE= 325.4  DECE=   7.0
MERCURY OP          X                 Y                  Z                 TOTAL
R MERCURY  4.7240817E+07   -3.7134906E+06    -3.7252903E-09    4.7386547E+07
V MERCURY -1.1276494E+00    5.7517523E+01     2.8421709E-14    5.7528575E+01
V S/C     -2.3026063E-01    6.3654883E+01    -8.1194461E-01    6.3660477E+01
VHP        8.9738880E-01    6.1373602E+00    -8.1194461E-01    6.2555376E+00
RAA=  81.7  DECA=  -7.5  RAS= 175.5  DECS=    .0  RAE= 256.6  DECE=   7.0
```

TABLE IV-1 TRAJECTORY PRINTOUT 6-17-85 LAUNCH (Continued)

```
JD=2446240.500    C3=  45.950   FLT TIM= 113.826    JUN 24 1985   0, 0, 0.
ECLIPTIC            X                   Y                    Z                   TOTAL
R EARTH      4.1083189E+06    -1.5200176E+08     1.2210674E+04      1.5205727E+08
V EARTH      2.9290610E+01     7.0306687E-01    -2.9113197E-04      2.9299046E+01
VEL S/C      2.2658295E+01     1.4894037E+00    -1.1597431E+00      2.2736791E+01
VHE         -6.6323144E+00     7.8633680E-01    -1.1594520E+00      6.7786612E+00
RAA=173.238 DECA= -9.849          SEVHE= 98.187
EQUATORIAL          X                   Y                    Z                   TOTAL
R EARTH      4.1083189E+06    -1.3946258E+08    -6.0439774E+07      1.5205727E+08
V EARTH      2.9290610E+01     6.4516169E-01     3.8037422E-01      2.9299046E+01
VEL S/C      2.2658295E+01     1.8278295E+00    -3.9345029E-01      2.2736791E+01
VHE         -6.6323144E+00     1.1826678E+00    -7.7382451E-01      6.7786612E+00
RAA=169.889 DECA= -6.552 RP= 63817756.28 APO=152221216.39
A=108019486.34 E= .40920 I=  2.926 NODE=271.638 W=183.107
TH1= 183.2   TH2= 341.3   DTH= 158.1   TYPE   II

JD=2446354.33     DEL V=    .400    OCT 15 1985 19 4943.182
ECLIPTIC            X                   Y                    Z                   TOTAL
RADIUS      -2.6123025E+07     6.0185942E+07     1.2466326E+06      6.5622513E+07
V S/C B     -5.0877728E+01    -1.4856460E+01     2.6209486E+00      5.3067193E+01
V S/C A     -5.0532395E+01    -1.4660404E+01     2.5712007E+00      5.2678852E+01
DEL VEL      3.4533291E-01     1.9605533E-01    -4.9747894E-02      4.0020915E-01
A=104525746.4 E=     .390562 I=    2.89 NODE=   91.38 W=  22.11
RP= 63702013.5 APO=145349479.4 TH1=  26.39 TH2= 117.41 DTH=  91.02 TYPE=  I

JD=2446390.900 VHA= 13.621 VHD= 13.621  NOV 21 1985  9, 36,    .001
ECLIPTIC            X                   Y                    Z                   TOTAL
R VENUS     -9.8141371E+07    -4.4794663E+07     5.0135381E+06      1.0799734E+08
V VENUS      1.4298211E+01    -3.2018462E+01    -1.2783753E+00      3.5089243E+01
V S/C A      9.5753943E-01    -3.4454596E+01    -6.4035679E-03      3.4467899E+01
VHA         -1.3340672E+01    -2.4361337E+00     1.2719717E+00      1.3620800E+01
V S/C D      8.7827018E-01    -2.9990452E+01    -2.4265040E+00      3.0101270E+01
VHD         -1.3419941E+01     2.0280101E+00    -1.1481287E+00      1.3620787E+01
RCA=  7641.5    BTH=208.0     B*T=      -8148     B*R=      -4331     HCA=  1591.5
RAA= 190.3 DECA=    5.4 SPA= 165.6 EPA= 146.1 CPA=  94.2    TYPE IV     I
RAE=  44.0 DECE=  -1.2 RAS=  24.5 DECS=  -2.7
AH=       1751.0 EH=  5.36404 I= 151.5 NODE=     .4 W= 158.0 TAU=  79.3
A= 85531966.7 E=     .453377 I=    6.7 NODE= 407.9 W=  11.6 TURN=  21.5
THI= 144.9 THF= 343.2 DTH= 198.3 FLT TIM= 267.600
PERIHELION= 46753705.8  APHELION=124310227.6
```

TABLE IV-2 TRAJECTORY PRINTOUT 6-24-85 LAUNCH

```
JD=2446658.500     VHP=  6.132   AUG 16 1986  0, 0, 0.
ECLIPTIC          X                 Y                 Z                 TOTAL
R MERCURY  3.4808005E+07    3.2150176E+07   -5.0371924E+05    4.7386547E+07
V MERCURY -4.2640845E+01    3.7975315E+01    7.0121840E+00    5.7528575E+01
V S/C     -4.6912472E+01    4.2358119E+01    7.3939285E+00    6.3636942E+01
VHP       -4.2716265E+00    4.3828037E+00    3.8174444E-01    6.1320054E+00
RAA= 134.3   DECA=   3.6   SPA=  88.4   EPA= 169.0   CPA=  81.3
RAE= 303.9   DECE=    .2   RAS=-137.3   DECS=    .6
EQUATORIAL        X                 Y                 Z                 TOTAL
R MERCURY -4.5408273E+07   -1.3548933E+07   -3.7252903E-09    4.7386547E+07
V MERCURY  2.1766265E+01   -5.3251917E+01    2.8421709E-14    5.7528575E+01
V S/C      2.3676960E+01   -5.9067150E+01   -3.6579314E-01    6.3636942E+01
VHP        1.9106952E+00   -5.8152325E+00   -3.6579314E-01    6.1320054E+00
RAA= 288.2  DECA=  -3.4  RAS=  16.6  DECS=    .0  RAE=  97.7  DECE=   7.0
MERCURY OP        X                 Y                 Z                 TOTAL
R MERCURY  4.7240817E+07   -3.7134906E+06   -3.7252903E-09    4.7386547E+07
V MERCURY -1.1276494E+00    5.7517523E+01    2.8421709E-14    5.7528575E+01
V S/C     -8.1584478E-01    6.3630661E+01   -3.6579314E-01    6.3636942E+01
VHP        3.1180464E-01    6.1131386E+00   -3.6579314E-01    6.1320054E+00
RAA=  87.1  DECA=  -3.4  RAS= 175.5  DECS=    .0  RAE= 256.6  DECE=   7.0
```

TABLE IV-2 TRAJECTORY PRINTOUT 6-24-85 LAUNCH (Continued)

```
JD=2446247.500    C3=  50.919  FLT TIM= 106.287   JUL  1 1985  0, 0, 0.
ECLIPTIC             X                   Y                   Z                   TOTAL
R EARTH     2.1753678E+07   -1.5052973E+08   1.1957288E+04    1.5209347E+08
V EARTH     2.8995213E+01    4.1588820E+00  -5.6743708E-04    2.9291955E+01
VEL S/C     2.2179651E+01    5.9409546E+00  -1.1367497E+00    2.2989651E+01
VHE        -6.8155617E+00    1.7820726E+00  -1.1361823E+00    7.1357252E+00
RAA=165.347 DECA= -9.162        SEVHE=112.569
EQUATORIAL           X                   Y                   Z                   TOTAL
R EARTH     2.1753678E+07   -1.3811194E+08  -5.9793573E+07    1.5209347E+08
V EARTH     2.8995213E+01    3.8158937E+00   1.7538531E+00    2.9291955E+01
VEL S/C     2.2179651E+01    5.9028671E+00   1.3968295E+00    2.2989651E+01
VHE        -6.8155617E+00    2.0869734E+00  -3.5702363E-01    7.1357252E+00
RAA=162.975 DECA= -2.867 RP= 64481392.87 APO=153684523.12
A=109082957.99 E= .40888 I=  2.854 NODE=278.313 W=189.887
TH1= 190.0    TH2= 354.8    DTH= 164.9    TYPE    II


JD=2446353.79     DEL V=    .400    OCT 15 1985  6 5344.450
ECLIPTIC             X                   Y                   Z                   TOTAL
RADIUS     -2.6259544E+07    6.0871271E+07   8.5645466E+05    6.6299388E+07
V S/C B    -5.0646181E+01   -1.4662749E+01   2.6036192E+00    5.2790252E+01
V S/C A    -5.0298860E+01   -1.4473657E+01   2.5431416E+00    5.2401619E+01
DEL VEL     3.4732084E-01    1.8909166E-01  -6.0477688E-02    4.0005622E-01
A=105536699.1 E=    .390094 I=   2.81 NODE=  98.07 W=  15.28
RP= 64367453.9 APO=146705944.2 TH1=  26.34 TH2= 116.06 DTH=  89.72 TYPE=  I

JD=2446390.000 VHA= 13.668 VHD= 13.668  NOV 20 1985 12,  0,  0.
ECLIPTIC             X                   Y                   Z                   TOTAL
R VENUS    -9.9221816E+07   -4.2290905E+07   5.1113372E+06    1.0797970E+08
V VENUS     1.3489497E+01   -3.2375302E+01  -1.2368875E+00    3.5094966E+01
V S/C A     9.2555136E-02   -3.4648761E+01   2.3412153E-01    3.4649675E+01
VHA        -1.3396941E+01   -2.2734585E+00   1.4710090E+00    1.3667864E+01
V S/C D     6.2000327E-02   -3.0056465E+01  -2.3025575E+00    3.0144596E+01
VHD        -1.3427496E+01    2.3188377E+00  -1.0656700E+00    1.3667857E+01
RCA=  7321.7    BTH=208.3     B*T=     -7828     B*R=     -4218     HCA=  1271.7
RAA= 189.6 DECA=    6.2 SPA= 166.1 EPA= 146.4 CPA=   94.9    TYPE IV     I
RAE=  42.9 DECE=  -1.2 RAS=  23.1 DECS=  -2.7
AH=      1739.0 EH=  5.21036 I= 151.1 NODE= 358.3 W= 156.1 TAU=  78.9
A= 85653887.6 E=     .453980 I=    6.5 NODE= 407.7 W=  10.6 TURN=  22.1
THI= 144.6 THF= 348.9 DTH= 204.3 FLT TIM= 269.250
PERIHELION= 46768744.4  APHELION=124539030.8
```

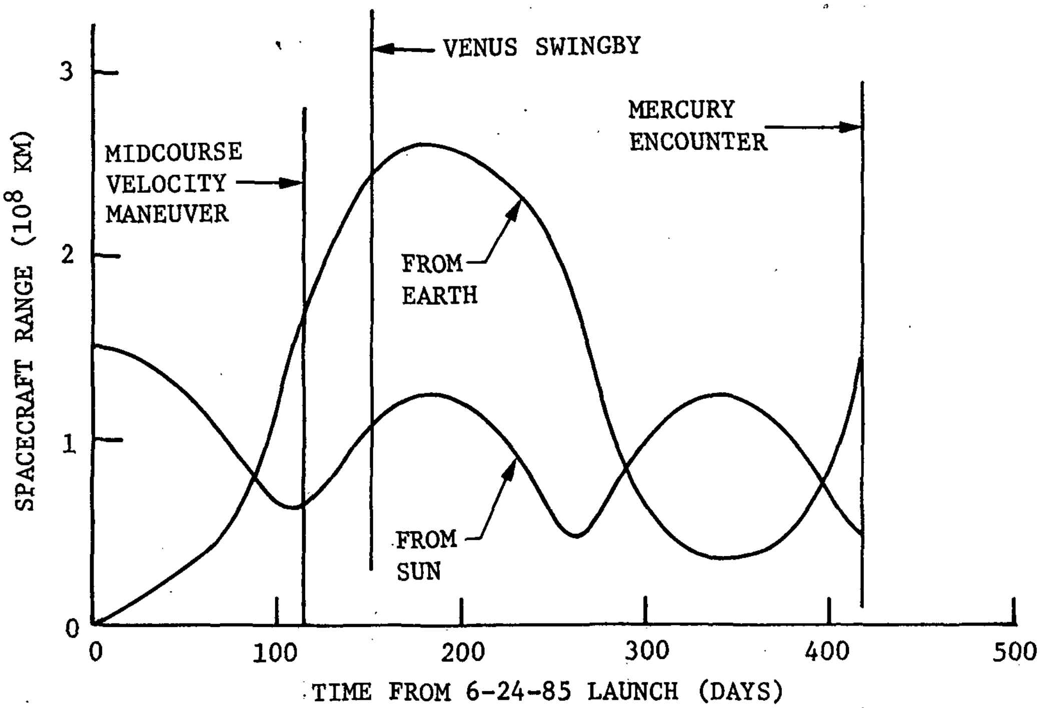
TABLE IV-3 TRAJECTORY PRINTOUT 7-1-85 LAUNCH

```
JD=2446659.250     VHP=  6.309   AUG 16 1986 18, 0, 0.
ECLIPTIC           X                    Y                    Z                    TOTAL
R MERCURY  3.1955525E+07     3.4524019E+07     -4.8402349E+04     4.7043234E+07
V MERCURY -4.5369793E+01     3.5249243E+01      7.0346876E+00     5.7882761E+01
V S/C     -4.9180798E+01     4.0273481E+01      7.2140105E+00     6.3974574E+01
VHP       -3.8110044E+00     5.0242388E+00      1.7932293E-01     6.3086359E+00
RAA= 127.2   DECA=   1.6    SPA= 100.0    EPA= 177.2    CPA=   78.6
RAE= 305.0   DECE=    .0    RAS=-132.8    DECS=     .1
EQUATORIAL         X                    Y                    Z                    TOTAL
R MERCURY -4.5098681E+07    -1.3385621E+07     -4.4237822E-09     4.7043234E+07
V MERCURY  2.1161822E+01    -5.3875703E+01      2.8421709E-14     5.7882761E+01
V S/C      2.1868940E+01    -6.0117898E+01     -5.7781058E-01     6.3974574E+01
VHP        7.0711763E-01    -6.2421956E+00     -5.7781058E-01     6.3086359E+00
RAA= 276.5  DECA=  -5.3  RAS=  16.5  DECS=      .0  RAE=  94.2  DECE=   6.8
MERCURY OP         X                    Y                    Z                    TOTAL
R MERCURY  4.7043229E+07     2.0171966E+04     -4.4237822E-09     4.7043234E+07
V MERCURY -4.9820946E+00     5.7667953E+01      2.8421709E-14     5.7882761E+01
V S/C     -3.8864893E+00     6.3853797E+01     -5.7781058E-01     6.3974574E+01
VHP        1.0956053E+00     6.1858444E+00     -5.7781058E-01     6.3086359E+00
RAA=  80.0  DECA=  -5.3  RAS=-180.0  DECS=      .0  RAE= 257.7  DECE=   6.8
```

TABLE IV-3 TRAJECTORY PRINTOUT 7-1-85 (Continued)

D. FLIGHT CHARACTERISTICS

Time histories of four geometry parameters for this opportunity are presented in Figure IV-5. All appear similar to baseline 1985 parameters; however, one important difference involves the 10-day delay in Venus encounter. This fact alleviates the zero declination geometry problem of the pre-Venus tracking period. Range from Earth is still high (200 Mkm) in this arc. The Sun-Earth-spacecraft angle does not present any problem for the desired tracking periods.



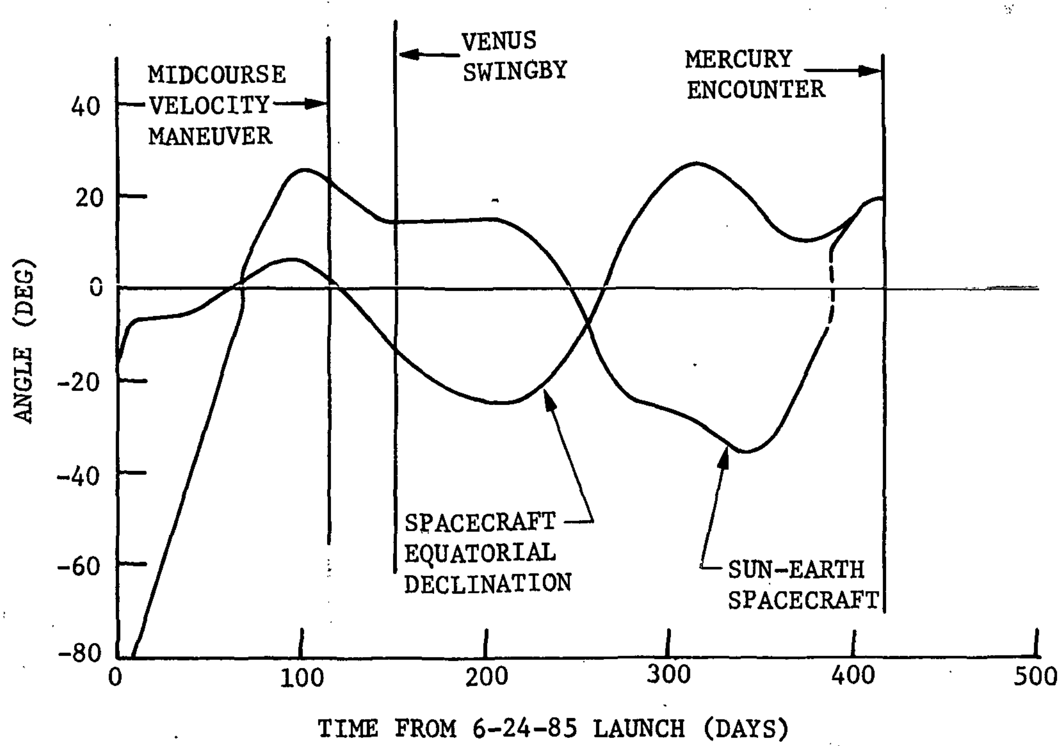


Figure IV-5 Typical Time Histories, 1985 Opportunity with Midcourse Velocity Maneuver

E. NAVIGATION REQUIREMENTS

Navigation analysis for a typical 1985 trajectory with a 400 m/s planned midcourse maneuver result in ΔV correction requirements of 134.7 m/s (adding mean-plus-three-sigma) as shown in the table below. A less conservative estimate is 113.3 m/s for this total and is described in Section VI. In either case, 400 m/s must be added for a total fuel budget of 534.7 m/s in the conservative case and 513.3 m/s in the other. The maneuver schedule on this table shows an extra correction ΔV at V-26 which is necessary to remove execution errors from the planned midcourse. As discussed in Section VI, the large post-Venus maneuver is half of that for the baseline 1985 case; this is due to the absence of the zero geocentric equatorial declination problem. Analytically, this largest maneuver is defined as 98 m/s for a cumulative probability level of .99 and as 125 m/s for .999.

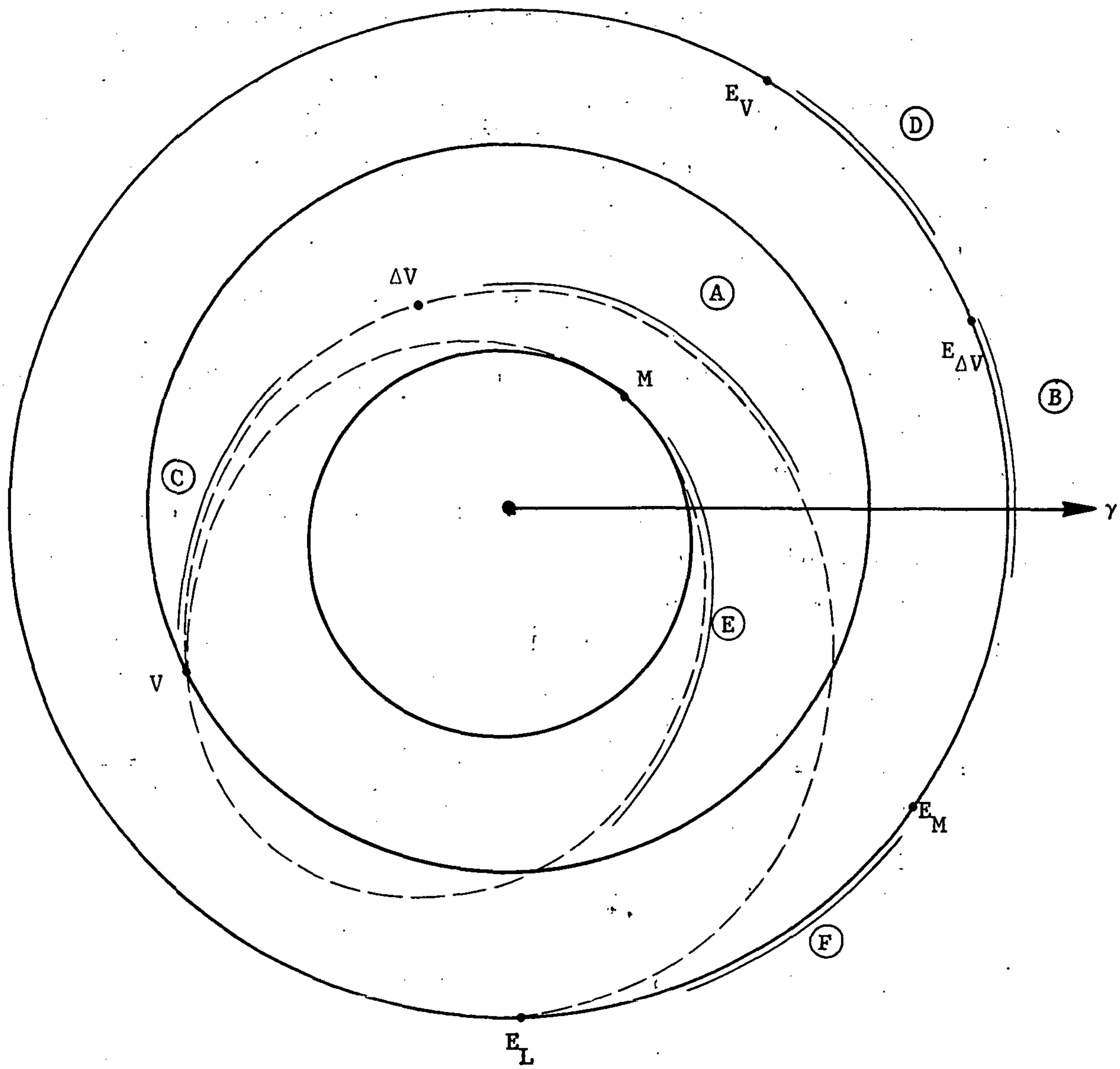
TABLE IV-4

1985 MANEUVER SCHEDULE AND STATISTICAL DESCRIPTION

MANEUVER TIME (days)	MEAN ΔV (m/s)	SIGMA ΔV (m/s)	MEAN PLUS THREE SIGMA (m/s)
E+10	6.67	4.45	20.01
V-26	4.34	2.19	10.92
V-3	0.36	0.22	1.03
V+2	33.80	21.72	98.97
M-100	0.55	0.31	1.48
M-3	0.70	0.53	2.28
		TOTAL	134.69 *

* 534.69 m/s when added with planned midcourse velocity maneuver at V-36.1 days.

Critical tracking periods prior to planned midcourse, Venus swingby and Mercury encounter are pictured in Figure IV-6. Dispersions at Venus closest approach are not a problem due to a nominal swingby altitude of 1600 km. Those at Mercury are shown in Figure VI-3 and are dominated by a 60 km spherical Mercury ephemeris error.



(A) SPACECRAFT DURING PRE-MIDCOURSE MANEUVER TRACKING PERIOD
(B) EARTH DURING PRE-MIDCOURSE MANEUVER TRACKING PERIOD
(C) SPACECRAFT DURING PRE-VENUS TRACKING PERIOD
(D) EARTH DURING PRE-VENUS TRACKING PERIOD
(E) SPACECRAFT DURING PRE-MERCURY TRACKING PERIOD
(F) EARTH DURING PRE-MERCURY TRACKING PERIOD

Figure IV-6 Critical Tracking Geometries, 1985 Opportunity with Midcourse Velocity Maneuver

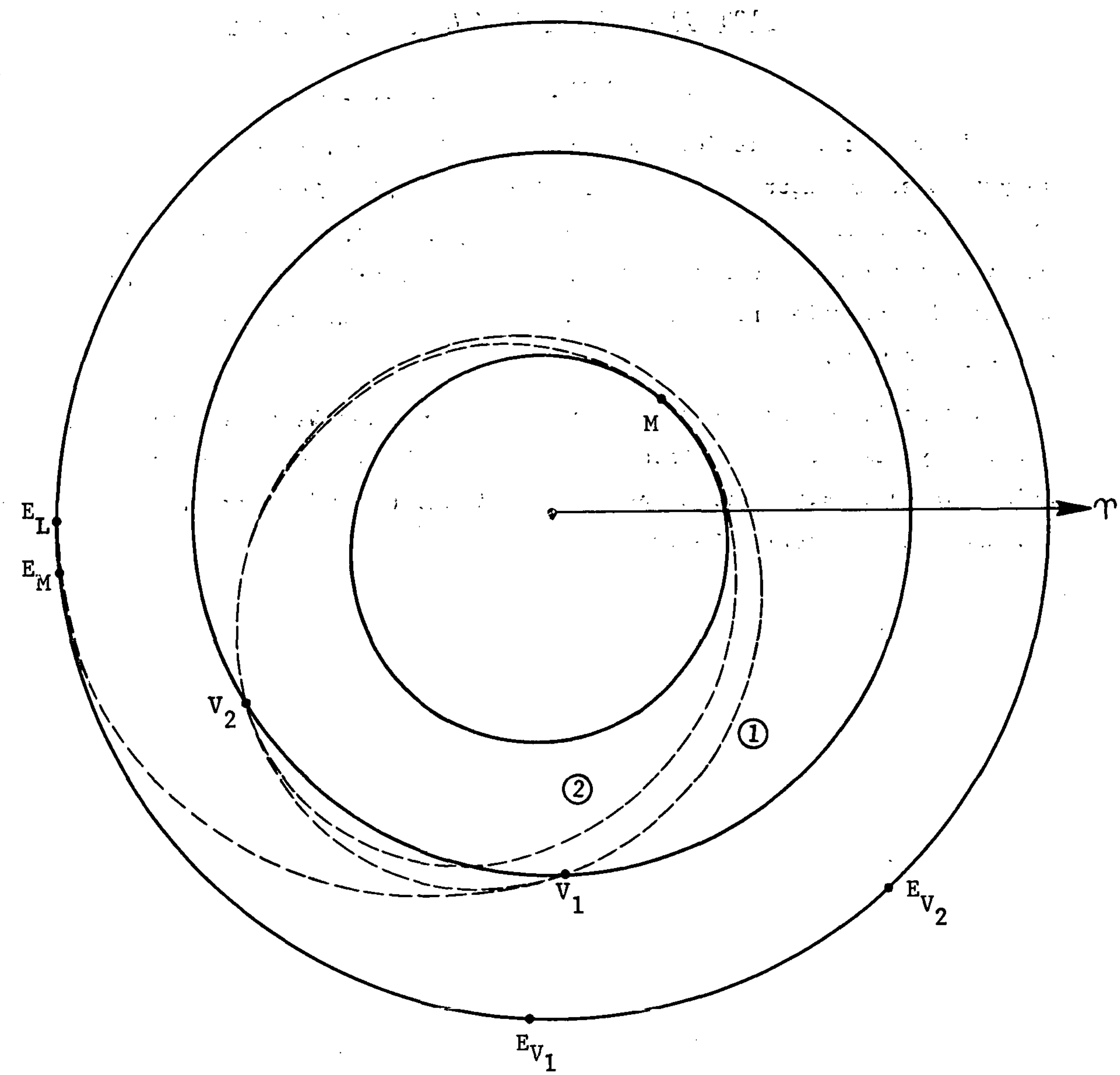
V. 1988 MULTIPLE VENUS SWINGBY OPPORTUNITY

V. 1988 MULTIPLE VENUS SWINGBY OPPORTUNITY

A. HELIOCENTRIC GEOMETRY

The flight profile for the 24-month 1988 multiple Venus swingby opportunity is presented in Figure V-1 . The Type I transfer from Earth to first Venus swingby is followed by two complete phasing revolutions of the spacecraft and one complete phasing orbit of Venus before second Venus swingby. Additionally, the mission profile includes an extra spacecraft phasing revolution prior to Mercury encounter.

The positions of Earth at launch and at the two Venus swingbys are substantially displaced from those of the 1983 multiple Venus opportunity. The effect of these Earth positions upon Earth-based tracking and navigation are discussed in Subsection V-E.



E_L: EARTH AT LAUNCH, 3-22-88

E_{V_1}: EARTH AT FIRST VENUS SWINGBY (V_1), 6-18-88

E_{V_2}: EARTH AT SECOND VENUS SWINGBY (V_2), 8-4-89

E_M: EARTH AT MERCURY ENCOUNTER (M), 3-27-90

① TWO COMPLETE SOLAR REVOLUTIONS BETWEEN FIRST AND SECOND VENUS SWINGBYS

② ONE COMPLETE SOLAR REVOLUTION BEFORE MERCURY ENCOUNTER

Figure V-1 Heliocentric Geometry, 1988 Multiple Venus Swingby Opportunity

B. PERFORMANCE PARAMETERS

Conditions at Earth launch and Mercury arrival of the non-integral multiple-swingby case are shown to be better than any single swingby missions. High utilization of the first Venus swingby requires a velocity maneuver at Venus to constrain the spacecraft altitude. As a result, performance parameters are presented for several values of this maneuver near Venus. Performance parameters are shown for minimum relative velocity at Mercury with an altitude limit at the first Venus swingby of 250 km in Figure V-2. Launch periods begin earlier for each successive increase in the magnitude of the maneuver at Venus. The earliest launch that each maneuver allows is constrained by the 250 km swingby altitude limit. Increasing the size of this maneuver decreases the relative velocity at Mercury for the launch window while it increases the required launch energy. The 200 m/s value for this maneuver was chosen as a reference trajectory case and all further data is presented for this opportunity assuming that value.

The same performance information is presented in Figure V-3 for a constant maneuver value and variations in Venus swingby altitude. Navigation analyses (sec. V-E and VI) show that swingby altitude constraint is not as critical as for the baseline single swingby missions. This figure shows that an increase in swingby altitude raises approach velocity at Mercury but lowers launch energy. Further explanation of the trajectory characteristics of this mission can be found in Section 2 of the Appendix. This includes the investigation of performing a midcourse velocity maneuver on either Earth-$Venus_1$ or $Venus_1$-$Venus_2$ trajectory segments which would alleviate maneuvers at the first swingby.

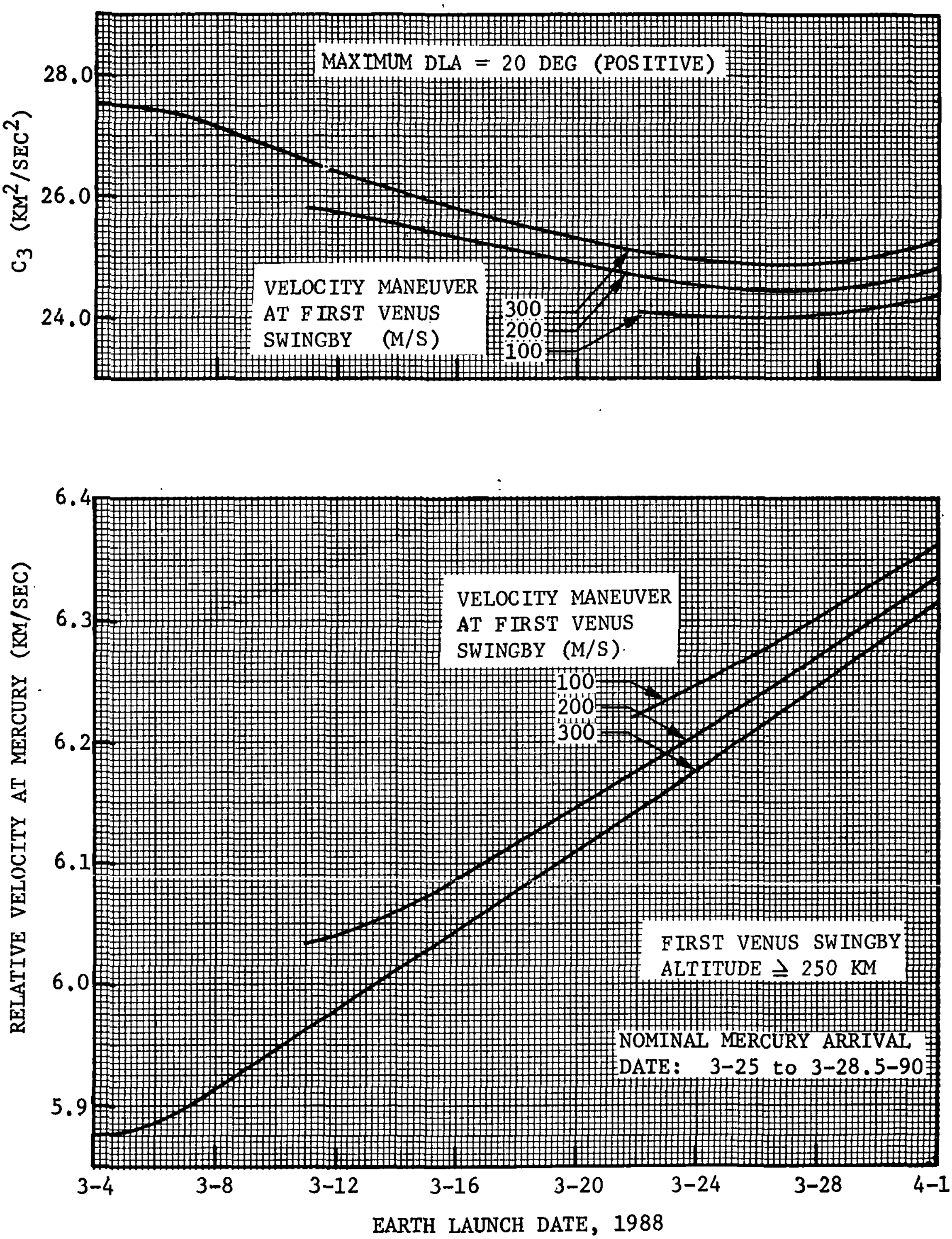


Figure V-2 Minimum Relative Velocity at Mercury and Corresponding C_3 vs Launch Date, 1988 Multiple Venus Swingby Opportunity (with Venus Altitude Constraint = 250 km)

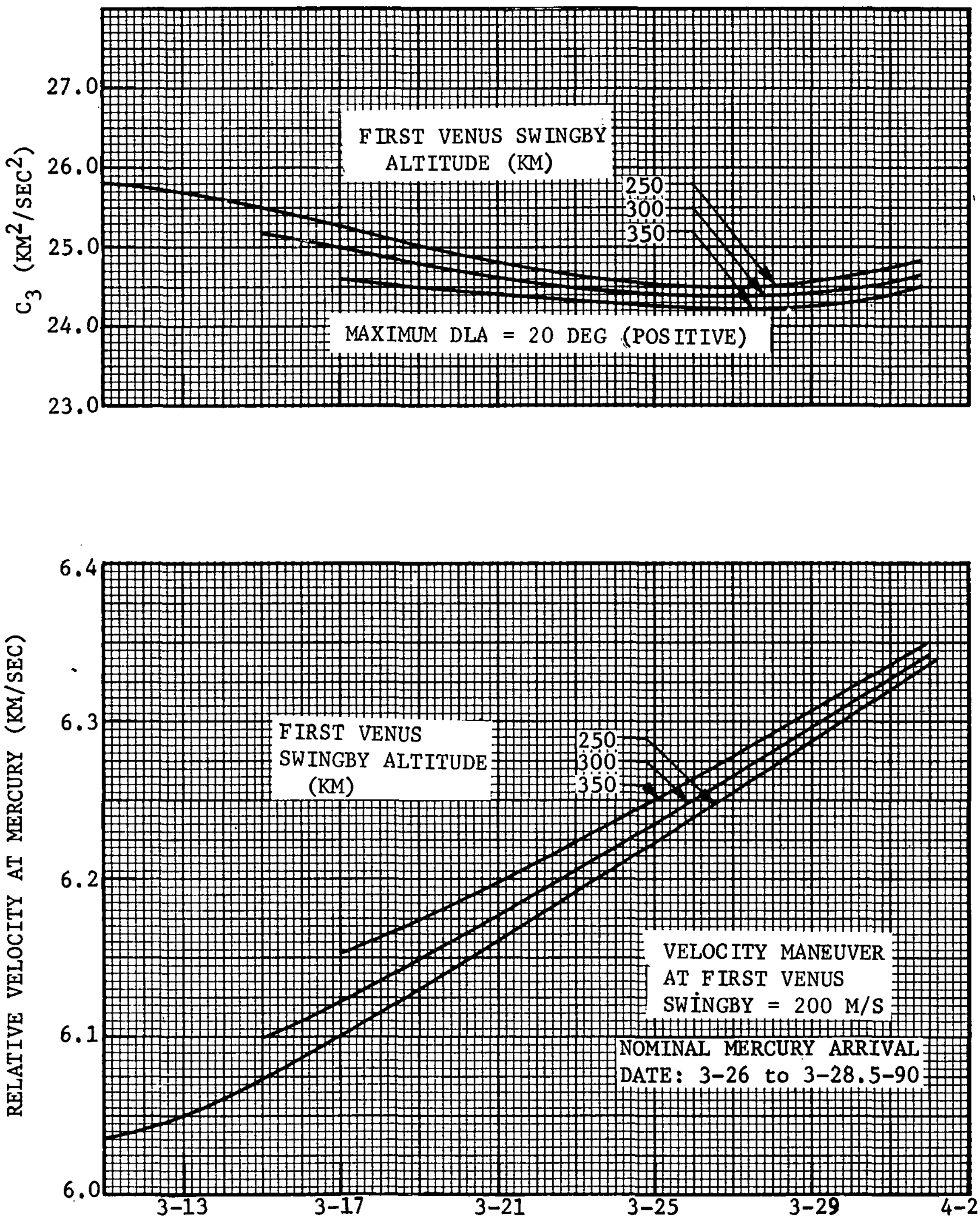


Figure V-3 Minimum Relative Velocity at Mercury and Corresponding C_3 vs Launch Date, 1988 Multiple Venus Swingby Opportunity (with 200 m/s Maneuver at Venus)

C. TRAJECTORY DATA

Tables V-1 through V-3 contain tabulated details for three representative trajectories for the 1988 multiple Venus swingby opportunity. The Earth launch dates (3-12, 3-19, 3-26) are approximately centered on the best performance 15-day launch period. Each representative trajectory includes a 200 m/s maneuver at first Venus swingby to attain a 250 km swingby altitude. Mercury arrival dates are selected to minimize Mercury approach velocity for each launch date. The print key which defines each listed parameter appears in Section 1 of the Appendix.

```
JD=2447232.500    C3=  25.816  FLT TIM=  96.762    MAR 12 1988   0, 0, 0.
ECLIPTIC          X                 Y                  Z                 TOTAL
R EARTH    -1.4669748E+08    2.4086717E+07    -8.2281830E+02    1.4866176E+08
V EARTH    -5.3139263E+00   -2.9496878E+01     2.6036047E-03    2.9971714E+01
VEL S/C    -6.2620115E+00   -2.4514406E+01    -3.0048127E-01    2.5303343E+01
VHE        -9.4808522E-01    4.9824724E+00    -3.0308487E-01    5.0809209E+00
RAA=100.774 DECA= -3.420          SEVHE= 69.939
EQUATORIAL        X                 Y                  Z                 TOTAL
R EARTH    -1.4669748E+08    2.2099354E+07     9.0361802E+06    1.4866176E+08
V EARTH    -5.3139263E+00   -2.7063765E+01    -1.1750727E+01    2.9971714E+01
VEL S/C    -6.2620115E+00   -2.2371895E+01    -1.0050368E+01    2.5303343E+01
VHE        -9.4808522E-01    4.6918709E+00     1.7003595E+00    5.0809209E+00
RAA=101.424 DECA= 19.556 RP= 81711611.92 APO=150066267.99
A=115888939.96 E= .29491 I=    .683 NODE=350.649 W= 12.228
TH1= 167.8    TH2= 264.8    DTH=   97.0    TYPE      I


JD=2447329.262 VHA= 10.770 VHD= 10.775   JUN 16 1988 18, 16, 49.707
ECLIPTIC          X                 Y                  Z                 TOTAL
R VENUS    -4.4921776E+06   -1.0864062E+08    -1.2865927E+06    1.0874107E+08
V VENUS     3.4754409E+01   -1.5758149E+00    -2.0232713E+00    3.4848899E+01
V S/C A     3.4860937E+01    8.9669209E+00     1.7299748E-01    3.5996118E+01
VHA         1.0652733E-01    1.0542736E+01     2.1962688E+00    1.0769597E+01
V S/C D     2.8503216E+01    7.1864941E+00    -1.5386781E+00    2.9435464E+01
VHD        -6.2511931E+00    8.7623089E+00     4.8459314E-01    1.0774521E+01
RCA=  6300.0    BTH=348.4      B*T=       8483      B*R=     -1739      HCA=   250.0
RAA=  89.4 DECA=  11.8  SPA=   11.2 EPA= 162.3 CPA=   88.1    TYPE VI     I
RAE= 257.8 DECE=   1.7 RAS=   87.6 DECS=      .7
AH=       2800.9 EH=   3.24928  I=   16.5 NODE= 314.3 W= 116.0 TAU=   72.1
A= 84291681.4 E=     .397040  I=    3.4 NODE= 436.1 W= 342.5 TURN=  35.8
THI= 209.1 THF= 509.7 DTH= 300.6 FLT TIM= 412.212
PERIHELION= 50824510.9   APHELION=117758852.0

RCA CONSTRAINED AT    6300.0
DV         -1.6177622E-01   -1.0399555E-01    -5.5655888E-02    2.0021038E-01
ACTUAL RCA USED IS    6300.0

JD=2447741.474 VHA= 10.742 VHD= 10.743   AUG  2 1989 23, 22, 22.630
ECLIPTIC          X                 Y                  Z                 TOTAL
R VENUS    -9.5000665E+07   -5.1244536E+07     4.7402075E+06    1.0804443E+08
V VENUS     1.6380186E+01   -3.0983198E+01    -1.3837894E+00    3.5073978E+01
V S/C A     5.8208063E+00   -2.9116002E+01    -7.4921449E-01    2.9701594E+01
VHA        -1.0559380E+01    1.8671960E+00     6.3457489E-01    1.0741956E+01
V S/C D     6.4134852E+00   -2.7611086E+01    -3.5516512E+00    2.8567798E+01
VHD        -9.9667012E+00    3.3721119E+00    -2.1678619E+00    1.0742714E+01
RCA= 15878.2    BTH=240.3      B*T=      -9157      B*R=    -16052      HCA=  9828.2
RAA= 170.0 DECA=    3.4  SPA=  141.7 EPA= 170.9 CPA=   87.5    TYPE IV     I
RAE= 341.1 DECE=   -1.3 RAS=   28.3 DECS=   -2.5
AH=       2815.3 EH=   6.63990  I= 119.6 NODE= 348.0 W= 167.4 TAU=   81.3
A= 80897138.4 E=     .412997  I=    8.4 NODE= 405.5 W=    6.0 TURN=  17.3
THI= 156.6 THF= 343.7 DTH= 187.2 FLT TIM= 235.321
PERIHELION= 47486846.1   APHELION=114307430.7
```

TABLE V-1 TRAJECTORY PRINTOUT 3-12-88 LAUNCH

```
JD=2447976.795     VHP=   6.036    MAR 26 1990   7, 4,27.902
ECLIPTIC             X                  Y                  Z                   TOTAL
R MERCURY  3.9135276E+07     2.7848296E+07     -1.2518742E+06      4.8048565E+07
V MERCURY -3.7778341E+01     4.1923661E+01      6.8967793E+00      5.6853865E+01
V S/C     -3.9627469E+01     4.7225172E+01      9.1124076E+00      6.2318449E+01
VHP       -1.8491281E+00     5.3015104E+00      2.2156283E+00      6.0360828E+00
RAA= 109.2   DECA=  21.5    SPA= 104.5   EPA=  82.9   CPA=  97.4
RAE= 191.8   DECE=    .4    RAS=-144.6   DECS=    1.5
EQUATORIAL           X                  Y                  Z                   TOTAL
R MERCURY  4.5074647E+07     1.6641537E+07      7.4505806E-09      4.8048565E+07
V MERCURY -2.5795865E+01     5.0664932E+01      2.8421709E-14      5.6853865E+01
V S/C     -2.6327542E+01     5.6461473E+01      1.5974131E+00      6.2318449E+01
VHP       -5.3167688E-01     5.7965409E+00      1.5974131E+00      6.0360828E+00
RAA=  95.2  DECA=   15.3  RAS=-159.7  DECS=      -.0   RAE= 176.9   DECE=  -3.7
MERCURY OP           X                  Y                  Z                   TOTAL
R MERCURY  4.7035960E+07    -9.8123924E+06      7.4505806E-09      4.8048565E+07
V MERCURY  5.0194954E+00     5.6631852E+01      2.8421709E-14      5.6853865E+01
V S/C      7.6446470E+00     6.1827152E+01      1.5974131E+00      6.2318449E+01
VHP        2.6251517E+00     5.1953003E+00      1.5974131E+00      6.0360828E+00
RAA=  63.2  DECA=   15.3  RAS= 168.2  DECS=      -.0   RAE= 144.8   DECE=  -3.7
```

TABLE V-1 TRAJECTORY PRINTOUT 3-12-88 LAUNCH (Continued)

```
JD=2447239.500    C3=  25.010   FLT TIM=  90.694    MAR 19 1988  0, 0, 0.
ECLIPTIC            X                     Y                     Z                  TOTAL
R EARTH    -1.4882307E+08      6.1139511E+06      7.5437762E+02      1.4894860E+08
V EARTH    -1.7101776E+00     -2.9865375E+01      2.6057689E-03      2.9914300E+01
VEL S/C    -2.5839485E+00     -2.4952796E+01     -3.3375737E-01      2.5088448E+01
VHE        -8.7377095E-01      4.9125789E+00     -3.3636314E-01      5.0010046E+00
RAA=100.085 DECA= -3.857          SEVHE= 77.591
EQUATORIAL          X                     Y                     Z                  TOTAL
R EARTH    -1.4882307E+08      5.6091142E+06      1.8801772E+06      1.4894860E+08
V EARTH    -1.7101776E+00     -2.7401855E+01     -1.1883936E+01      2.9914300E+01
VEL S/C    -2.5839485E+00     -2.2760872E+01     -1.0241637E+01      2.5088448E+01
VHE        -8.7377095E-01      4.6409829E+00      1.6422989E+00      5.0010046E+00
RAA=100.662 DECA= 19.176 RP= 80659238.59 APO=149632393.25
A=115145815.92 E= .29950 I=    .764 NODE=357.669 W=  8.382
TH1= 171.6   TH2= 263.1   DTH=  91.5   TYPE    I


JD=2447330.194 VHA= 10.937 VHO= 10.821  JUN 17 1988 16, 39, 36.202
ECLIPTIC            X                     Y                     Z                  TOTAL
R VENUS    -1.6909486E+06     -1.0873118E+08     -1.4491520E+06      1.0875398E+08
V VENUS     3.4780114E+01     -6.7215350E-01     -2.0118982E+00      3.4844740E+01
V S/C A     3.4454999E+01      1.0943394E+01      1.5245081E-01      3.5889273E+01
VHA        -3.2511553E-01      1.0715547E+01      2.1643490E+00      1.0936775E+01
V S/C D     2.8293895E+01      7.9757190E+00     -1.5154004E+00      2.9435574E+01
VHD        -6.4862193E+00      8.6478725E+00      4.9649776E-01      1.0821425E+01
RCA=  6300.0    BTH=348.5      B*T=       8425     B*R=      -1710     HCA=    250.0
RAA=  91.7 DECA=  11.4 SPA=  11.0 EPA= 160.4 CPA=  87.6   TYPE VI    I
RAE= 257.3 DECE=   1.9 RAS=  89.1 DECS=     .8
AH=      2715.9 EH=  3.31965 I=  16.1 NODE= 316.0 W= 117.0 TAU=  72.5
A= 84307551.4 E=    .398194 I=   3.4 NODE= 436.1 W= 343.8 TURN=  35.1
THI= 209.2 THF= 509.6 DTH= 300.5 FLT TIM= 412.083
PERIHELION= 50736749.6   APHELION=117878353.2

RCA CONSTRAINED AT   6300.0
DV          -5.7983536E-02   -1.8345686E-01   -4.9820602E-02     1.9874759E-01
ACTUAL RCA USED IS   6300.0

JD=2447742.277 VHA= 10.789 VHO= 10.789  AUG  3 1989 18, 39,    .735
ECLIPTIC            X                     Y                     Z                  TOTAL
R VENUS    -9.3839942E+07     -5.3381545E+07      4.6429820E+06      1.0806054E+08
V VENUS     1.7069536E+01     -3.0601268E+01     -1.4180422E+00      3.5068754E+01
V S/C A     6.4208684E+00     -2.8987509E+01     -7.8193352E-01      2.9700415E+01
VHA        -1.0648668E+01      1.6137594E+00      6.3610872E-01      1.0789021E+01
V S/C D     7.0189481E+00     -2.7397992E+01     -3.6824759E+00      2.8521505E+01
VHD        -1.0050588E+01      3.2032761E+00     -2.2644337E+00      1.0789020E+01
RCA= 15125.7    BTH=240.0      B*T=      -8855     B*R=     -15323     HCA=   9075.7
RAA= 171.4 DECA=   3.4 SPA= 141.8 EPA= 170.5 CPA=  87.8   TYPE IV    I
RAE= 342.1 DECE=  -1.3 RAS=  29.6 DECS=  -2.5
AH=      2790.8 EH=  6.41982 I= 120.0 NODE= 349.4 W= 167.1 TAU=  81.0
A= 80785037.1 E=    .414409 I=   8.7 NODE= 406.0 W=   6.7 TURN=  17.9
THI= 156.8 THF= 346.2 DTH= 189.5 FLT TIM= 235.133
PERIHELION= 47307022.0   APHELION=114263052.2
```

TABLE V-2 TRAJECTORY PRINTOUT 3-19-88 LAUNCH

```
JD=2447977.410     VHP=  6.133   MAR 26 1990 21,50,  .106
ECLIPTIC           X                  Y                  Z                 TOTAL
R MERCURY  3.7062623E+07     3.0027168E+07    -8.8351273E+05     4.7707959E+07
V MERCURY -4.0226946E+01     4.0063415E+01     6.9653640E+00     5.7199656E+01
V S/C     -4.2149635E+01     4.5330687E+01     9.4492562E+00     6.2615903E+01
VHP       -1.9226890E+00     5.2672721E+00     2.4838922E+00     6.1327489E+00
RAA= 110.1   DECA=  23.9   SPA= 106.8   EPA=  83.5   CPA=  99.8
RAE= 193.0   DECE=    .3   RAS=-141.0   DECS=   1.1
EQUATORIAL         X                  Y                  Z                 TOTAL
R MERCURY  4.4803977E+07     1.6390639E+07    -3.7252903E-09     4.7707959E+07
V MERCURY -2.5326122E+01     5.1287311E+01     2.8421709E-14     5.7199656E+01
V S/C     -2.5571513E+01     5.7126089E+01     1.8598553E+00     6.2615903E+01
VHP       -2.4539094E-01     5.8387782E+00     1.8598553E+00     6.1327489E+00
RAA=  92.4  DECA=  17.7  RAS=-159.9  DECS=     .0  RAE= 174.3  DECE=  -3.7
MERCURY OP         X                  Y                  Z                 TOTAL
R MERCURY  4.7222523E+07    -6.7884240E+06    -3.7252903E-09     4.7707959E+07
V MERCURY  1.9901776E+00     5.7165023E+01     2.8421709E-14     5.7199656E+01
V S/C      4.5398711E+00     6.2423408E+01     1.8598553E+00     6.2615903E+01
VHP        2.5496935E+00     5.2583848E+00     1.8598553E+00     6.1327489E+00
RAA=  64.1  DECA=  17.7  RAS= 171.8  DECS=     .0  RAE= 146.1  DECE=  -3.7
```

TABLE V-2 TRAJECTORY PRINTOUT 3-19-88 LAUNCH (Continued)

```
JD=2447246.500    C3=   24.509  FLT TIM=  84.877   MAR 26 1988   0, 0, 0.
ECLIPTIC           X                   Y                   Z                  TOTAL
R EARTH    -1.4876527E+08    -1.1948771E+07     2.3221049E+03     1.4924436E+08
V EARTH     1.8975317E+00    -2.9794854E+01     2.5697927E-03     2.9855217E+01
VEL S/C     1.2032273E+00    -2.4908024E+01    -3.7979303E-01     2.4939961E+01
VHE        -6.9430444E-01     4.8868307E+00    -3.8236282E-01     4.9506943E+00
RAA= 98.086 DECA= -4.430        SEVHE= 86.516
EQUATORIAL         X                   Y                   Z                  TOTAL
R EARTH    -1.4876527E+08    -1.0963656E+07    -5.3035132E+06     1.4924436E+08
V EARTH     1.8975317E+00    -2.7337140E+01    -1.1842517E+01     2.9855217E+01
VEL S/C     1.2032273E+00    -2.2701482E+01    -1.0251999E+01     2.4939961E+01
VHE        -6.9430444E-01     4.6356576E+00     1.5905181E+00     4.9506943E+00
RAA= 98.518 DECA= 18.743 RP= 80095242.90 APO=149420312.92
A=114757777.91 E= .30205 I=    .873 NODE=364.651 W=  4.172
THI= 175.8   TH2= 262.2   OTH=  86.4    TYPE     I


JD=2447331.377 VHA= 11.018 VHD= 10.861  JUN 18 1988 21,  2, 19.977
ECLIPTIC           X                   Y                   Z                  TOTAL
R VENUS     1.8625870E+06    -1.0874130E+08    -1.6538788E+06     1.0876983E+08
V VENUS     3.4779211E+01     4.7386468E-01    -1.9955461E+00     3.4839637E+01
V S/C A     3.4015202E+01     1.1257733E+01     1.2895769E-01     3.5829975E+01
VHA        -7.6400977E-01     1.0783869E+01     2.1245038E+00     1.1017670E+01
V S/C D     2.8002117E+01     8.9457954E+00    -1.4848026E+00     2.9433831E+01
VHD        -6.7770949E+00     8.4719307E+00     5.1074346E-01     1.0861100E+01
RCA=  6300.0   BTH=348.8      B*T=        8405     B*R=      -1665     HCA=    250.0
RAA=   94.1 DECA=   11.1  SPA=   10.7 EPA= 158.2 CPA=   87.2    TYPE VI      I
RAE= 256.6 DECE=    2.2 RAS=   91.0 DECS=     .9
AH=       2676.2 EH=  3.35409 I=   15.7 NODE= 318.3 W= 117.3 TAU=   72.7
A= 84321102.4 E=      .399255 I=    3.4 NODE= 436.1 W= 345.6 TURN=   34.7
THI= 209.2 THF= 509.6 OTH= 300.3 FLT TIM= 411.976
PERIHELION= 50655512.1   APHELION=117986692.7

RCA CONSTRAINED AT    6300.0
DV          3.6550518E-03    -1.9449445E-01    -4.0215408E-02     1.9864221E-01
ACTUAL RCA USED IS    6300.0

JD=2447743.353 VHA= 10.829 VHD= 10.829  AUG  4 1989 20, 28, 12.122
ECLIPTIC           X                   Y                   Z                  TOTAL
R VENUS    -9.2210923E+07    -5.6201293E+07     4.5090835E+06     1.0808224E+08
V VENUS     1.7978760E+01    -3.0065743E+01    -1.4627683E+00     3.5061723E+01
V S/C A     7.2443564E+00    -2.8787336E+01    -8.2649582E-01     2.9696372E+01
VHA        -1.0734404E+01     1.2784070E+00     6.3627248E-01     1.0828970E+01
V S/C D     7.8332228E+00    -2.7094240E+01    -3.8088418E+00     2.8459875E+01
VHD        -1.0145538E+01     2.9715028E+00    -2.3460735E+00     1.0828935E+01
RCA= 14472.5   BTH=239.3      B*T=       -8676     B*R=     -14641     HCA=  8422.5
RAA= 173.2 DECA=    3.4  SPA= 141.9 EPA= 169.9 CPA=   88.2    TYPE IV      I
RAE= 343.4 DECE=   -1.3 RAS=   31.4 DECS=   -2.4
AH=       2773.3 EH=  6.22422 I= 120.6 NODE= 351.2 W= 166.8 TAU=   80.8
A= 80636866.8 E=      .416136 I=    8.9 NODE= 406.8 W=    7.4 TURN=   18.5
THI= 157.0 THF= 349.4 OTH= 192.3 FLT TIM= 234.825
PERIHELION= 47080923.6   APHELION=114192810.1
```

TABLE V-3 TRAJECTORY PRINTOUT 3-26-88 LAUNCH

```
JD=2447978.178     VHP=  6.242    MAR 27 1990  16,16,12.489
ECLIPTIC          X                  Y                  Z                  TOTAL
R MERCURY  3.4294522E+07     3.2602376E+07     -4.1922751E+05     4.7320238E+07
V MERCURY -4.3158387E+01     3.7489675E+01      7.0188126E+00     5.7596752E+01
V S/C     -4.5212194E+01     4.2706446E+01      9.7639602E+00     6.2954888E+01
VHP       -2.0538069E+00     5.2167703E+00      2.7451476E+00     6.2424875E+00
RAA= 111.5   DECA=  26.1    SPA= 109.5    EPA=  83.7   CPA= 102.0
RAE= 194.6   DECE=    .1    RAS=-136.4    DECS=    .5
EQUATORIAL        X                  Y                  Z                  TOTAL
R MERCURY  4.4480268E+07     1.6146540E+07     -3.7252903E-09     4.7320238E+07
V MERCURY -2.4743243E+01     5.2011131E+01      2.8421709E-14     5.7596752E+01
V S/C     -2.4661192E+01     5.7885103E+01      2.1114876E+00     6.2954888E+01
VHP        8.2050452E-02     5.8739713E+00      2.1114876E+00     6.2424875E+00
RAA=  89.2  DECA=  19.8  RAS=-160.0  DECS=     .0  RAE= 171.2  DECE=  -3.7
MERCURY OP        X                  Y                  Z                  TOTAL
R MERCURY  4.7226360E+07    -2.9792476E+06     -3.7252903E-09     4.7320238E+07
V MERCURY -1.8905484E+00     5.7565716E+01      2.8421709E-14     5.7596752E+01
V S/C      5.3261901E-01     6.2917214E+01      2.1114876E+00     6.2954888E+01
VHP        2.4231674E+00     5.3514979E+00      2.1114876E+00     6.2424875E+00
RAA=  65.6  DECA=  19.8  RAS= 176.4  DECS=     .0  RAE= 147.6  DECE=  -3.7
```

TABLE V-3 TRAJECTORY PRINTOUT 3-26-88 LAUNCH (Continued)

D. FLIGHT CHARACTERISTICS

Geometry parameter time histories are shown for a typical trajectory of this mission opportunity in Figure V-4. During the tracking phase prior to first Venus swingby, the Earth-spacecraft range is less than 40 Mkm; this is due to an Earth-Venus_1 Type I trajectory segment. Constant range prior to the second swingby ($\sim$200 Mkm) is indicative of the plane-of-the-sky problem which exists in that tracking arc. A low Sun-Earth-spacecraft angle makes it necessary to initiate the pre-Mercury 30-day tracking arc earlier. Geocentric equatorial declination is not zero in any of the tracking areas.

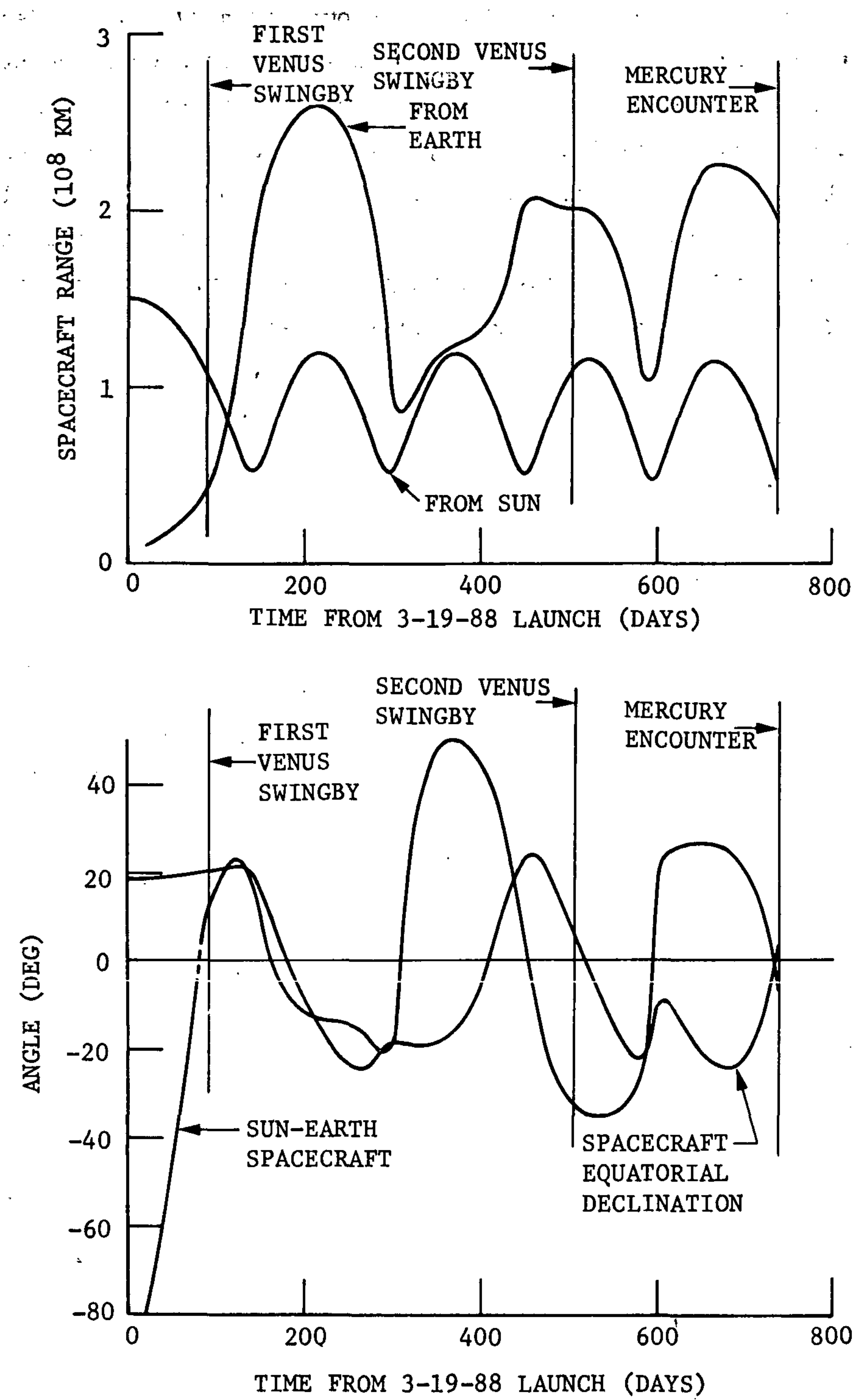
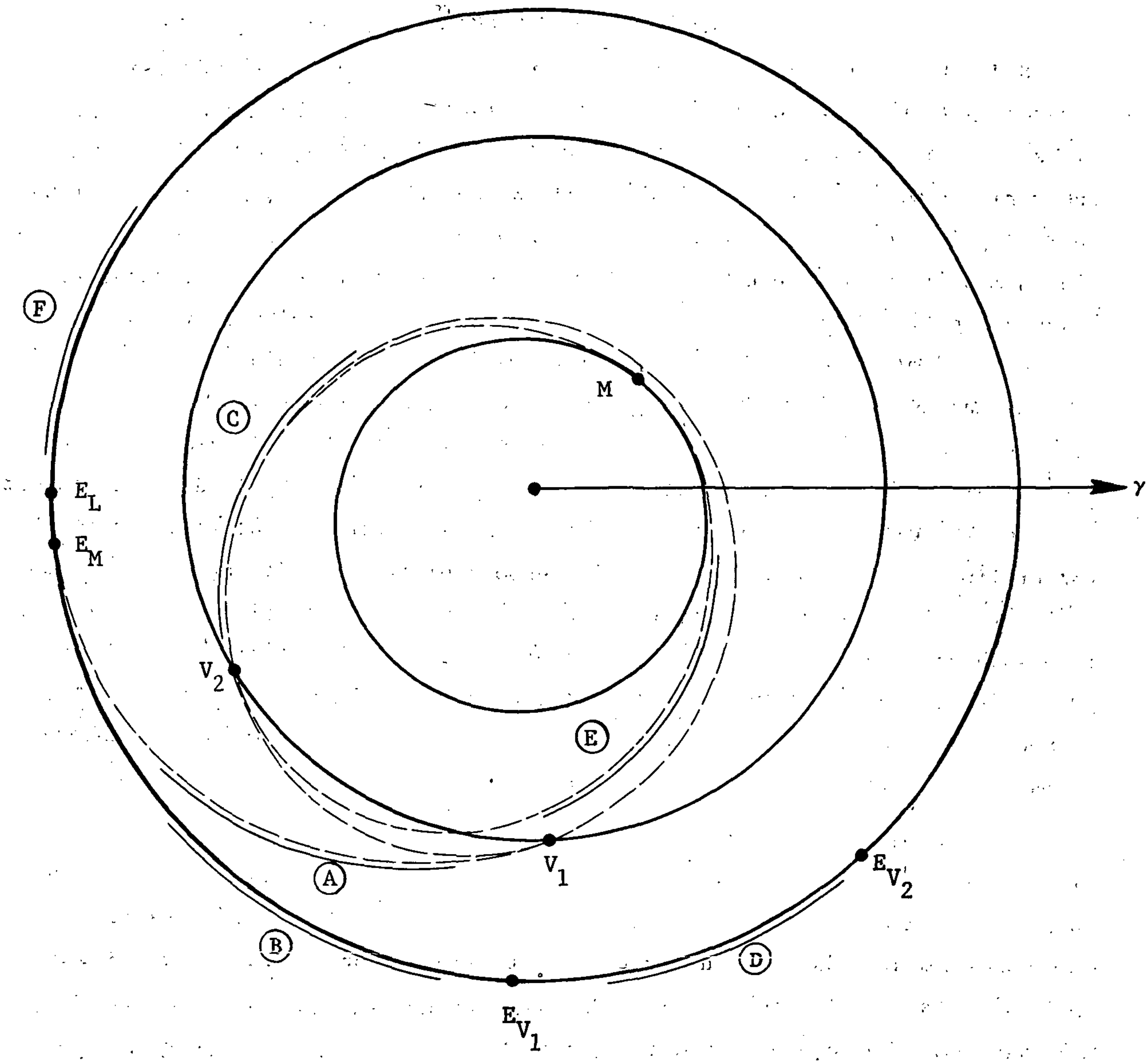


Figure V-4 Typical Time Histories, 1988 Multiple Venus Swingby Opportunity

E. NAVIGATION RESULTS

Midcourse requirements for this opportunity have been assessed using a trajectory targeted to a 250 km altitude at the first Venus swingby. Dispersions in periapsis altitude at Venus are 60.5 km (3 sigma), due to the Venus ephemeris error assumptions (20 km, 1 sigma) and the close-range tracking (20-40 Mkm) prior to Venus encounter. These navigational accuracies also result in a 52.5 m/s (mean-plus-three-sigma) post-Venus$_1$ correction maneuver. Analytic computation of this ΔV shows 52.0 m/s for a cumulative probability level of .99 and 66.7 m/s for a .999 probability. Addition of the planned trajectory shaping maneuver of 200 m/s results in a combined total of 234.5 m/s (see figs. VI-1 and VI-2 for correction distributions). At the second swingby, pre-Venus orbit determination errors are larger than might be expected for a closest approach radius of 9200 km. The fact that the spacecraft relative velocity vector lies in the plane-of-the-sky is responsible for a post-Venus correction maneuver as large as that required after the first swingby, 51.4 m/s (mean-plus-three-sigma). Again, analytical values are 50.8 m/s for .99 and 65.2 m/s for .999. Results of totaling all these correction maneuvers is given as 98.5 m/s in Section VI compared to a more conservative summing of all mean-plus-three-sigma values, 315.8 m/s, shown in Table V-4.

Tracking arcs prior to both Venus swingbys and to Mercury are shown in Figure V-6. B-plane dispersions at Mercury are depicted in Figure VI-3 which shows T-axis uncertainty dominated by a 60 km ephemeris error and R-axis uncertainty which also has an orbit determination error contribution. Since the Mercury approach maneuver must be executed at M-11 to avoid solar interference, out-of-the-ecliptic knowledge errors appear in the R-axis as they are mapped forward 11 days to Mercury.



Ⓐ SPACECRAFT DURING PRE-VENUS$_1$ TRACKING PERIOD

Ⓑ EARTH DURING PRE-VENUS$_1$ TRACKING PERIOD

Ⓒ SPACECRAFT DURING PRE-VENUS$_2$ TRACKING PERIOD

Ⓓ EARTH DURING PRE-VENUS$_2$ TRACKING PERIOD

Ⓔ SPACECRAFT DURING PRE-MERCURY TRACKING PERIOD

Ⓕ EARTH DURING PRE-MERCURY TRACKING PERIOD

Figure V-5 Critical Tracking Geometries, 1988 Multiple Venus Swingby Opportunities

TABLE V-4

1988 MANEUVER SCHEDULE AND STATISTICAL DESCRIPTION

MANEUVER TIME (days)	MEAN ΔV (m/s)	SIGMA ΔV (m/s)	MEAN PLUS THREE SIGMA (m/s)
E+10	8.16	5.60	24.96
V_1-3	1.51	0.87	4.13
V_1+2	20.91	10.53	52.50*
V_1+300	0.40	0.27	1.20
V_2-3	0.18	0.11	0.51
V_2+2	16.41	11.65	51.35
M-100	0.16	0.99	0.46
M-11	0.64	0.48	2.07
		TOTAL	137.18

* 234.5 m/s when combined with 200 m/s planned velocity maneuver at Venus.

VI. NAVIGATION ANALYSIS

VI. NAVIGATION ANALYSIS

The navigation analysis concentrated on one case from each of the three following mission opportunities: 1985 with planned velocity midcourse maneuver (400 m/s applied near perihelion of the Earth-Venus trajectory segment); 1983 multiple Venus swingby; and 1988 multiple Venus swingby. Error level assumptions and orbit determination methods are the same as in the original Handbook (NASA CR-2298). Strategies for the trajectory correction maneuvers and the tracking schedules are also the same. More of these velocity correction maneuvers are required with an increase in the number of swingbys and the number of extra solar revolutions. Even with the added number of maneuvers, the correction ΔV for each mission has been reduced from the baseline requirements. These differences between the baseline missions and the three missions discussed in this section are due to geometry dissimilarities in the trajectories which affect navigation accuracy.

Reference trajectories used for these analyses are identified in Table VI-1 by planet encounter dates. In Table VI-2, maneuver times are tabulated for each case. These trajectory correction maneuvers are scheduled before and after each planet encounter and midway in each spacecraft heliocentric revolution. Also, in 1985, a correction maneuver has been added after the planned midcourse to correct for any execution errors of this 400 m/s maneuver. The proximity of this maneuver to Venus encounter necessitates shortening the tracking periods for the correction maneuvers at V-26 and V-3 to 10 days and 22 days respectively (a 30-day tracking arc is assumed prior to execution of the planned midcourse). In the 1983 and 1988 cases, the last maneuvers must be scheduled before M-3 due to solar interference during the accompanying tracking period.

TABLE VI-1 SAMPLE TRAJECTORIES

1983	1985	1988
7-9-83 Launch	6-24-85 Launch	3-18-88 Launch
8-25-84 Swingby	10-16-85 Midcourse	6-17-88 Swingby
4-6-85 Swingby	11-21-85 Swingby	8-3-89 Swingby
11-17-85 Swingby	8-16-86 Encounter	3-26-90 Encounter
2-14-86 Encounter		

TABLE VI-2 MANEUVER SCHEDULES

EVENT	TRAJECTORY		
	1983	1985	1988
Maneuver	E+10	E+10	E+10
Planned Midcourse Maneuver		E+114.3	
Maneuver		V-26	
Maneuver	V_1-3	V-3	V_1-3
Venus Swingby	E+413.1=V_1	E+150.4=V	E+91.5=V_1
Maneuver	V_1+2	V+2	V_1+2
Maneuver	V_1+112		V_1+300
Maneuver	V_2-3		V_2-3
Venus Swingby	V_1+224.7=V_2		V_1+412.1=V_2
Maneuver	V_2+2		V_2+2
Maneuver	V_2+112		
Maneuver	V_3-3		
Venus Swingby	V_2+224.7=V_3		
Maneuver	V_3+2	M-100	M-100
Maneuver	M-19	M-3	M-11
Mercury Encounter	V_3+88.6=M	V+267.6=M	V_2+235.2=M

A statistical description of the results of the midcourse correction analyses are presented in the same form as for the baseline missions in Table VI-3. The values presented represent an approximation (Hoffman-Young) to mean and standard deviation assuming a Gamma distribution. A total of combined mean-plus-three-sigma values for all correction maneuvers of each opportunity represents an extremely conservative estimate of the total midcourse requirements. Since the tails of the distributions of these ΔV magnitudes behave similarly and look Gaussian, a realistic estimate for the combined total can be made with Gaussian assumptions. That is, the mean is the sum of the individual means and the variance is the sum of the variances. Estimated values using this technique for correction fuel budget requirements are 127.7 m/s, 113.3 m/s, and 98.5 m/s for 1983, 1985, and 1988 respectively. The addition of planned maneuvers increases this to 539.5 m/s for 1985 and 280.5 m/s for 1988. (In 1985, the entire magnitude of the planned maneuver must be added but in 1988 the planned maneuver is executed simultaneously with a post-Venus correction maneuver which results in a small ΔV savings, as will be discussed later).

Differences in post-Venus correction maneuvers between these missions and the baseline cases are significant. Navigational characteristics of these missions are determined by Earth-relative geometries during the Venus approach trajectories. The navigation accuracy depends on such parameters as Earth-spacecraft range, geocentric equatorial declination of the spacecraft, and the angle of the spacecraft relative velocity vector to the plane-of-the-sky. The cause of the large post-Venus dispersions is the inaccurate determination of the trajectory prior to Venus encounter; hence, any errors not corrected at V-3 are amplified by the Venus gravity-assist. Magnification effects of the Venus swingby on trajectory errors due to uncertainty in Venus' position and improper application of the pre-Venus maneuver vary with swingby condition (relative velocity and radius of closest approach).

The 1985 case with a planned 400 m/s midcourse has a statistical post-Venus correction maneuver on the order of half that of the 1985 baseline case. Delaying Venus encounter by approximately ten days changes the geocentric equatorial declination in the Venus approach tracking to values ranging from

TABLE VI-3 STATISTICAL DESCRIPTION OF MANEUVERS (m/s)

YEAR	MANEUVER TIME	MEAN	SIGMA	MEAN PLUS THREE SIGMA
1983	E+10	8.58	6.02	26.65
	E+200	0.13	0.071	0.34
	V_1-3	0.33	0.23	1.03
	V_1+2	1.61	1.19	5.16
	V_1+112	0.028	0.021	0.092
	V_2-3	0.19	0.12	0.55
	V_2+2	6.27	4.73	20.47
	V_2+112	0.081	0.06	0.26
	V_3-3	0.34	0.25	1.10
	V_3+2	37.58	22.13	103.97
	M-19	2.06	1.52	6.61
1985	E+10	6.67	4.45	20.01
	V-26	4.34	2.19	10.92
	V-3	0.36	0.22	1.03
	V+2	33.80	21.72	98.97
	M-100	0.55	0.31	1.48
	M-3	0.70	0.53	2.28
1988	E+10	8.16	5.60	24.96
	V_1-3	1.51	0.87	4.13
	V_1+2	20.91	10.53	52.50
	V_1+300	0.40	0.27	1.20
	V_2-3	0.18	0.11	0.51
	V_2+2	16.41	11.65	51.35
	M-100	0.16	0.099	0.46
	M-11	0.64	0.48	2.07

-4^{o} to -14^{o} rather than 5^{o} to -10^{o} (passing through 0^{o}) for the baseline case. This results in a decrease in the previously large knowledge uncertainty in Z-height at V-4 days from 146 km to 55 km which is sufficient to change the ΔV requirement (mean-plus-three-sigma) from 211 m/s to 99 m/s.

In the multiple swingby category, an alternative for Earth-spacecraft geometry prior to Venus encounter exists that did not exist in single swingby missions. Due to mission identification criteria, the single swingby missions identified have only two possibilities for Earth-Venus gometry, both with a range greater than 200 million km (Mkm). Alternate geometry options provided by the multiple swingby opportunities allow ranges as low as 20 Mkm at the beginning of the 1988 pre-Venus_1 (first swingby) tracking arc. In none of the critical Venus approach tracking does the spacecraft pass through zero equatorial declination, and in only two cases does the plane-of-the-sky problem exist, 1988 second swingby and 1983 first swingby. (However, the 1983 first flyby is so far away from Venus that this geometry problem does not cost much.)

More important than geometric considerations for the multiple swingby cases, in all but the first 1988 swingby, are the swingby conditions at Venus. Increasing either the relative velocity or radius of closest approach reduces the sensitivity of post-encounter to pre-encounter errors. It should be noted that the relative velocities at Venus are on the order of 11 km/sec rather than an average of 13 km/sec (baseline single swingby). However, this decrease is overshadowed by the large increases in closest approach radii. Of the five swingbys combined from these two missions, only one swingby reaches the lower bound of 250 km (1988 first Venus swingby). The other values of the altitude at Venus, are in 1983: 41,000 km, 3400 km, and 760 km, and in 1988: 250 km, and and 9200 km. The original Handbook (fig. VI-2) shows typical pre-encounter orbit determination based on planet relative approach velocity.
Tracking in the region of large Venus perturbations allows a decrease in knowledge error to the planetocentric plateau. Large values of V_{HP} and R_{CA} preclude this tracking before the spacecraft reaches V-4. Again, the slight decrease ($\sim$15%) in V_{HP} from the single swingby cases is not sufficient to provide any of this information.

In 1983 ΔV correction magnitudes decrease with increasing altitude at Venus swingby. However, in 1988, the two post-Venus maneuvers have nearly the same magnitude. Orbit determination is very good for the low-range (20 to 40 Mkm) first Venus approach, while for the second Venus approach it is bad due to the plane-of-the-sky problem.

Since the 1988 opportunity involves a trajectory shaping maneuver at the same time as the post-Venus correction maneuver, these were combined using Monte Carlo techniques as in the previous analysis. Due to the relative size of the two maneuvers, not as much savings was achieved as in the single swingby missions. Histograms appear in Figures VI-1 and VI-2 for the correction maneuver distribution with and without this planned 200 m/s maneuver. The net savings amounts to 18 m/s.

Although closest approach uncertainties at Venus were important for the close swingbys in the previous study, the only close flyby (nominal altitude = 250 km) has dispersions in h_p of 60.5 km (3 sigma). This h_p dispersion is entirely dominated by the assumed 60km (3 sigma) ephemeris error. Mercury approach uncertainties for all three opportunities are depicted in Figure VI-3 in B-plane coordinates. All of these include a 60 km (1 sigma) Mercury ephemeris error. Differences in the size of these dispersions result from the different scheduling of the pre-Mercury velocity corrections. These are at M-19, M-3, and M-11 for 1983, 1985, and 1988 respectively. (The reason for the scheduling differences is solar interference with spacecraft tracking.) The size of the uncorrected errors increases because of the extended time in 1983 and 1988 producing larger errors at Mercury encounter (knowledge errors at M-18 and M-12 were mostly out-of-plane resulting in larger R-axis dispersions).

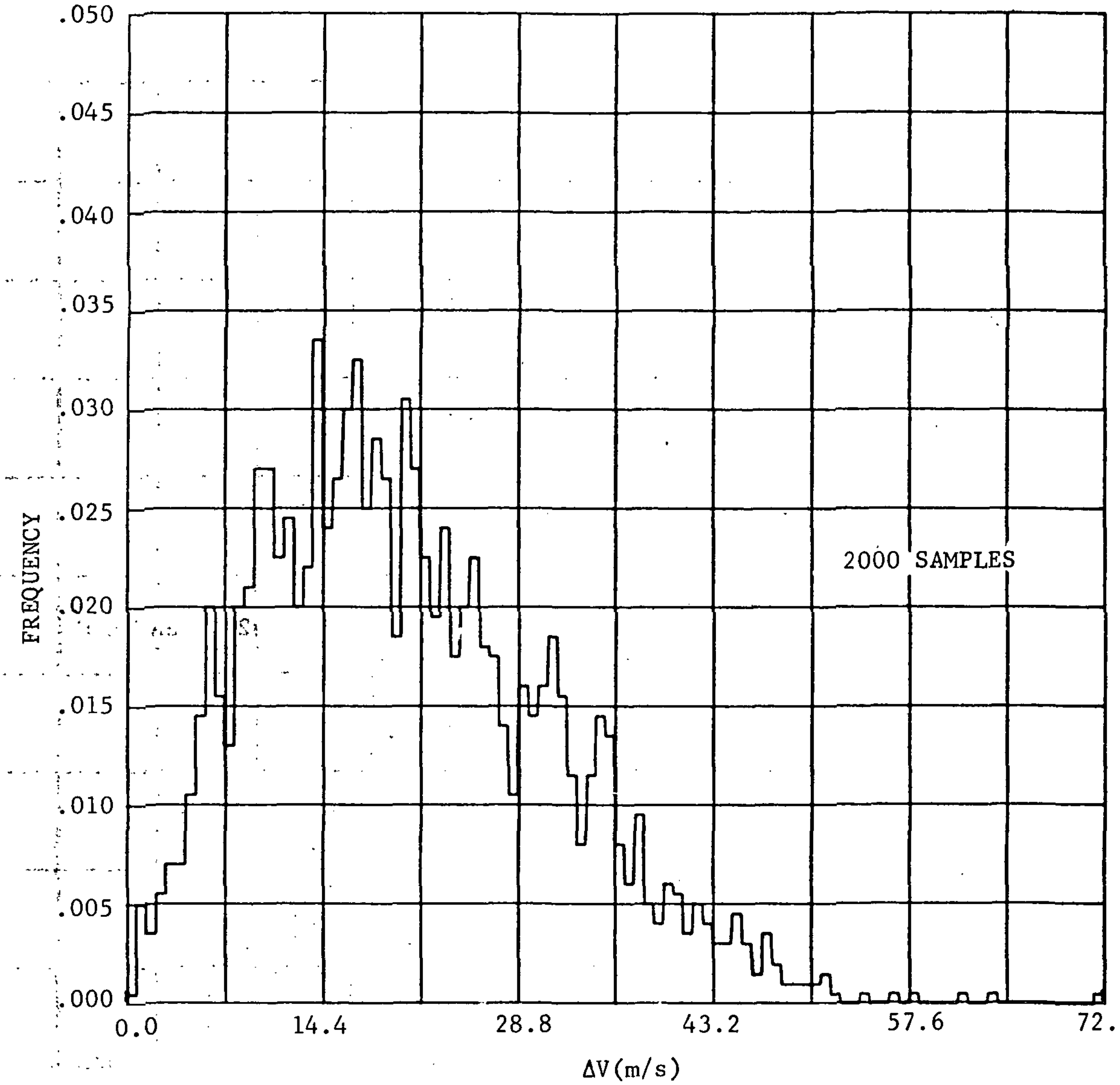


Figure VI-1 Post-Venus Correction Distribution, 1988 Multiple Venus Swingby Opportunity Without Venus Maneuver

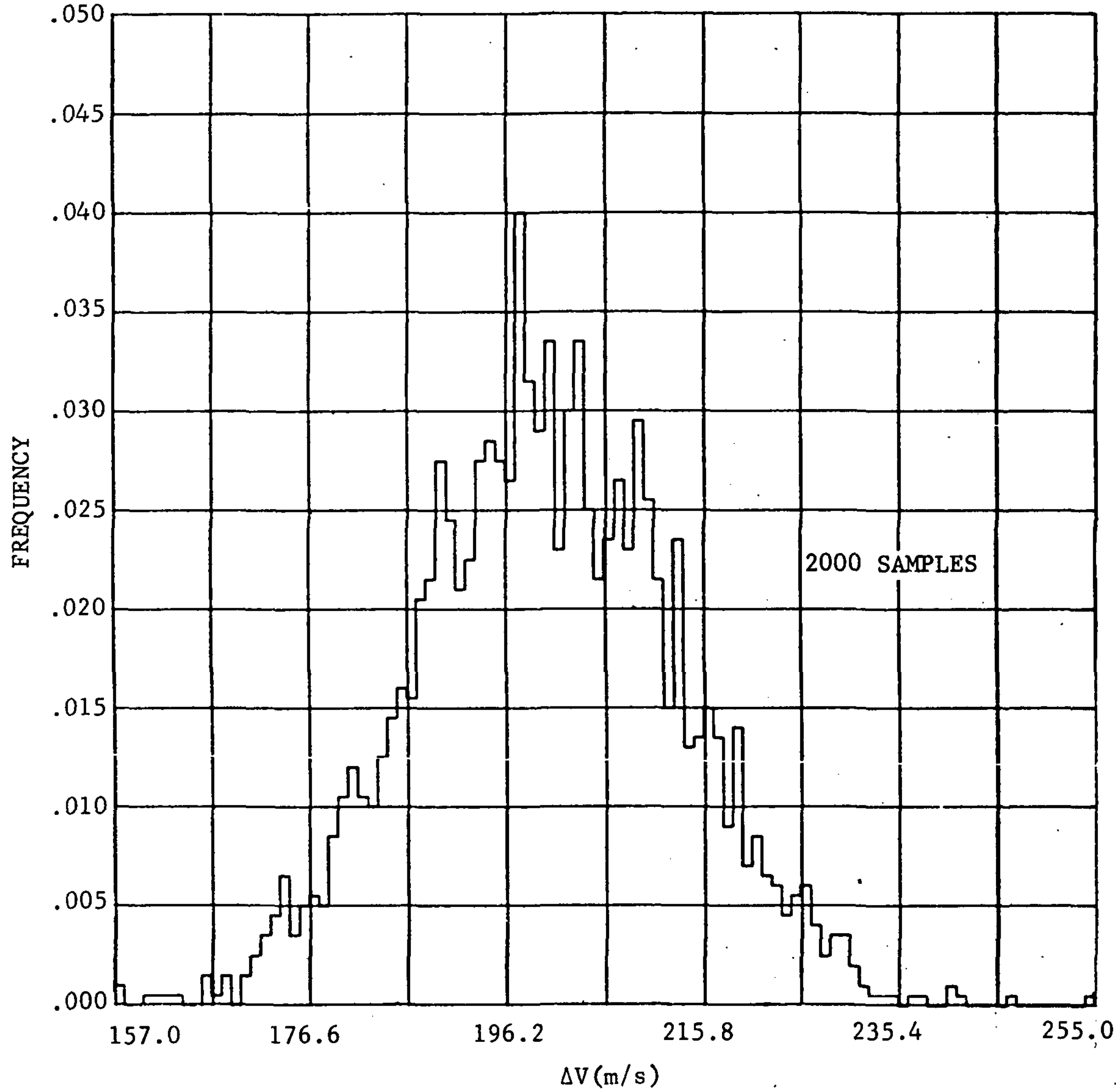


Figure VI-2 Post-Venus Correction Distribution, 1988 Multiple Venus Swingby Opportunity with 200 m/s Venus Maneuver

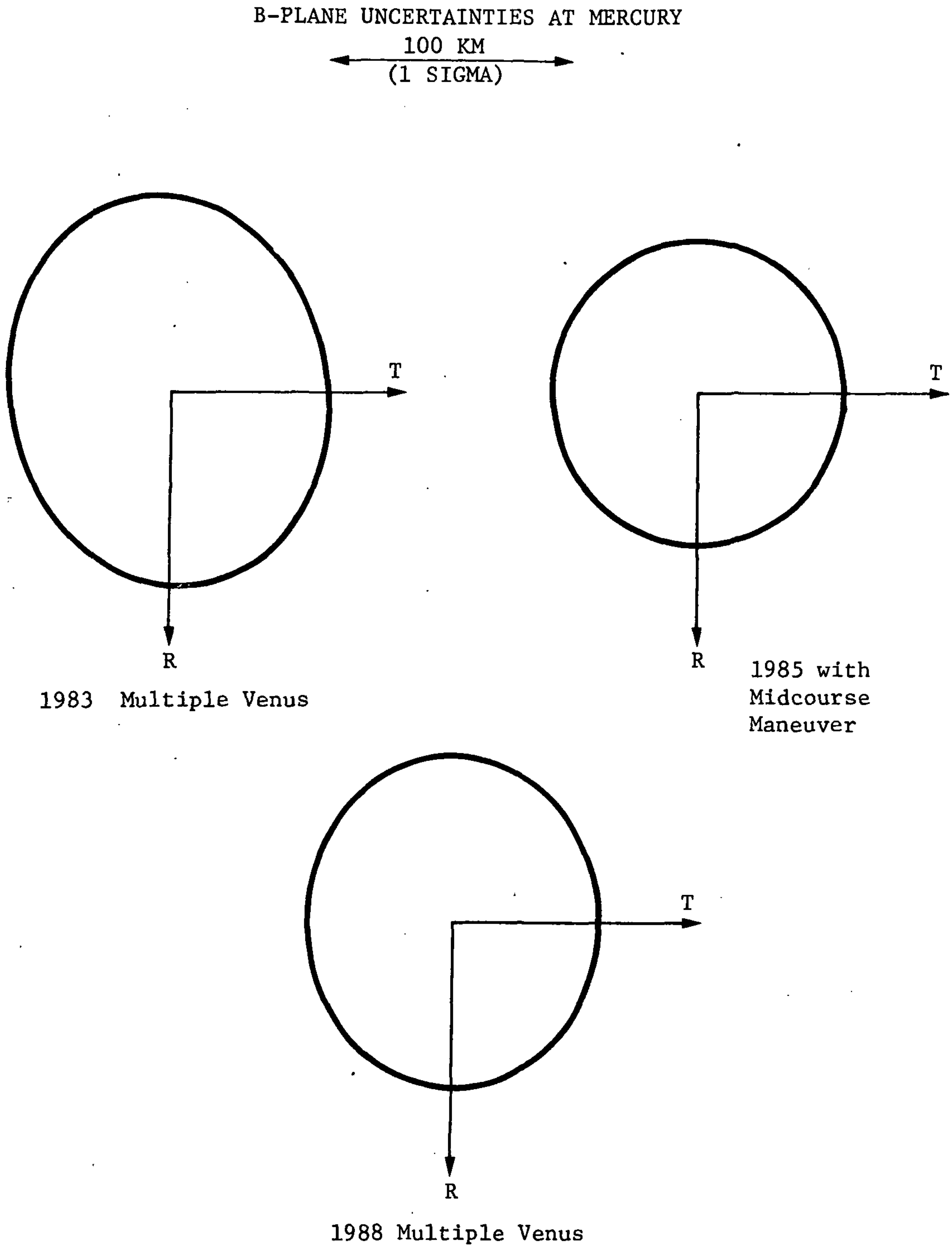


Figure VI-3 Mercury Encounter Dispersions

VII. 1990 MISSION OPPORTUNITIES

VII. 1990 MISSION OPPORTUNITIES

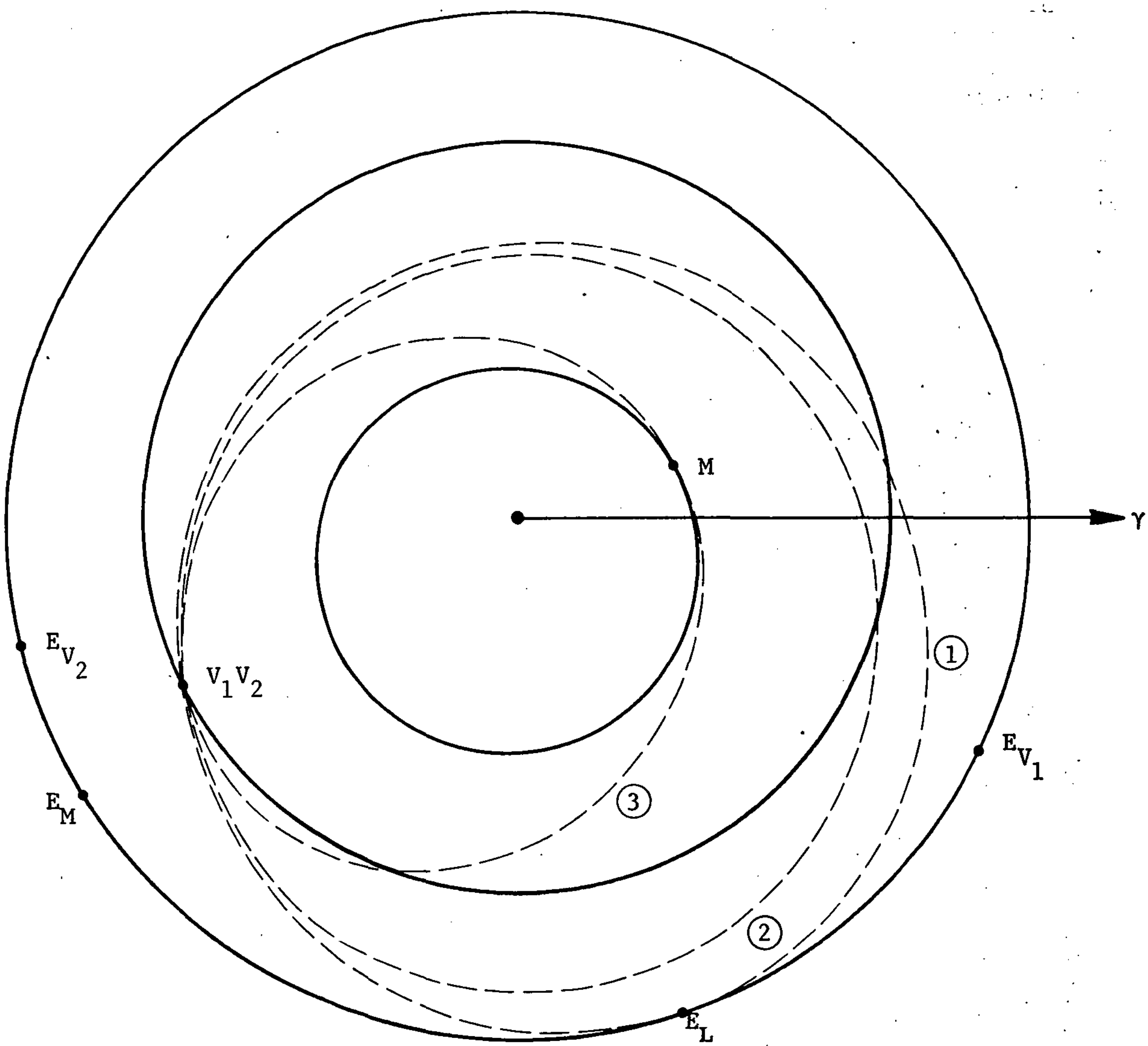
Four Mercury Orbiter mission opportunities covering the last decade of this century are presented in this section. These opportunities, corresponding to launch years 1991, 1994, 1996, and 1999, represent selected high-performance multiple Venus opportunities and are not the only mission possibilities within this time frame. None of these mission opportunities have been fully optimized. Consequently, the mission performance presented in this section corresponds in each case to verified minimum potential.

A. 1991 MISSION OPPORTUNITY

The flight profile for the 34-month 1991 mission opportunity is shown in Figure VII-1. This double Venus swingby geometry is similar to the 1983 multiple Venus flight profile. However, the middle Venus swingby required for phasing in the 1983 opportunity, is not required here. One complete spacecraft phasing orbit is necessary prior to first Venus swingby, with second swingby occurring a Venus period later. The heliocentric geometry also includes two complete solar revolutions of the spacecraft between second Venus swingby and Mercury encounter.

Relative arrival velocities at Mercury and corresponding launch energies for a range of Earth launch dates and Mercury arrival dates are presented in Figure VII-2. The best 15-day ballistic launch period for this mission opportunity is composed of both Type I and Type II transfers from Venus to Mercury. Mercury arrival dates of 4-24 through 4-27 in Figure VII-2 represent Type I transfers, while the 4-29 and 4-30 lines correspond to Type II transfers from Venus to Mercury. No relative velocities for the 4-28 arrival are shown since, in general, transfer angles from Venus to Mercury on this date are nearly 180^0 resulting in large relative arrival velocities. Although the Type II transfers on the 4-29 arrival date have swingby altitudes at second Venus swingby of less than 250 kilometers for the later launch dates, a 15-day ballistic launch window with a maximum relative arrival velocity of 6.65 km/sec and swingby altitudes greater than 250 km may be identified. Relative arrival velocities of this magnitude are comparable with those obtained for the 1983 multiple Venus Mission. Mission performance for the 1991 opportunity is shown in Figure I-1. A value of 250 m/s for midcourse corrections was used in determining performance for the 1991 mission as well as the other 1990 mission opportunities.

Table VII-1 contains tabulated details of one representative trajectory for the 1991 mission opportunity. This trajectory has an Earth launch on 7-3; Mercury encounter date is selected as 4-27-94. The print key which defines each listed parameter is given in Section I of the Appendix.



E_L: EARTH AT LAUNCH, 7-13-91

E_{V_1}: EARTH AT FIRST VENUS SWINGBY (V_1), 8-27-92

E_{V_2}: EARTH AT SECOND VENUS SWINGBY (V_2), 4-9-93

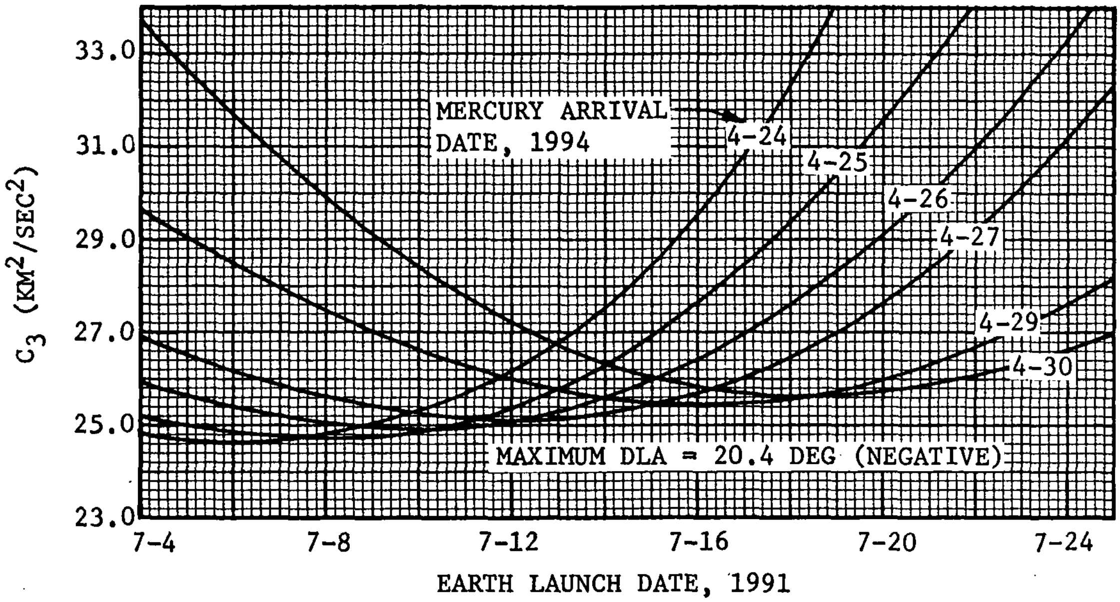
E_M: EARTH AT MERCURY ENCOUNTER (M), 4-27-94

1 ONE COMPLETE SOLAR REVOLUTION BEFORE FIRST VENUS SWINGBY

2 ONE COMPLETE SOLAR REVOLUTION BETWEEN VENUS SWINGBYS

3 TWO COMPLETE SOLAR REVOLUTIONS BEFORE MERCURY ENCOUNTER

Figure VII-1 Heliocentric Geometry, 1991 Multiple Venus Swingby Opportunity



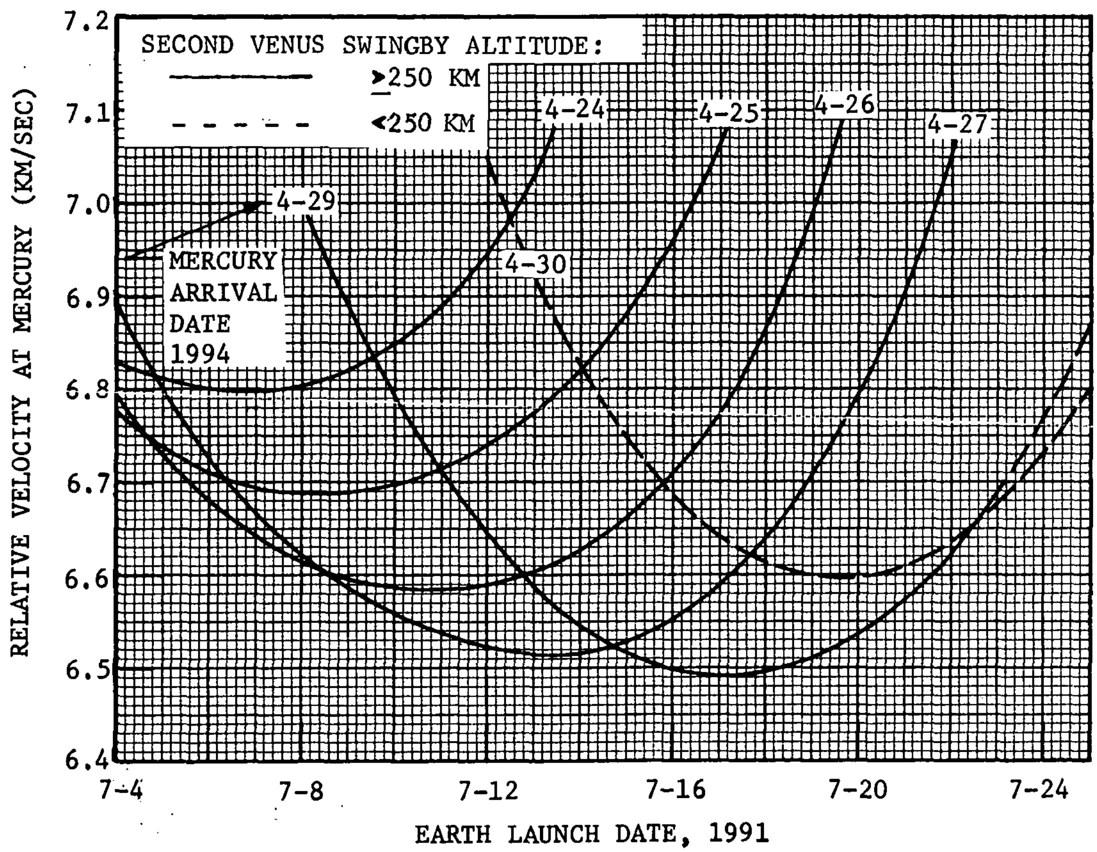


Figure VII-2 Relative Velocity at Mercury and C_3 vs Launch/Arrival Date, 1991 Multiple Venus Swingby Opportunity

```
JD=2448450.500   C3=  25.181  FLT TIM= 411.430    JUL 13 1991  0, 0, 0.
ECLIPTIC            X                 Y                  Z                 TOTAL
R EARTH     4.9720565E+07   -1.4371938E+08    1.3082763E+04    1.5207694E+08
V EARTH     2.7664389E+01    9.6379403E+00   -1.1685768E-03    2.9295193E+01
VEL S/C     2.2949206E+01    8.3664589E+00   -1.1548201E+00    2.4453983E+01
VHE        -4.7151832E+00   -1.2714814E+00   -1.1536515E+00    5.0180204E+00
RAA=195.091 DECA=-13.291       SEVHE= 93.886
EQUATORIAL          X                 Y                  Z                 TOTAL
R EARTH     4.9720565E+07   -1.3186514E+08   -5.6955248E+07    1.5207694E+08
V EARTH     2.7664389E+01    8.8431008E+00    3.9442751E+00    2.9295193E+01
VEL S/C     2.2949206E+01    8.1354362E+00    2.3610415E+00    2.4453983E+01
VHE        -4.7151832E+00   -7.0766463E-01   -1.5832336E+00    5.0180204E+00
RAA=188.535 DECA=-18.369 RP= 79218158.34 APO=152122024.60
A=115670091.47 E= .31514 I=  2.707 NODE=289.288 W=181.952
TH1= 182.1   TH2= 456.4   DTH= 274.4   TYPE   IV    I

JD=2448861.930 VHA= 11.028 VHD= 11.028  AUG 27 1992 10, 19, 49.690
ECLIPTIC            X                 Y                  Z                 TOTAL
R VENUS    -9.8959301E+07   -4.2915859E+07    5.0859757E+06    1.0798417E+08
V VENUS     1.3691434E+01   -3.2288425E+01   -1.2478030E+00    3.5093515E+01
V S/C A     3.4521099E+00   -3.6035829E+01    4.0583552E-01    3.6203077E+01
VHA        -1.0239324E+01   -3.7474043E+00    1.6536385E+00    1.1028205E+01
V S/C D     3.5677296E+00   -3.4553265E+01   -4.9897846E+00    3.5093515E+01
VHD        -1.0123704E+01   -2.2648398E+00   -3.7419816E+00    1.1028205E+01
RCA=  7855.4    BTH=255.5    B*T=      -2544    B*R=      -9859    HCA=  1805.4
RAA= 200.1 DECA=   8.6 SPA= 173.2 EPA= 152.9 CPA=  99.8   TYPEIII    I
RAE= 353.9 DECE=  -1.2 RAS=  23.4 DECS=  -2.7
AH=      2671.1 EH=  3.94090 I= 104.3 NODE=  17.9 W= 156.4 TAU=  75.3
A=108209149.3 E=    .291452 I=   9.8 NODE= 399.3 W=  57.3 TURN=  29.4
THI= 106.6 THF= 106.6 DTH= 360.  FLT TIM= 224.704
PERIHELION= 76671358.9  APHELION=139746939.7

JD=2449086.634 VHA= 11.028 VHD= 11.027  APR  9 1993  3, 13, 26.201
ECLIPTIC            X                 Y                  Z                 TOTAL
R VENUS    -9.8959301E+07   -4.2915859E+07    5.0859757E+06    1.0798417E+08
V VENUS     1.3691434E+01   -3.2288425E+01   -1.2478030E+00    3.5093515E+01
V S/C A     3.5677296E+00   -3.4553265E+01   -4.9897846E+00    3.5093515E+01
VHA        -1.0123704E+01   -2.2648398E+00   -3.7419816E+00    1.1028205E+01
V S/C D     3.8780496E+00   -2.8202140E+01   -4.1780615E+00    2.8772489E+01
VHD        -9.8133840E+00    4.0862855E+00   -2.9302586E+00    1.1026634E+01
RCA=  6518.8    BTH=178.2    B*T=      -8789    B*R=        273    HCA=   468.8
RAA= 192.6 DECA= -19.8 SPA= 155.1 EPA=  15.1 CPA=  70.4   TYPE  V    I
RAE= 185.1 DECE=  -6.7 RAS=  23.4 DECS=  -2.7
AH=      2671.1 EH=  3.44053 I= 160.1 NODE= 107.8 W= 258.0 TAU=  73.1
A= 81411570.7 E=    .408116 I=   9.8 NODE= 399.3 W=   8.3 TURN=  33.8
THI= 155.6 THF= 332.1 DTH= 176.5 FLT TIM= 382.866
PERIHELION= 48186182.6  APHELION=114636958.7
```

TABLE VII-1 TRAJECTORY PRINTOUT 7-13-91 LAUNCH

```
JD=2449469.500     VHP=  6.509   APR 27 1994   0, 0, 0.
ECLIPTIC             X                  Y                  Z                 TOTAL
R MERCURY  4.6797793E+07     1.6996464E+07    -2.8443067E+06     4.9869864E+07
V MERCURY -2.6061362E+01     4.8075054E+01     6.3412029E+00     5.5051033E+01
V S/C     -2.7693757E+01     5.3134940E+01     1.0096714E+01     6.0763555E+01
VHP       -1.6323950E+00     5.0598860E+00     3.7555109E+00     6.5093027E+00
RAA= 107.9    DECA=  35.2    SPA=  89.8    EPA= 100.7    CPA= 111.1
RAE= 211.6    DECE=    .8    RAS=-160.0    DECS=   3.3
EQUATORIAL           X                  Y                  Z                 TOTAL
R MERCURY -4.5004517E+07    -2.1484802E+07    -1.4901161E-08     4.9869864E+07
V MERCURY  3.1047158E+01    -4.5460865E+01     0.                5.5051033E+01
V S/C      3.3517043E+01    -5.0584574E+01     3.1651683E+00     6.0763555E+01
VHP        2.4698857E+00    -5.1237092E+00     3.1651683E+00     6.5093027E+00
RAA= 295.7  DECA=  29.1  RAS=  25.5  DECS=    .0  RAE=  37.3  DECE=  -1.1
MERCURY OP           X                  Y                  Z                 TOTAL
R MERCURY  4.4321446E+07    -2.2860725E+07    -1.4901161E-08     4.9869864E+07
V MERCURY  1.7443357E+01     5.2214419E+01     0.                5.5051033E+01
V S/C      2.0031594E+01     5.7279373E+01     3.1651683E+00     6.0763555E+01
VHP        2.5882367E+00     5.0649543E+00     3.1651683E+00     6.5093027E+00
RAA=  62.9  DECA=  29.1  RAS= 152.7  DECS=    .0  RAE= 164.5  DECE=  -1.1
```

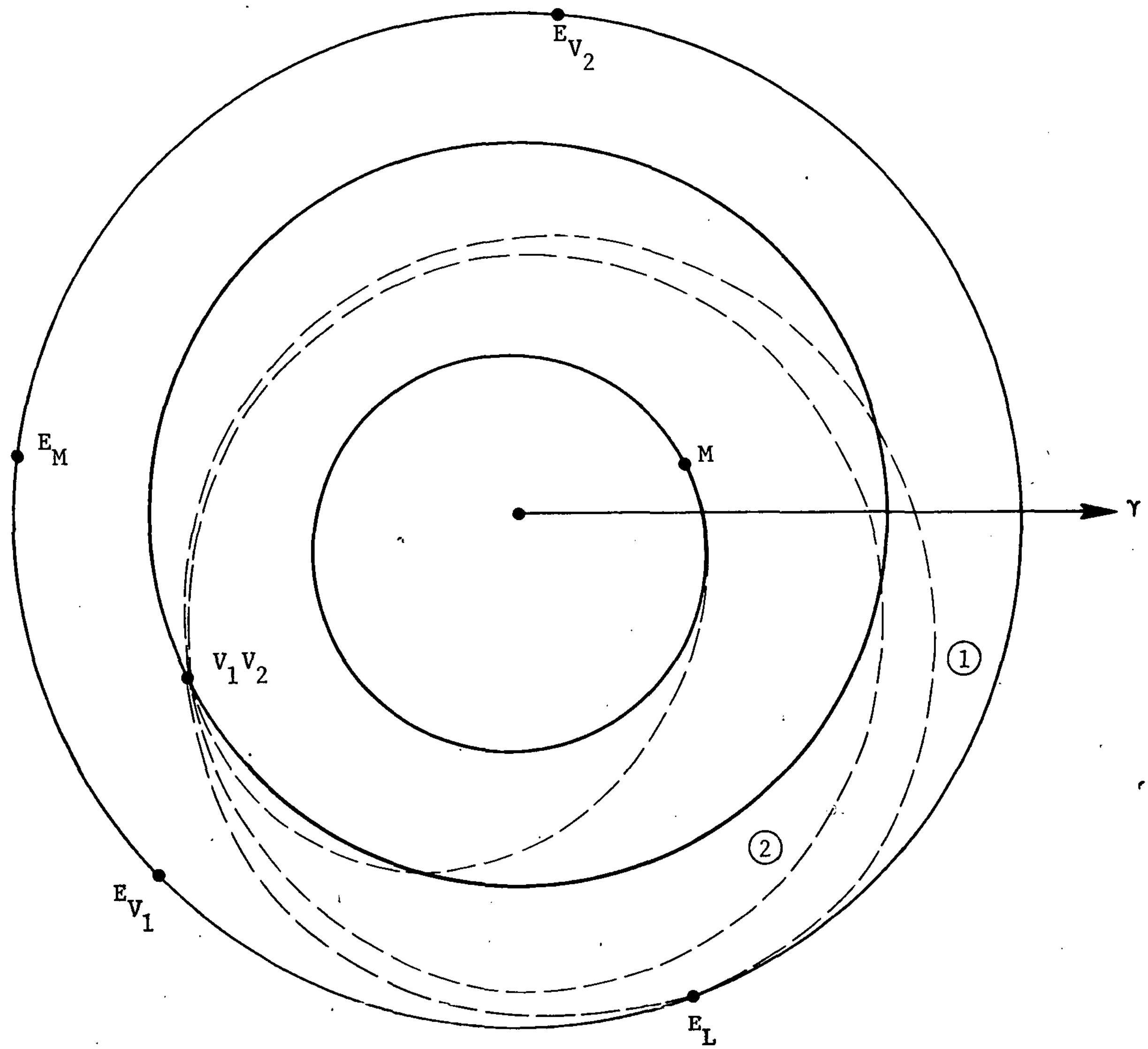
TABLE VII-1 TRAJECTORY PRINTOUT 7-13-91 LAUNCH (Continued)

B. 1994 MISSION OPPORTUNITY

The 1994 mission opportunity is a double swingby mission very similar to the 1991 opportunity. The basic difference between the missions is the number of phasing orbits utilized on the Earth-Venus and Venus-Mercury legs. The heliocentric geometry for the 33-month 1994 double Venus swingby opportunity is presented in Figure VII-3. Two complete phasing orbits are included prior to initial Venus swingby with second Venus swingby occuring a Venus period later at the same ecliptic longitude. The Venus-Mercury transfer segment is Type I with no extra phasing revolutions. The inclusion of the two initial phasing orbits on the Earth-Venus leg accounts for the increase in flight time over that of the 1991 opportunity.

Mission performance for the 1994 multiple Venus opportunity is significantly higher than for the 1983 and 1991 multiple Venus missions. The reason for this may be seen from Figure VII-4 which indicates the relative arrival velocities and required launch energies for a range of launch dates. The maximum relative arrival velocity for the best 15-day ballistic launch period is considerably lower than the corresponding value for both the 1983 and 1991 missions, with comparable launch energies. As a result, mission performance in 1994 shows a large increase (fig. I-1) over both the 1983 and 1991 performance. Again, mission potential has not been fully optimized, although the Mercury encounter date of 3-17-97 appears to be near-optimum over the entire 15-day launch period.

Tabulated details of a representative trajectory for the 1994 opportunity are shown in Table VII-2. This trajectory has an Earth launch on 7-13-94, with a Mercury arrival date of 3-17-97. Section 1 of the Appendix contains the print key which defines each of the parameters listed in the table.



E_L: EARTH AT LAUNCH, 7-13-94

E_{V_1}: EARTH AT FIRST VENUS SWINGBY (V_1), 5-7-96

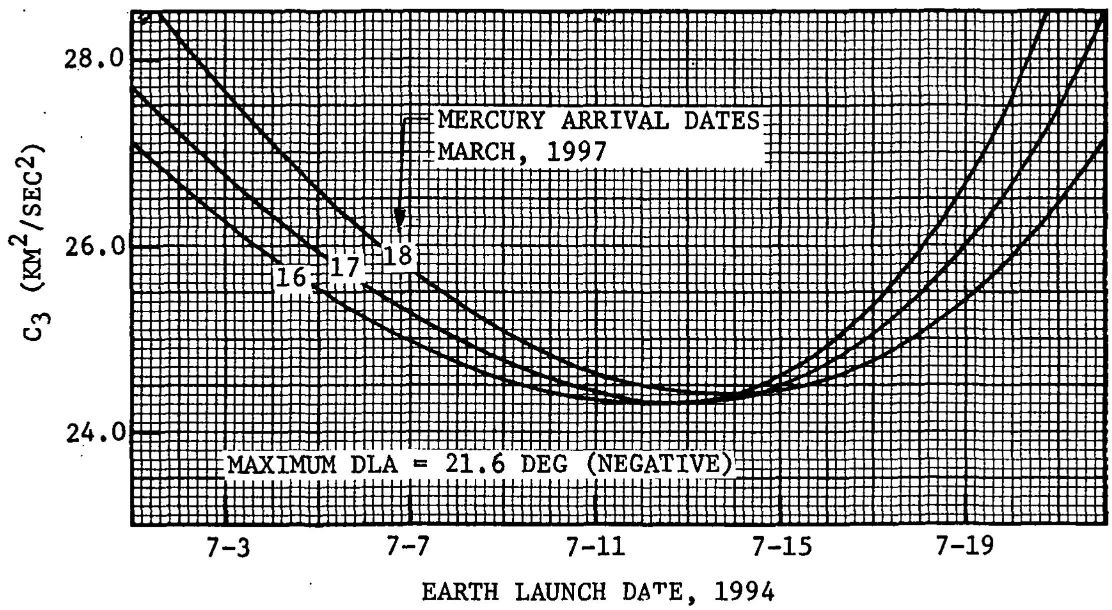
E_{V_2}: EARTH AT SECOND VENUS SWINGBY (V_2), 12-17-96

E_M: EARTH AT MERCURY ENCOUNTER (M), 3-17-97

1 TWO COMPLETE SOLAR REVOLUTIONS BEFORE FIRST VENUS SWINGBY

2 ONE COMPLETE SOLAR REVOLUTION BETWEEN VENUS SWINGBYS

Figure VII-3 Heliocentric Geometry, 1994 Multiple Venus Swingby Opportunity



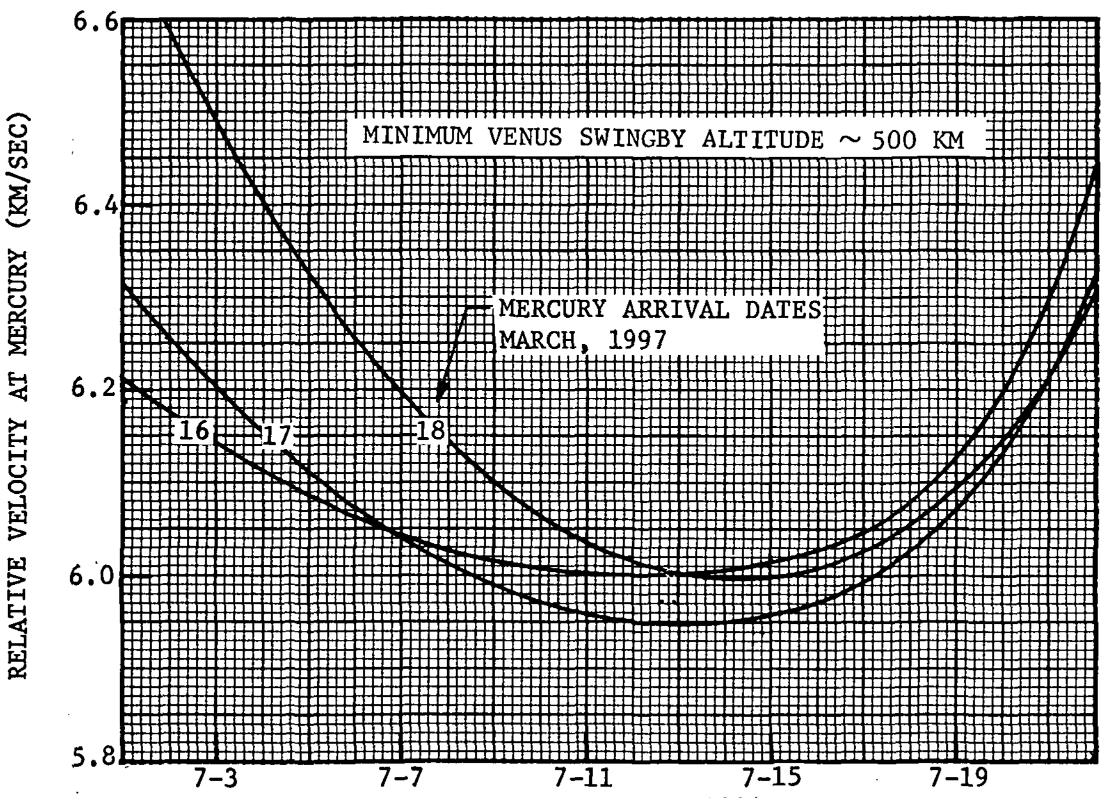


Figure VII-4 Relative Velocity at Mercury and C_3 vs Launch/Arrival Date, 1994 Multiple Venus Swingby Opportunity

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JD=2449546.500   C3=  24.373  FLT TIM= 663.725   JUL 13 1994  0, 0, 0.
ECLIPTIC            X                  Y                  Z                  TOTAL
R EARTH      5.0187970E+07    -1.4355533E+08     1.4005682E+04     1.5207552E+08
V EARTH      2.7632509E+01     9.7298008E+00    -1.2622953E-03     2.9295471E+01
VEL S/C      2.3054621E+01     8.2867293E+00    -1.1558980E+00     2.4525936E+01
VHF         -4.5778879E+00    -1.4430715E+00    -1.1546357E+00     4.9368711E+00
RA A=197.496 DECA=-13.526        SEVHE= 91.726
EQUATORIAL          X                  Y                  Z                  TOTAL
R EARTH      5.0187970E+07    -1.3171554E+08    -5.6871291E+07     1.5207552E+08
V EARTH      2.7632509E+01     8.9274557E+00     3.9885648E+00     2.9295471E+01
VEL S/C      2.3054621E+01     8.0627361E+00     2.3354039E+00     2.4525936E+01
VHE         -4.5778879E+00    -8.6471963E-01    -1.6531609E+00     4.9368711E+00
RA A=190.697 DECA=-19.537 RP= 79961303.13 APO=152088370.87
A=116024837.00 F= .31083 I=  2.701 NODE=289.382 W=180.997
TH1= 181.1    TH2= 455.4    DTH= 274.3   TYFE   VI     I


JD=2450210.225 VHA= 10.858 VHO= 10.858  MAY  6 1996 17, 24,  8.936
ECLIPTIC            X                  Y                  Z                  TOTAL
R VENUS     -9.8855625E+07    -4.3159756E+07     5.0757894E+06     1.0798594E+08
V VENUS      1.3770246E+01    -3.2254101E+01    -1.2521367E+00     3.5092942E+01
V S/C A      3.7345814E+00    -3.6055856E+01     3.9834982E-01     3.6250939E+01
VH A        -1.0035664E+01    -3.8017548E+00     1.6504865E+00     1.0857808E+01
V S/C D      3.5638912E+00    -3.4675106E+01    -4.0558966E+00     3.5092942E+01
VH D        -1.0206354E+01    -2.4210042E+00    -2.8037599E+00     1.0857808E+01
RC A= 10067.6     BTH=252.7      B*T=      -3714     B*R=     -11960     HCA=  4017.6
RA A= 200.7 DECA=    8.7 SPA= 173.3 FPA=   63.9 CPA= 100.1    TYPEIII     I
RA E= 263.5 DECE=   -4.5 RAS=   23.6 DECS=  -2.7
AH =      2755.6 EH=  4.65355 I= 107.0 NODE=  18.0 W= 158.4 TAU=  77.6
A=108209149.3 E=     .296525 I=    8.3 NODE= 402.5 W=   54.0 TURN=  24.8
TH I= 106.9 THF= 106.9 DTH=  360.  FLT TIM= 224.702
PERIHELION= 76122381.6  APHELICN=140295917.0

JD=2450434.927 VHA= 10.858 VHO= 10.855  DEC 17 1996 10, 14, 28.136
ECLIPTIC            X                  Y                  Z                  TOTAL
R VENUS     -9.8855625E+07    -4.3159756E+07     5.0757894E+06     1.0798594E+08
V VENUS      1.3770246E+01    -3.2254101E+01    -1.2521367E+00     3.5092942E+01
V S/C A      3.5638912E+00    -3.4675106E+01    -4.0558966E+00     3.5092942E+01
VH A        -1.0206354E+01    -2.4210042E+00    -2.8037599E+00     1.0857808E+01
V S/C D      3.8746897E+00    -2.8348122E+01    -3.4100391E+00     2.8814191E+01
VH D        -9.8955558E+00     3.9059797E+00    -2.1579024E+00     1.0855194E+01
RC A=  6640.9     BTH=178.4      B*T=      -8980     B*R=        249     HCA=   590.9
RA A= 193.3 DECA= -15.0 SPA= 159.6 FPA= 131.7 CPA=   75.3    TYPE  I
RAE=  59.3 DECE=   -1.3 RAS=   23.6 DECS=  -2.7
AH =      2755.6 EH=  3.41000 I= 165.0 NODE= 109.5 W= 258.9 TAU=  72.9
A= 81533692.8 E=     .409726 I=    8.3 NODE= 402.5 W=    5.8 TURN=  34.1
TH I= 155.1 THF= 328.1 DTH= 173.0 FLT TIM=  89.573
PERIHELION= 48127052.2  APHELION=114940333.4
```

TABLE VII-2 TRAJECTORY PRINTOUT 7-13-94 LAUNCH

```
JD=2450524.500     VHP=  5.946   MAR 17 1997  0, 0, 0.
ECLIPTIC            X                 Y                 Z                 TOTAL
R MERCURY  4.8145487E+07    1.4348796E+07   -3.1851713E+06    5.0339062E+07
V MERCURY -2.3328583E+01    4.8976989E+01    6.1676254E+00    5.4598607E+01
V S/C     -2.5579443E+01    5.4056318E+01    8.2854981E+00    6.0374191E+01
VHP       -2.2508609E+00    5.0793284E+00    2.1178727E+00    5.9456990E+00
RA A= 113.9   DECA=  20.9   SPA=  81.9   EFA=  67.9   CPA=  96.9
RA F= 180.6   DECE=    .9   RAS=-163.4   DECS=   3.6
EQUATORIAL          X                 Y                 Z                 TOTAL
R MERCURY -4.4153865E+07   -2.4175554E+07   -1.4901161E-08    5.0339062E+07
V MERCURY  3.3550568E+01   -4.3073974E+01    0.               5.4598607E+01
V S/C      3.7022206E+01   -4.7667617E+01    1.4824024E+00    6.0374191E+01
VHP        3.4716371E+00   -4.5936429E+00    1.4824024E+00    5.9456990E+00
RA A= 307.1  DECA=  14.4  RAS=  28.7  DECS=    .0  RAE=  13.0  DECE=  -4.2
MERCURY OP          X                 Y                 Z                 TOTAL
R MERCURY  4.3320671E+07   -2.5638656E+07   -1.4901161E-08    5.0339062E+07
V MERCURY  1.9926451E+01    5.0832513E+01    0.               5.4598607E+01
V S/C      2.2105794E+01    5.6162080E+01    1.4824024E+00    6.0374191E+01
VHP        2.1793430E+00    5.3295670E+00    1.4824024E+00    5.9456990E+00
RA A=  67.8  DECA=  14.4  RAS= 149.4  DECS=    .0  RAE= 133.7  DECE=  -4.2
```

TABLE VII-2 TRAJECTORY PRINTOUT 7-13-94 LAUNCH (Continued)

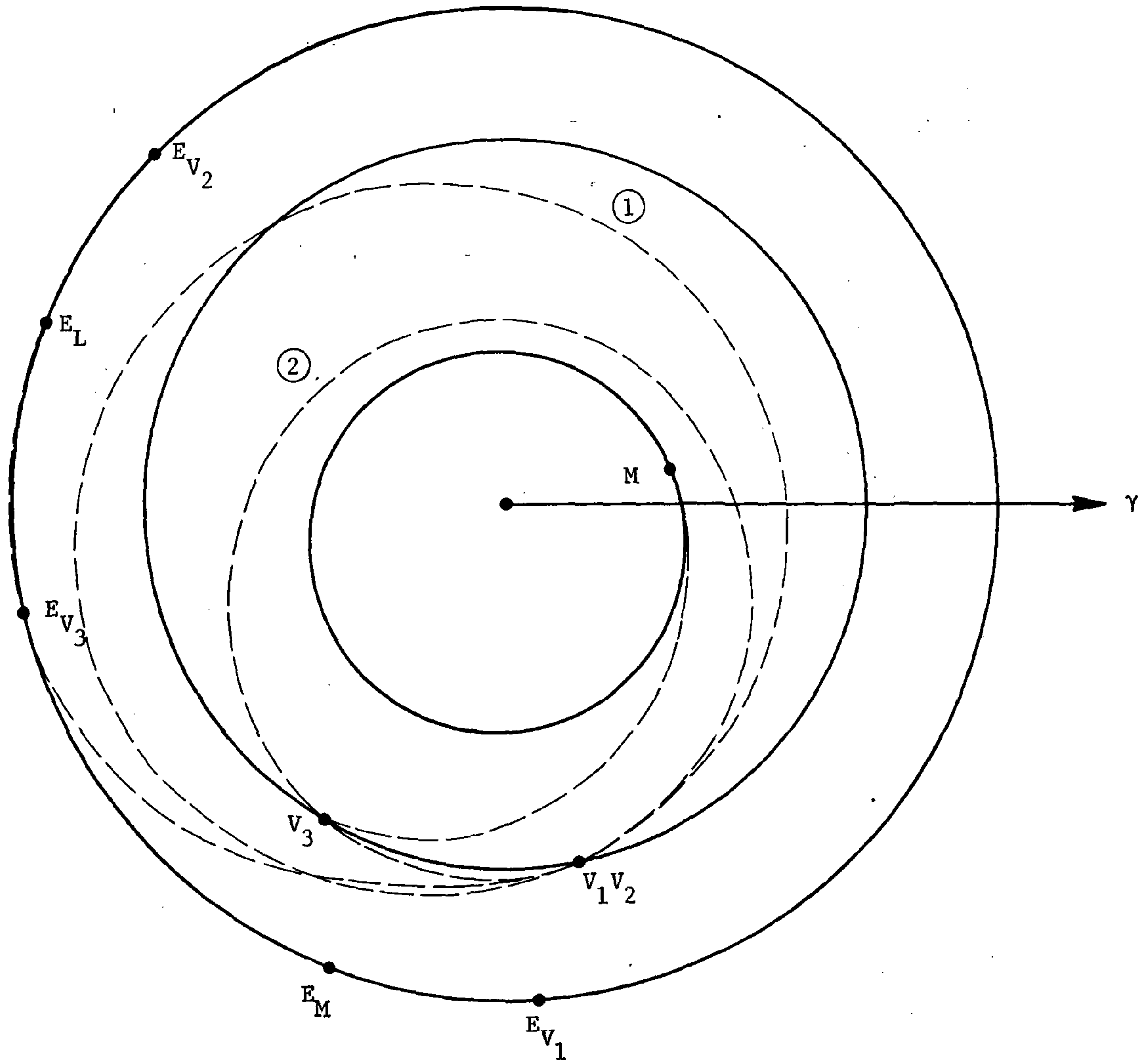
C. 1996 MISSION OPPORTUNITY

The heliocentric geometry for the 28-month 1996 multiple Venus opportunity is shown in Figure VII-5. The flight profile for this triple swingby mission departs significantly from the geometries associated with all other multiple Venus missions thus far identified. The trajectory segment from Earth to first Venus swingby is Type I. Second Venus swingby occurs one Venus period later with both the spacecraft and Venus completing exactly one solar revolution. Two complete solar revolutions of the spacecraft and one complete solar revolution of Venus occur between second and third Venus encounters. The combination of Venus positions at the respective swingbys and Mercury position at encounter results in a Type I transfer of 135^{o} from Venus to Mercury, rather than the nearly 180^{o} transfers associated with other high-performance opportunities.

Performance parameters for the 1996 mission opportunity are presented in Figure VII-6 . The behavior of the relative velocity at Mercury encounter is unusual in that useful values of relative arrival velocity are achievable over an unusually wide range of Earth launch dates (1-4 to 2-14). Additionally, relative swingby velocities at Venus are considerably lower (8.0 km/sec) than for other multiple Venus swingby opportunities (10.6 to 11.0 km/sec). The launch energy behavior also differs quite significantly from that of other missions thus far identified. Not only is the required launch energy radically reduced from that of other multiple Venus opportunities, but it also appears to be nearly independent of Mercury arrival date.

A conflict between relative arrival velocity and launch energy is evident in Figure VII-6. The lower values of arrival velocity occur at the earlier launch dates while the lower values of launch energy occur at the later launch dates, where swingby altitude decreases until, at launch dates later than 2-14-96, the useful ballistic trajectories have swingby altitudes less than the required 250 km. The low launch energy requirements have a dominating effect upon the mission performance, placing the upper end of the best performance 15-day launch period at the 2-14-96 launch date, where the swingby altitude is constrained at 250 kilometers. Performance for the 1996 triple Venus swingby opportunity is shown in Figure I-1. Indicated performance is comparable to that of the high-performance 1994 opportunity.

Tabulated details of a representative ballistic trajectory for the 1996 opportunity are shown in Table VII-3. This representative case has an Earth launch date of 2-9-96 and a Mercury arrival date of 5-30-98. A description of the parameters listed in Table VII-3 is included in Section I of the Appendix.



E_L: EARTH AT LAUNCH, 2-9-96

E_{V_1}: EARTH AT FIRST VENUS SWINGBY (V_1), 6-21-96

E_{V_2}: EARTH AT SECOND VENUS SWINGBY (V_2), 2-1-97

E_{V_3}: EARTH AT THIRD VENUS SWINGBY (V_3), 4-1-98

E_M: EARTH AT MERCURY ENCOUNTER (M), 5-30-98

(1) ONE COMPLETE SOLAR REVOLUTION BETWEEN FIRST AND SECOND VENUS SWINGBYS

(2) TWO COMPLETE SOLAR REVOLUTIONS BETWEEN SECOND AND THIRD VENUS SWINGBYS

Figure VII-5 Heliocentric Geometry, 1996 Multiple Venus Swingby Opportunity

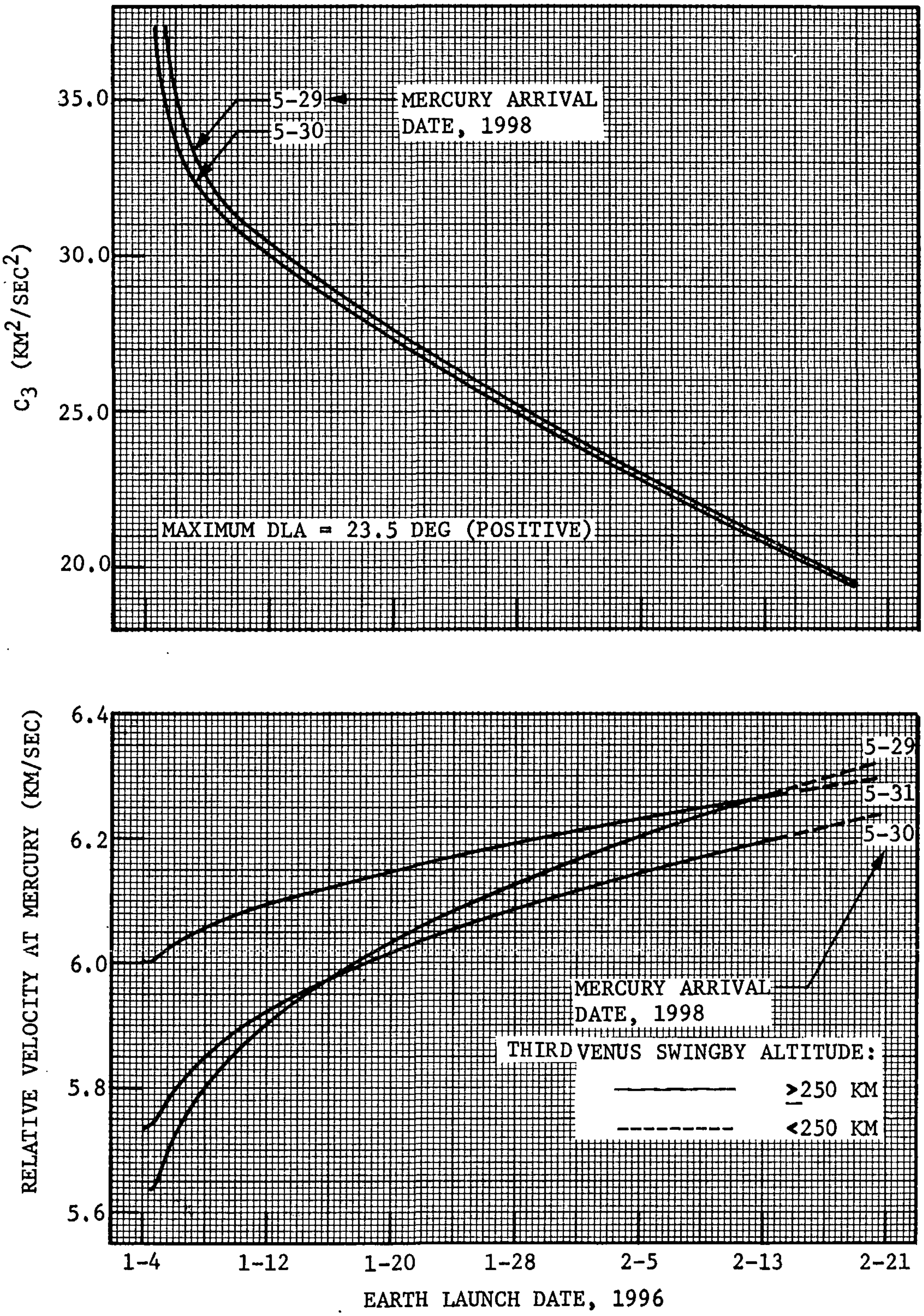


Figure VII-6 Relative Velocity at Mercury and C_3 vs Launch/Arrival Date, 1996 Multiple Venus Swingby Opportunity

```
JD=2450122.500   C3=  21.803  FLT TIM= 133.328   FEB  9 1996  0, 0, 0.
ECLIPTIC            X                 Y                  Z                 TOTAL
R EARTH    -1.1027104E+08    9.8078381E+07    -9.1132275E+03     1.4757734E+08
V EARTH    -2.0284832E+01   -2.2359537E+01     2.5523080E-03     3.0189788E+01
VEL S/C    -2.0319608E+01   -1.7763165E+01    -8.1893047E-01     2.7001614E+01
VHE        -3.4776287E-02    4.5963723E+00    -8.2148278E-01     4.6693342E+00
RAA= 90.433 DECA=-10.133        SEVHE= 48.717
EQUATORIAL          X                 Y                  Z                 TOTAL
R EARTH    -1.1027104E+08    8.9989342E+07     3.8509320E+07     1.4757734E+08
V EARTH    -2.0284832E+01   -2.0515618E+01    -8.9822548E+00     3.0189788E+01
VEL S/C    -2.0319608E+01   -1.5971746E+01    -7.9078506E+00     2.7001614E+01
VHE        -3.4776287E-02    4.5438717E+00     1.0744042E+00     4.6693342E+00
RAA= 90.439 DECA= 13.303 RP= 96095103.72 APO=152090588.68
A=124092846.20 E= .22562 I=  1.751 NODE=318.233 W= 26.603
TH1= 153.5   TH2= 291.4   DTH= 137.9   TYPE    I

JD=2450255.828 VHA=  7.852 VHD=  7.852  JUN 21 1996  7, 51, 49.575
ECLIPTIC            X                 Y                  Z                 TOTAL
R VENUS     1.1878005E+07   -1.0813779E+08    -2.2242019E+06     1.0881091E+08
V VENUS     3.4574833E+01    3.7021326E+00    -1.9375489E+00     3.4826411E+01
V S/C A     3.5339530E+01    1.0956256E+01     9.6959799E-01     3.7011647E+01
VHA         7.6469683E-01    7.2541231E+00     2.9071469E+00     7.8522969E+00
V S/C D     3.2874230E+01    1.1365268E+01    -1.7304912E+00     3.4826411E+01
VHD        -1.7006024E+00    7.6631355E+00     2.0705775E-01     7.8522969E+00
RCA= 17221.5    BTH=314.2     B*T=     15250     B*R=    -15668    HCA= 11171.5
RAA=  84.0 DECA=  21.7 SPA=  23.8 FPA= 152.8 CPA=  98.4   TYPE  I
RAE= 251.8 DECE=   2.8 RAS=  96.3 DECS=   1.2
AH=      5268.7 EH=  4.26864 I=  49.6 NODE= 283.8 W= 137.4 TAU=  76.5
A=108209145.2 E=     .220330 I=   3.4 NODE= 436.1 W= 304.3 TURN=  27.1
THI= 255.9 THF= 255.9 DTH= 360.  FLT TIM= 224.702
PERIHELION= 84367434.2  APHELION=132050856.3

JD=2450480.529 VHA=  7.852 VHD=  7.852  FEB  1 1997  0, 42,  7.693
ECLIPTIC            X                 Y                  Z                 TOTAL
R VENUS     1.1878005E+07   -1.0813779E+08    -2.2242019E+06     1.0881091E+08
V VENUS     3.4574833E+01    3.7021326E+00    -1.9375489E+00     3.4826411E+01
V S/C A     3.2874230E+01    1.1365268E+01    -1.7304912E+00     3.4826411E+01
VHA        -1.7006024E+00    7.6631355E+00     2.0705775E-01     7.8522969E+00
V S/C D     2.7973678E+01    7.9316824E+00    -1.4970843E+00     2.9114936E+01
VHD        -6.6011547E+00    4.2295498E+00     4.4046462E-01     7.8522828E+00
RCA=  8548.8    BTH=  3.0     B*T=     12756     B*R=       678    HCA=  2498.8
RAA= 102.5 DECA=   1.5 SPA=   6.3 FPA=  13.9 CPA=  77.3   TYPE VI    I
RAE= 116.3 DECE=    .5 RAS=  96.3 DECS=   1.2
AH=      5268.7 EH=  2.62256 I=   3.4 NODE=  76.1 W=   4.0 TAU=  67.6
A= 83380777.4 E=     .343005 I=   3.4 NODE= 436.1 W=   1.0 TURN=  44.8
THI= 199.2 THF= 519.5 DTH= 320.3 FLT TIM= 424.422
PERIHELION= 54780730.3  APHELION=111980824.5
```

TABLE VII-3 TRAJECTORY PRINTOUT 2-9-96 LAUNCH

```
JD=2450904.951 VHA=  7.830 VHD=  7.830  APR  1 1998 10, 49, 55.609
ECLIPTIC          X                   Y                   Z                 TOTAL
R VENUS    -5.9631630E+07    -9.0502188E+07    2.1429133E+06    1.0840281E+08
V VENUS     2.8998115E+01    -1.9426385E+01   -1.9460505E+00    3.4958007E+01
V S/C A     2.1210534E+01    -2.0117250E+01   -1.5074058E+00    2.9272219E+01
VHA        -7.7875814E+00    -6.9086535E-01    4.3864467E-01    7.8304615E+00
V S/C D     2.3610180E+01    -1.3752827E+01   -2.2582440E+00    2.7416793E+01
VHD        -5.3879353E+00     5.6735580E+00   -3.1219355E-01    7.8304899E+00
RCA=  6827.0   BTH=185.4    B*T=    -10857    B*R=     -1035    HCA=   777.0
RAA= 185.1 DECA=   3.2 SPA= 128.5 FPA=  41.4 CPA=  90.9   TYPE  I
RAE= 143.9 DECE=  -1.1 RAS=  56.6 DECS=  -1.1
AH=      5298.1 EH=  2.28858 I= 173.7 NODE= 334.6 W= 123.5 TAU=  64.1
A= 78212198.5 E=     .389519 I=    4.8 NODE= 430.2 W= 341.2 TURN=  51.8
THI= 185.1 THF= 320.6 DTH= 135.5 FLT TIM=  58.549
PERIHELION= 47747060.1  APHELION=108677337.0

JD=2450963.500     VHP=  6.170    MAY 30 1998  0, 0, 0.
ECLIPTIC           X                   Y                   Z                TOTAL
R MERCURY  4.9718011E+07     1.0731146E+07    -3.6268903E+06    5.0992082E+07
V MERCURY -1.9675323E+01     4.9913895E+01     5.9133943E+00    5.3976694E+01
V S/C     -2.2862201E+01     5.4538361E+01     3.3586803E+00    5.9231696E+01
VHP       -3.1868780E+00     4.6244657E+00    -2.5547140E+00    6.1699626E+00
RAA= 124.6    DECA= -24.5    SPA=  71.6    FPA= 108.3    CPA=  52.4
RAE= 234.2    DECE=   1.1    RAS=-167.8    DECS=    4.1
EQUATORIAL         X                   Y                   Z                TOTAL
R MERCURY  4.3897345E+07     2.5946397E+07    -2.9802322E-08    5.0992082E+07
V MERCURY -3.4905868E+01     4.1171153E+01     5.6843419E-14    5.3976694E+01
V S/C     -3.9079411E+01     4.4395250E+01    -3.2023708E+00    5.9231696E+01
VHP       -4.1735428E+00     3.2240969E+00    -3.2023708E+00    6.1699626E+00
RAA= 142.3  DECA= -31.3  RAS=-149.4  DECS=     .0  RAE= 252.6  DECE=   1.9
MERCURY OP         X                   Y                   Z                TOTAL
R MERCURY  4.1755420E+07    -2.9269051E+07    -2.9802322E-08    5.0992082E+07
V MERCURY  2.3087013E+01     4.8790095E+01     5.6843419E-14    5.3976694E+01
V S/C      2.4300392E+01     5.3922440E+01    -3.2023708E+00    5.9231696E+01
VHP        1.2133787E+00     5.1323457E+00    -3.2023708E+00    6.1699626E+00
RAA=  76.7  DECA= -31.3  RAS= 145.0  DECS=     .0  RAE= 187.0  DECE=   1.9
```

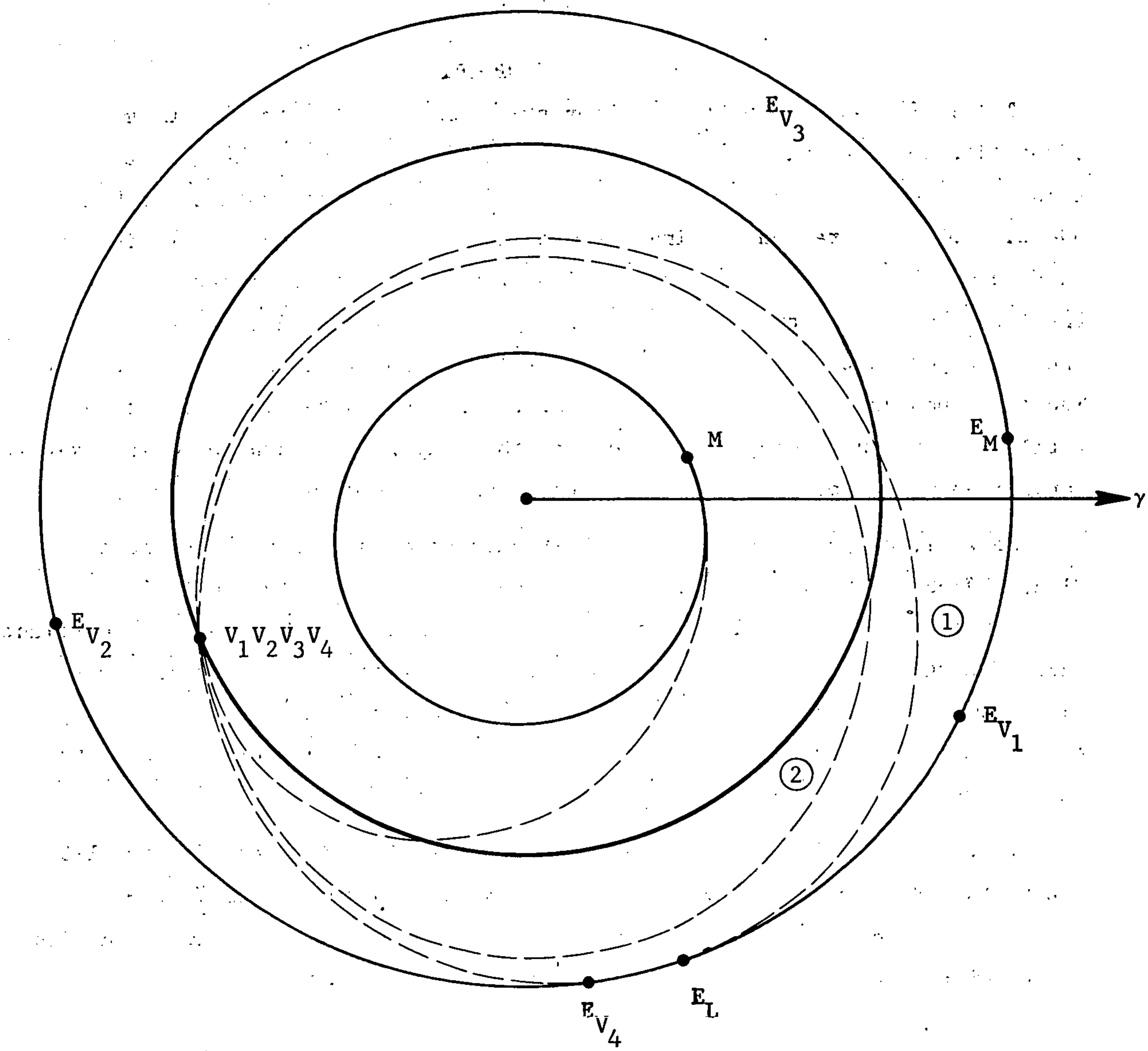
TABLE VII-3 TRAJECTORY PRINTOUT 2-9-96 LAUNCH (Continued)

D. 1999 MISSION OPPORTUNITY

The 1999 mission opportunity represents the only multiple Venus mission identified to date which incorporates four Venus swingbys. The geometry of this 39-month mission is similar to the 1983 heliocentric profile, with the addition of an extra Venus swingby to accommodate planet phasing, as indicated in Figure VII-7. An extra phasing revolution is also incorporated prior to the first Venus swingby. Successive swingbys are displaced in time by exactly one Venus period with Venus at the same ecliptic longitude at each encounter. The extra phasing orbit prior to the first swingby and the inclusion of a total of four Venus swingbys account for the long flight duration. As a result, Mercury encounter occurs late in the year 2002.

Performance parameters for the 1999 mission opportunity are presented in Figure VII-8. The maximum relative arrival velocity for the best 15-day launch period is comparable to that of the 1994 mission, with nearly equivalent launch energies. Verified minimum mission performance, therefore, is almost as high as that for the 1994 multiple Venus opportunity (fig. I-1). A Mercury arrival date of 9-30-2002 appears to yield near-optimum performance over the entire best 15-day launch interval.

Tabulated details of a representative ballistic trajectory for the 1999 opportunity are shown in Table VII-4. The Earth launch date is 7-13-99 with a Mercury arrival date of 9-30-2002. Section 1 of the Appendix contains the print key which defines each of the listed parameters.



E_L: EARTH AT LAUNCH, 7-13-1999

E_{V_1}: EARTH AT FIRST VENUS SWINGBY (V_1), 8-26-2000

E_{V_2}: EARTH AT SECOND VENUS SWINGBY (V_2), 4-7-2001

E_{V_3}: EARTH AT THIRD VENUS SWINGBY (V_3), 11-18-2001

E_{V_4}: EARTH AT FOURTH VENUS SWINGBY (V_4), 7-1-2002

E_M: EARTH AT MERCURY ENCOUNTER (M), 9-30-2002

(1) ONE COMPLETE SOLAR REVOLUTION BEFORE FIRST VENUS SWINGBY

(2) ONE COMPLETE SOLAR REVOLUTION BETWEEN EACH VENUS SWINGBY

Figure VII-7 Heliocentric Geometry, 1999 Multiple Venus Swingby Opportunity

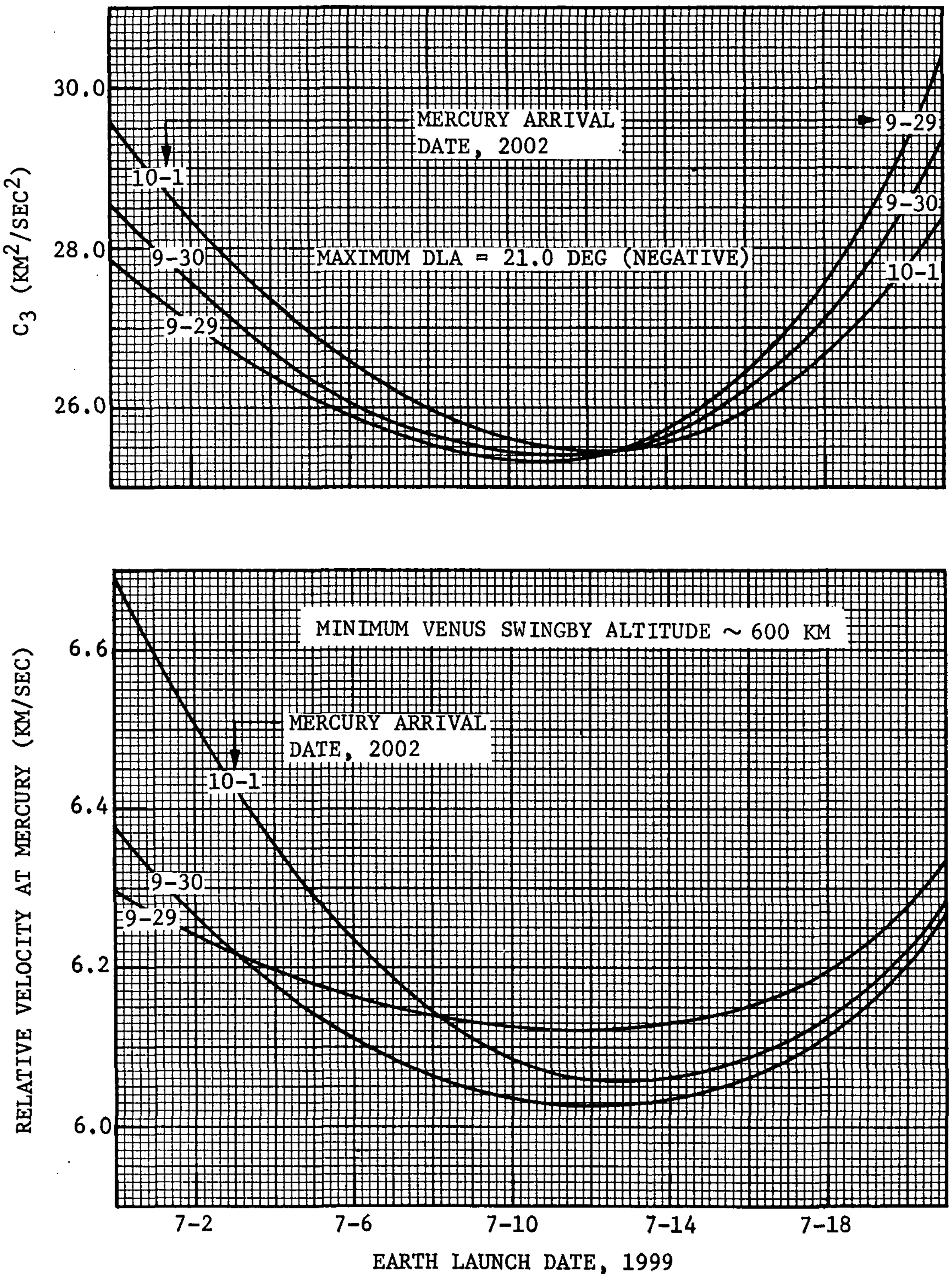


Figure VII-8 Relative Velocity at Mercury and C_3 vs Launch/Arrival Date, 1999 Multiple Venus Swingby Opportunity

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```
JD=2451372.500   C3=  25.490  FLT TIM= 410.341   JUL 13 1999  0, 0, 0.
ECLIPTIC           X                    Y                    Z                  TOTAL
R EARTH     4.9374133E+07   -1.4383868E+08    1.5617077E+04    1.5207686E+08
V EARTH     2.7687755E+01    9.5706545E+00   -1.3873278E-03    2.9295208E+01
VEL S/C     2.2915850E+01    8.3956636E+00   -1.1580571E+00    2.4432856E+01
VHE        -4.7719049E+00   -1.1749909E+00   -1.1566698E+00    5.0487192E+00
RA A=193.833 DECA=-13.244       SEVHE= 94.978
EQUATORIAL         X                    Y                    Z                  TOTAL
R EARTH     4.9374133E+07   -1.3197710E+08   -5.6959765E+07    1.5207686E+08
V EARTH     2.7687755E+01    8.7815536E+00    3.9386801E+00    2.9295208E+01
VEL S/C     2.2915850E+01    8.1635780E+00    2.3871427E+00    2.4432856E+01
VHE        -4.7719049E+00   -6.1797561E-01   -1.5515375E+00    5.0487192E+00
RA A=187.379 DECA=-17.872 RP= 78985915.09 APO=152146020.93
A=115565968.01 E= .31653 I=  2.717 NODE=289.069 W=182.415
TH1= 182.5   TH2= 456.7   DTH= 274.2   TYPE   IV     I

JD=2451782.841 VHA= 11.083 VHD= 11.083  AUG 26 2000  8, 11, 13.056
ECLIPTIC           X                    Y                    Z                  TOTAL
R VENUS    -9.9197151E+07   -4.2350997E+07    5.1061077E+06    1.0798034E+08
V VENUS     1.3509018E+01   -3.2366853E+01   -1.2390403E+00    3.5094757E+01
V S/C A     3.1864630E+00   -3.6047047E+01    4.1599504E-01    3.6190002E+01
VH A       -1.0322555E+01   -3.6801944E+00    1.6550354E+00    1.1083235E+01
V S/C D     2.8646425E+00   -3.4975199E+01    4.1381075E-01    3.5094757E+01
VH D       -1.0644375E+01   -2.6083459E+00    1.6528511E+00    1.1083235E+01
RC A= 49737.5    BTH=179.7     B*T=   -52314     B*R=         296    HCA= 43687.5
RA A= 199.6 DECA=    8.6 SPA= 173.2 EPA= 152.6 CPA=  99.6   TYPE  I
RA E= 353.1 DECE=  -1.2 RAS=  23.1 DECS=  -2.7
AH=       2644.6 EH= 19.80703 I= 171.4 NODE= 287.5 W=  85.0 TAU=  87.1
A=108209149.3 E=     .316452 I=    2.7 NODE= 109.1 W= 346.0 TURN=   5.8
THI= 108.1 THF= 108.1 DTH= 360.  FLT TIM= 224.702
PERIHELION= 73966190.3  APHELION=142452108.3

JD=2452007.543 VHA= 11.083 VHD= 11.083  APR  8 2001  1,  1, 32.264
ECLIPTIC           X                    Y                    Z                  TOTAL
R VENUS    -9.9197151E+07   -4.2350997E+07    5.1061077E+06    1.0798034E+08
V VENUS     1.3509018E+01   -3.2366853E+01   -1.2390403E+00    3.5094757E+01
V S/C A     2.8646425E+00   -3.4975199E+01    4.1381075E-01    3.5094757E+01
VH A       -1.0644375E+01   -2.6083459E+00    1.6528511E+00    1.1083235E+01
V S/C D     2.7419258E+00   -3.4943253E+01   -1.7586599E+00    3.5094757E+01
VH D       -1.0767092E+01   -2.5763997E+00   -5.1961959E-01    1.1083235E+01
RC A= 24293.5    BTH=268.4     B*T=     -746     B*R=     -26798    HCA= 18243.5
RA A= 193.8 DECA=    8.6 SPA= 169.0 EPA=  19.3 CPA=  98.2   TYPE  I
RA E= 181.8 DECE=  -6.6 RAS=  23.1 DECS=  -2.7
AH=       2644.6 EH= 10.18501 I=  91.6 NODE=  13.5 W= 165.8 TAU=  84.4
A=108209149.3 E=     .316380 I=    4.8 NODE= 417.6 W= 235.4 TURN=  11.3
THI= 108.1 THF= 108.1 DTH= 360.  FLT TIM= 224.702
PERIHELION= 73973976.2  APHELION=142444322.4
```

TABLE VII-4 TRAJECTORY PRINTOUT 7-13-99 LAUNCH

```
JD=2452232.244 VHA= 11.083 VHD= 11.083  NOV 18 2001 17, 51, 51.472
ECLIPTIC          X                  Y                  Z                 TOTAL
R VENUS     -9.9197151E+07    -4.2350997E+07     5.1061077E+06     1.0798034E+08
V VENUS      1.3509018E+01    -3.2366853E+01    -1.2390403E+00     3.5094757E+01
V S/C A      2.7419258E+00    -3.4943253E+01    -1.7586599E+00     3.5094757E+01
VHA         -1.0767092E+01    -2.5763997E+00    -5.1961959E-01     1.1083235E+01
V S/C D      3.0182859E+00    -3.4745623E+01    -3.9081427E+00     3.5094757E+01
VHD         -1.0490732E+01    -2.3787701E+00    -2.6691024E+00     1.1083235E+01
RCA= 24293.5    BTH=266.6     B*T=     -1583    B*R=    -26761    HCA= 18243.5
RAA= 193.5 DECA=  -2.7 SPA= 168.9 EPA= 151.5 CPA=  87.2   TYPE  I
RAE=  41.7 DECE=  -1.2 RAS=  23.1 DECS=  -2.7
AH=     2644.6 EH= 10.18601 I=  93.4 NODE=  13.6 W= 177.1 TAU=  84.4
A=108209149.3 E=     .304041 I=   8.1 NODE= 402.7 W= 250.3 TURN=  11.3
THI= 270.0 THF= 270.0 DTH= 360.  FLT TIM= 224.702
PERIHELION= 75309142.3  APHELION=141109156.3

JD=2452456.946 VHA= 11.083 VHD= 11.082  JUL  1 2002 10, 42, 10.680
ECLIPTIC          X                  Y                  Z                 TOTAL
R VENUS     -9.9197151E+07    -4.2350997E+07     5.1061077E+06     1.0798034E+08
V VENUS      1.3509018E+01    -3.2366853E+01    -1.2390403E+00     3.5094757E+01
V S/C A      3.0182859E+00    -3.4745623E+01    -3.9081427E+00     3.5094757E+01
VHA         -1.0490732E+01    -2.3787701E+00    -2.6691024E+00     1.1083235E+01
V S/C D      3.3480468E+00    -2.8510264E+01    -3.4073031E+00     2.8907685E+01
VHD         -1.0160971E+01     3.8565894E+00    -2.1682628E+00     1.1082417E+01
RCA=  6713.4    BTH=179.3     B*T=     -8976    B*R=       114    HCA=    663.4
RAA= 192.8 DECA= -13.9 SPA= 160.4 EPA= 123.6 CPA=  76.1   TYPE  I
RAE= 318.1 DECE=  -1.8 RAS=  23.1 DECS=  -2.7
AH=     2644.6 EH=  3.53851 I= 166.0 NODE= 105.8 W= 256.5 TAU=  73.6
A= 81798495.2 E=     .412615 I=   8.3 NODE= 402.1 W=   6.7 TURN=  32.8
THI= 154.2 THF= 326.1 DTH= 171.9 FLT TIM=  90.554
PERIHELION= 48047213.5  APHELION=115549776.9

JD=2452547.500     VHP=  6.029    SEP 30 2002  0, 0, 0.
ECLIPTIC          X                  Y                  Z                 TOTAL
R MERCURY    4.8722016E+07     1.3102915E+07    -3.3397356E+06     5.0563575E+07
V MERCURY   -2.2060069E+01     4.9335153E+01     6.0820920E+00     5.4383782E+01
V S/C       -2.4617553E+01     5.4336182E+01     8.2737830E+00     6.0223750E+01
VHP         -2.5574840E+00     5.0010296E+00     2.1916910E+00     6.0294719E+00
RAA= 117.1    DECA=  21.3    SPA=  77.4    EPA= 113.9    CPA=  97.5
RAE=    .5    DECE=   1.9    RAS=-164.9    DECS=   3.8
EQUATORIAL        X                  Y                  Z                 TOTAL
R MERCURY    4.1868039E+07     2.8350352E+07     0.                5.0563575E+07
V MERCURY   -3.7431361E+01     3.9452363E+01     2.8421709E-14     5.4383782E+01
V S/C       -4.1704038E+01     4.3420258E+01     1.5344650E+00     6.0223750E+01
VHP         -4.2726764E+00     3.9678943E+00     1.5344650E+00     6.0294719E+00
RAA= 137.1   DECA=  14.7   RAS=-145.9   DECS=  -0.    RAE=  20.1   DECE=   7.0
MERCURY OP        X                  Y                  Z                 TOTAL
R MERCURY    4.2841579E+07    -2.6856549E+07     0.                5.0563575E+07
V MERCURY    2.0979930E+01     5.0174080E+01     2.8421709E-14     5.4383782E+01
V S/C        2.2884841E+01     5.5685093E+01     1.5344650E+00     6.0223750E+01
VHP          1.9049111E+00     5.5110128E+00     1.5344650E+00     6.0294719E+00
RAA=  70.9   DECA=  14.7   RAS= 147.9   DECS=  -0.    RAE= 313.9   DECE=   7.0
```

TABLE VII-4 TRAJECTORY PRINTOUT 7-13-99 LAUNCH (Continued)

APPENDIX

APPENDIX 1. TRAJECTORY TARGETING PROGRAM

As described in the original Handbook (NASA CR-2298) all tabular trajectory data presented in this document were generated with the MMC computer program AIMS (Advanced Interplanetary Mission Search). The only differences involve multiple Venus swingby dates and the option for a midcourse velocity maneuver, the strategy for which is described in Section IV-C. Selected trajectories from the 1985 opportunity with midcourse velocity maneuver and the 1983 and 1988 multiple Venus swingby opportunities which define the best performance 15-day launch period are tabulated in detail in Sections III through V. One sample trajectory from the 1980 single swingby with midcourse maneuver and the 1980, 1991, 1994, 1996, and 1999 multiple swingby opportunities is shown in Sections II and VII. The table below defines each parameter in that tabular data. The number of print blocks for each trajectory depends on the number of planet encounters and maneuvers. All units are km, kg, degrees, and seconds unless otherwise specified.

TABLE A-1

PRINT KEY FOR TABULAR DATA

- - - LAUNCH BLOCK - - -

JD	= Julian Date at launch
C3	= Twice the required launch energy
FLT TIM	= Time from Earth to Venus (days)
Calendar Date:	Month, day, year, hour, minutes, seconds

(The next six parameters are defined in ecliptic and equatorial coordinates)

R Earth	= Radius from Sun to Earth at launch
V Earth	= Velocity of Earth in Heliocentric coordinates
VEL S/C	= Velocity of Spacecraft (S/C) in Heliocentric coordinates
VHE	= Earth Relative Departure Velocity
RAA	= Right Ascension of V_{HE}
DECA	= Declination of V_{HE} (DECA in equatorial coordinates is commonly DLA).
SEVHE	= Angle between Earth-Sun line and V_{HE} (departure asymptote).
RP	= Perihelion of Earth-Venus (E-V) leg
APO	= Aphelion of E-V leg

TABLE A-1 (Continued)

A = Semi-major axis E-V leg

E = Eccentricity of E-V leg

(The following three parameters are defined in the ecliptic).

I = Inclination of E-V leg

NODE = Right Ascension of the ascending node of E-V leg

W = Argument of periapsis of E-V leg

TH1 = Initial true anomaly of E-V leg

TH2 - Final true anomaly of E-V leg

DTH = TH2 - TH1

TYPE DEFINITIONS

I - 0 < DTH < 180

II - 180 < DTH < 360

III - 360 < DTH < 540

IV - 540 < DTH < 720

V - 720 < DTH < 900

VI - 900 < DTH < 1080

If type is greater than two; a second Roman Numeral occurs.

I - indicates the left-hand solution

II - indicates the right-hand solution

from the Lancaster-Blanchard formulation of Lambert's Theorem.

- - - SWINGBY BLOCK - - -

JD = Julian Date at Venus closest approach

VHA = Venus relative approach velocity

VHD = Venus relative departure velocity

Calendar Date: Same as Launch Block

R Venus = Radius from Sun to Venus

V Venus = Heliocentric velocity of Venus

V S/C A = Heliocentric S/C approach velocity

V S/C D = Heliocentric S/C departure velocity

TABLE A-1 (Continued)

RCA	= Radius of closest approach to Venus
BTH	= B-plane aiming angle θ
B·T	= B-plane B·T
B·R	= B-plane B·R
HCA	= Altitude of closest approach to Venus Surface (6050 km Radius).

DATA PRESENTED IN ECLIPTIC COORDINATE SYSTEM (TRANSFERRED TO VENUS, PARALLEL TO ECLIPTIC)

RAA	= Right ascension of VHA (asymptote)
DECA	= Declination of VHA
SPA	= Sun-Venus-Asymptote (VHA) angle = 180-ZAP
EPA	= Earth-Venus-asymptote (VHA) angle = 180-ZAE
CPA	= Canopus-Venus-Asymptote (VHA) angle
TYPE	= Same as Launch Block but for Venus-Mercury leg
RAE	= Right ascension of Earth from Venus
DECE	= Declination of Earth from Venus
RAS	= Right Ascension of the Sun from Venus
DECS	= Declination of the Sun from Venus
AH	= Semi-major axis of Venus relative hyperbola
EH	= Eccentricity of Venus relative hyperbola
I	= Inclination of Venus relative hyperbola
NODE	= Right ascension of ascending node of Venus relative hyperbola
W	= Argument of periapsis of Venus relative hyperbola
TAU	= Angle between RCA and VHA at Venus
A,E,I, NODE, W	= Same as Launch Block but for Venus-Mercury (V-M) leg
TURN	= Turn Angle relative to Venus
THI	= Initial true anomaly for V-M leg
THF	= Final true anomaly for V-M leg
DTH	= THF-THI for V-M leg
FLT TIM	= Flight time of V-M leg (days)

TABLE A-1 (Continued)

PERIHELION	Of V-M leg
APHELION	Of V-M leg

- - - VENUS-SPHERE-EXIT MANEUVER BLOCK - - -

DV = ΔV_V

Includes minimum allowable and actual RCA at Venus.

- - - MIDCOURSE MANEUVER BLOCK - - -

JD	= Julian Date at Maneuver
DEL V	= Midcourse Velocity Maneuver
CALENDAR DATE	= Same as Launch Block
RADIUS	= Radius from Sun to Maneuver
V S/C B	= Heliocentric S/C Velocity Before Maneuver
V S/C A	= Heliocentric S/C Velocity After Maneuver
DEL VEL	= Midcourse Velocity Maneuver
A,E,I,NODE,W RP, APO TH1, TH2, DTH THPE	= Same as Launch Block but for Maneuver-Venus Leg

- - - ENCOUNTER BLOCK - - -

JD	= Julian Date at Mercury encounter
VHP	= Mercury approach velocity
Calendar Date:	See Launch Block

Data presented in 3 coordinate systems

ECLIPTIC	- Transferred to Mercury, Parallel to Ecliptic
EQUATORIAL	- Rotating Relative to Mercury Prime Meridian.
MERCURY OP	- Orbit plane with X-axis toward Mercury's ascending node (SP-35 Handbook Series used Mercury Perihelion Reference)
R-Mercury	= Sun-Mercury vector
V-Mercury	= Heliocentric velocity
V S/C	= Heliocentric S/C velocity

TABLE A-1 (Continued)

VHP	= Mercury relative S/C approach velocity
RAA	= Right Ascension of VHP
DECA	= Declination of VHP
SPA	= Sun-Mercury-Asymptote (VHP) angle = 180-ZAP
EPA	= Earth-Mercury-Asymptote angle = 180-ZAE
CPA	= Canopus-Mercury-Asymptote angle
RAE	= Right ascension of Earth from Mercury
DECE	= Declination of Earth from Mercury
RAS	= Right ascension of Sun from Mercury
DECS	= Declination of Sun from Mercury

2. Midcourse Maneuvers

The nature of planetary geometry misalignments for both the 1983 and 1988 multiple Venus mission opportunities suggests that midcourse maneuvers of the type incorporated in the 1985 opportunity (Sec. IV) might have application to these multiple swingby missions. The performance improvement potential of such maneuvers as applied to the 1983 and 1988 multiple Venus opportunities is the subject of this section. Investigation of midcourse maneuvers has led to a much better understanding of multiple-Venus flight techniques and an appreciation for the necessity of complete understanding of Venus arrival/departure characteristics.

In general, midcourse maneuvers may be used to alter ballistic trajectories in a number of ways. The discussion which follows concerns only maneuvers executed near spacecraft orbit perihelion or in the vicinity of Venus and designed to modify purely ballistic geometries. Maneuvers designed to correct for out-of-plane effects (broken-plane maneuvers) are not considered here. Midcourse maneuvers on both the Earth-Venus and Venus-Venus trajectory segments of the 1983 opportunity and on the Venus-Venus leg of the 1988 opportunity are treated.

The discussion of maneuver effectiveness is based primarily upon the Venus arrival/departure characteristics presented in Figures A-1 through A-5. These figures are indispensable for evaluating mission performance improvement potential of midcourse maneuvers and are useful in understanding planetary geometry conditions which affect multiple Venus mission performance. Midcourse maneuver potential is estimated by using these figures to assess the change in spacecraft relative velocity magnitude at Venus swingby required to effect a reduction in relative arrival velocity at Mercury for a given Mercury arrival date. The required change in relative velocity at Venus swingby, ΔV_{HV}, may be accomplished with the use of a maneuver in the vicinity of Venus (ΔV_V), executed entirely as a powered swingby maneuver. For such a maneuver, the magnitude required to effect a change in swingby relative velocity magnitude is equal to ΔV_{HV}. However, the same change in V_{HV} may, in general, be accomplished with less maneuver requirement when the maneuver is executed prior to Venus swingby near perihelion of the pre-Venus trajectory. The effect of such a midcourse maneuver (ΔV_{MC}) upon V_{HV} may be determined analytically. Typically, a value for $\Delta V_{HV}/\Delta V_{MC}$ of about 2 can be realized, as compared to $\Delta V_{HV}/\Delta V_V = 1$ for the powered swingby maneuver at Venus. Midcourse velocity maneuver effect upon arrival relative velocity at Mercury may then be determined by evaluating $\Delta V_{HM}/\Delta V_{MC} = \frac{\Delta V_{HM}}{\Delta V_{HV}} \cdot \frac{\Delta V_{HV}}{\Delta V_{MC}}$. This approach will first be used to evaluate mission improvement potential of midcourse maneuvers for the 1983 multiple Venus opportunity. A comparison of midcourse maneuver effectiveness vs ΔV_V effectiveness will then be made for the 1988 multiple Venus opportunity using a similar approach.

Venus arrival/departure characteristics for the 1983 mission are presented in Figures A-1 and A-2. Figure A-1 contains the information associated with Type I Venus-Mercury transfers, while Figure A-2 corresponds to Type II Venus-Mercury transfers. The best-performance launch period identified in Section III-2 consists entirely of the Type I transfer geometry. Although Type II ballistic solutions do exist over the same range of launch dates, they represent higher values of V_{HM} than the Type I solutions. As shown in Figure A-1, the intersections of the Earth-Venus trajectories with the Type I Venus-Mercury trajectories result in near-optimum Mercury arrival velocities. For example, the Earth-Venus ballistic trajectory with launch date of 7-8-83 intersects the Venus-Mercury ballistic trajectory with Mercury arrival date of 2-15-86 at a third Venus swingby date of about 11-18-85. The relative arrival velocity for a 2-15-86 Mercury date corresponding to this final-swingby date is about 6.5 km/s. However, if a final-swingby date of 11-20-85 is used, a V_{HM} of 5.9 km/s results. The ballistic Venus-Mercury trajectory for this swingby date and Mercury arrival date of 2-15-86 corresponds to a value of $V_{HV} \simeq 10.4$ km/s. For an Earth launch date of 7-8-83, the ballistic value of V_{HV} on the 11-20-85 swingby date is 10.9 km/s. This represents a ballistic mismatch in Venus arrival/departure velocities of $\Delta V_{HV} \simeq 0.5$ km/s. Since $\Delta V_{HV}/\Delta V_V = 1$, about 500 m/s is required if the mismatch is to be corrected by the application of a maneuver at Venus. Thus $\Delta V_{HM}/\Delta V_V \simeq 1.2$ for this Mercury date.

As stated previously, the ballistic mismatch at Venus swingby may also be corrected with the use of ΔV_{MC}. Analytical assessment of $\Delta V_{HV}/\Delta V_{MC}$ for

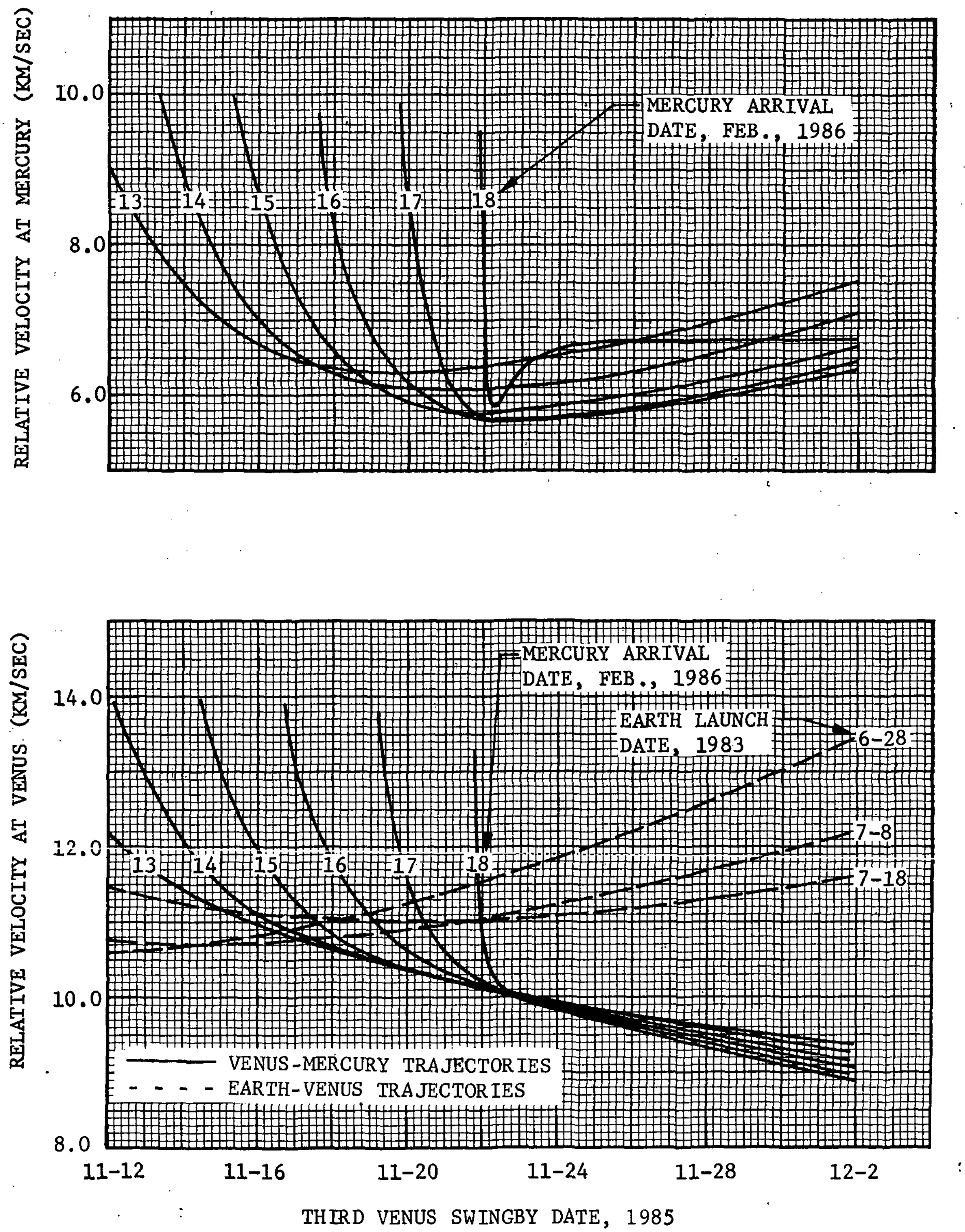

Figure A-1 Venus Arrival/Departure Characteristics, 1983 Multiple Venus Swingby Opportunity (Type I Venus-Mercury Transfer)

this opportunity yields a value of 1.8 when the midcourse maneuver is used prior to first swingby on the Earth-Venus leg and 2.1 when the maneuver is used between Venus swingbys. Thus, the maximum advantage of the midcourse maneuver in reducing relative arrival velocity at Mercury is $\Delta V_{HM}/\Delta V_{MC} \sim 2.5$. This value is a representative value for the various launch and arrival dates shown in Figure A-1, and is comparable to that for the 1985 opportunity with midcourse maneuver (Sec. IV), where the maneuver represented a very efficient means of improving mission performance. A similar maneuver used on either the Earth-Venus leg or between Venus swingbys for the 1983 opportunity has the same initial effect in reducing V_{HM}. However, the amount that the ballistic values of V_{HM} may be reduced in 1983 is small compared to 1985. Thus, the midcourse maneuver represents only modest potential for improvement of the near-optimum ballistic performance.

The Venus arrival/departure characteristics corresponding to Type II Venus-Mercury transfers for the 1983 multiple Venus opportunity are shown in Figure A-2. The ballistic Earth-Venus trajectories which match these ballistic Type II Venus-Mercury trajectories result in high values of relative arrival velocities for the Earth launch dates and Mercury arrival dates shown. Shifting swingby date to that corresponding to minimum V_{HM} by using a midcourse maneuver on either the Earth-Venus leg or between Venus swingbys requires a ΔV_{HV} of nearly 0.8 km/s in all cases shown. This requires 800 m/s ΔV_V or about 400 m/s ΔV_{MC}. The minimum relative arrival velocities which can be achieved are not as low as those which can be realized using the Type I Venus-Mercury transfer geometry discussed earlier. Therefore, use of a midcourse maneuver with the Type II geometries does not represent a favorable option, since lower arrival velocities may be achieved for less maneuver requirement using the Type I geometry.

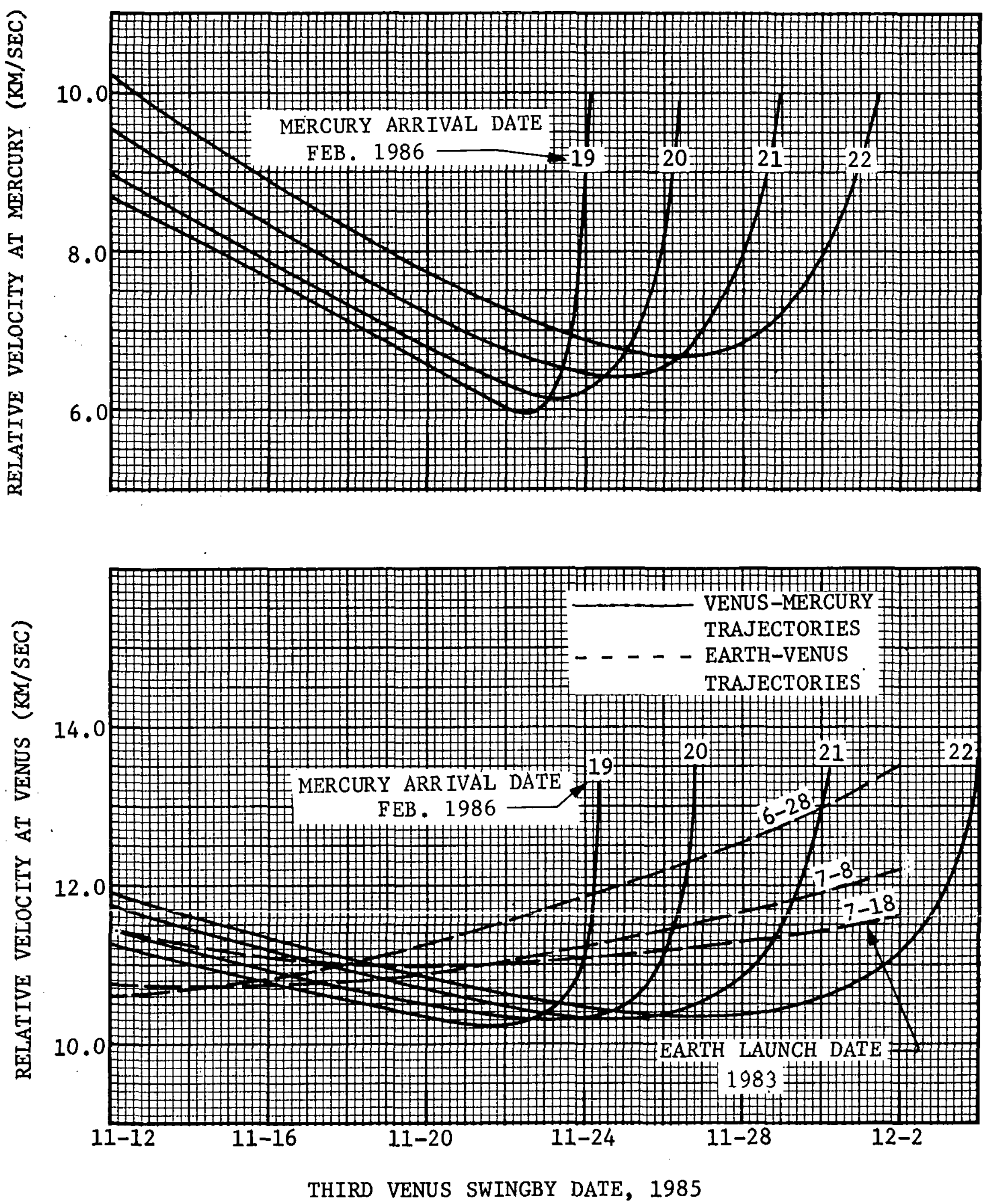

Figure A-2 Venus Arrival/Departure Characteristics, 1983 Multiple Venus Swingby Opportunity (Type II Venus-Mercury Transfer)

Assessment of midcourse maneuver potential for increasing mission performance for the 1988 multiple-Venus opportunity is complicated by the existance of an altitude constraint at first-Venus swingby (see Sec. V). The Venus arrival/departure characteristics for this mission are presented in Figures A-3 through A-5. Figure A-3 shows the nature of the altitude constraint at first-Venus swingby for several values of closest approach Venus altitude (HCA_V). Figure A-3 also depicts lines of constant first swingby date as well as contours of constant launch energy. As shown by Figures A-4 and A-5, the ballistic trajectories from Earth to Venus which match ballistic trajectories from Venus to Mercury have swingby altitudes at first Venus swingby of less than 250 km (assumed to represent a minimum practical value). Consequently, a radius-adjust maneuver is required over the entire launch period identified in Section V. The Mercury arrival velocities for this opportunity are near-optimum due to relatively good matches in arrival/departure conditions at second Venus swingby. It is the altitude constraint at first swingby with the associated radius-adjust maneuver (ΔV_V) which prevents mission performance from reaching maximum potential. Therefore, use of a near-perihelion maneuver was investigated as an alternate flight technique.

This analysis considered only ballistic trajectories from Earth to first Venus swingby which permit swingby altitudes greater than 250 km. In this manner, ΔV_V maneuvers to adjust swingby radius could be eliminated entirely and the effects of the midcourse maneuver assessed independently. Only midcourse maneuvers near perihelion of the Venus-Venus trajectory were considered, since the option of using a near-perihelion maneuver does not exist for the Type I Earth-Venus trajectory.

Referring to the ballistic Earth-Venus trajectories and the Type II Venus-Mercury trajectories shown in Figure A-4, it is desired to use ballistic Earth-Venus trajectories that lie within the region of acceptable altitude at first swingby ($HCA_V \geq 250$ km). This establishes the permissable ballistic combinations of relative velocity (VH_V), first Venus date, and second Venus date. The midcourse maneuver may then be used between Venus gravity assists to decrease relative velocity at second swingby in order to match ballistic Venus-Mercury trajectories which have low Mercury arrival velocities.

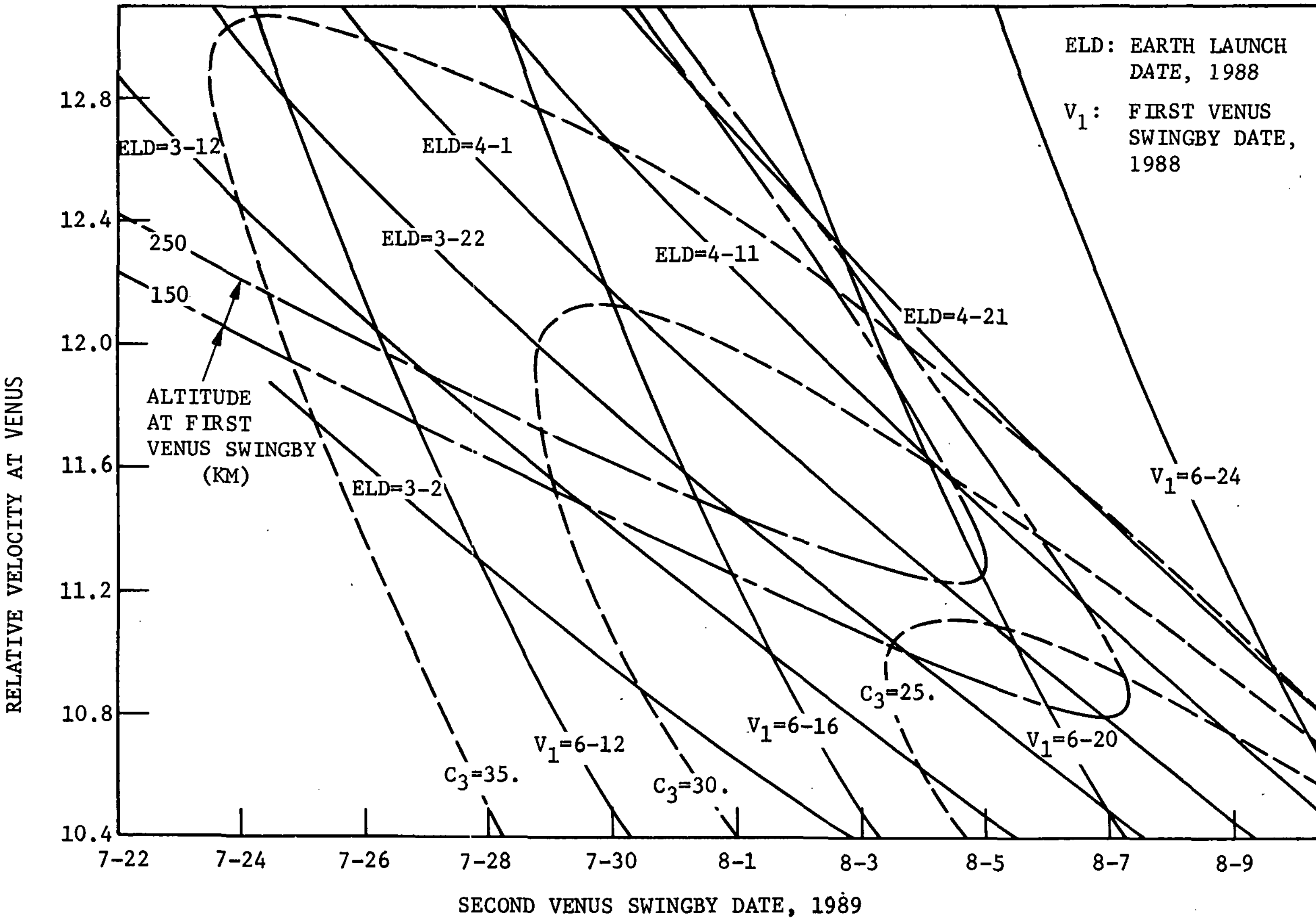

Figure A-3 Venus Arrival Contours, 1988
Multiple Venus Swingby Opportunity

For example, the Mercury arrival date of 3-27-90 reaches a minimum value of V_{HM} = 6.15 km/s for a second swingby date of 8-3-89. The value of V_{HV} on this date is 10.75 km/s. The swingby relative velocity for the ballistic Earth-Venus trajectory with HCA_V = 250 km on this date is 11.3 km/s, 550 m/s greater than the desired V_{HV}. Thus a 550 m/s maneuver (ΔV_v) at second Venus swingby would be required to match arrival/departure velocities for this date. Analytical assessment of $\Delta V_{HV}/\Delta V_{MC}$ for the near-perihelion maneuver yields a value of 3.5. (This unusually high value is due to the low perihelion radius of the Venus-Venus leg for this mission.) Therefore, a ΔV_{MC} of about 160 m/s is required to achieve minimum V_{HM} for a Mercury arrival date of 3-27-90. Similarly, Mercury arrival dates of 3-25, 3-26, and 3-28 require maneuvers of about 270 m/s, 230 m/s, and 150 m/s respectively. These values are comparable to the values of ΔV_v required when powered swingby maneuvers are executed at first Venus swingby to constrain swingby altitude. As a result, the use of the midcourse maneuver, ΔV_{MC}, offers no significant advantage over the use of ΔV_v.

The Venus arrival/departure characteristics for the Type I Venus-Mercury transfers are shown in Figure A-5. Analysis similar to that used above for the Type II geometry could be presented to evaluate midcourse maneuver effectiveness for the Type I geometry. However, it is clear from the figure that the mismatches (ΔV_{HV}) in Venus arrival/departure velocities are even greater than those for the Type II transfers. Consequently, greater ΔV_{MC} magnitudes would be required and midcourse maneuvers would be even less effective.

In summary, the use of midcourse maneuvers on the Earth-Venus or Venus-Venus trajectory segments of the 1983 opportunity have a modest potential for improving mission performance when used with the Type I Venus-Mercury transfer geometry. Midcourse maneuvers on the Venus-Venus leg of the 1988 opportunity have about the same advantage in producing low Mercury arrival velocities as the powered swingby maneuver at Venus. Since use of the midcourse maneuver technique does not significantly improve performance for these missions, no three-planet computer analyses were conducted.

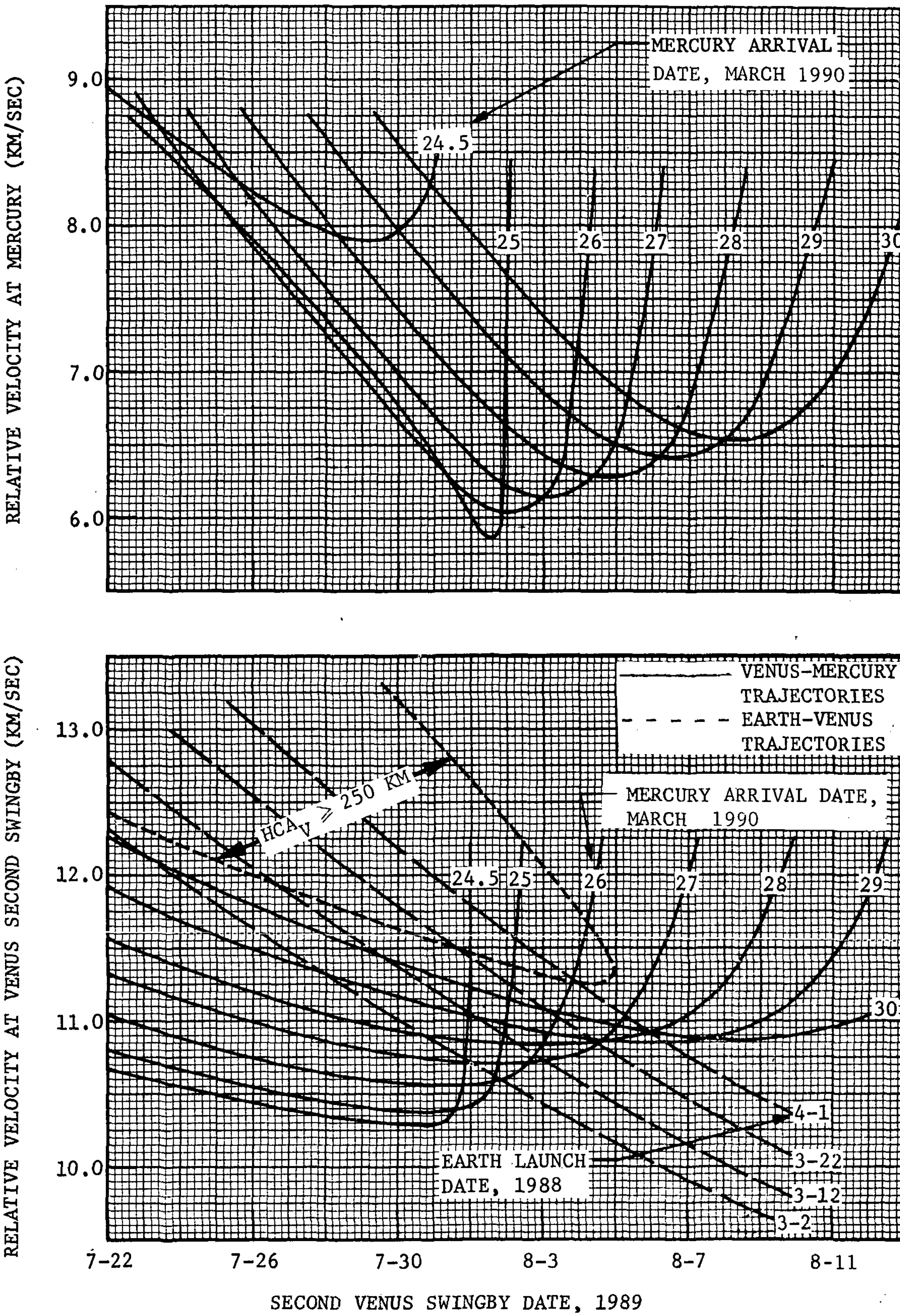

Figure A-4 Venus Arrival/Departure Characteristics, 1988 Multiple Venus Opportunity (Type II Venus-Mercury Transfer)

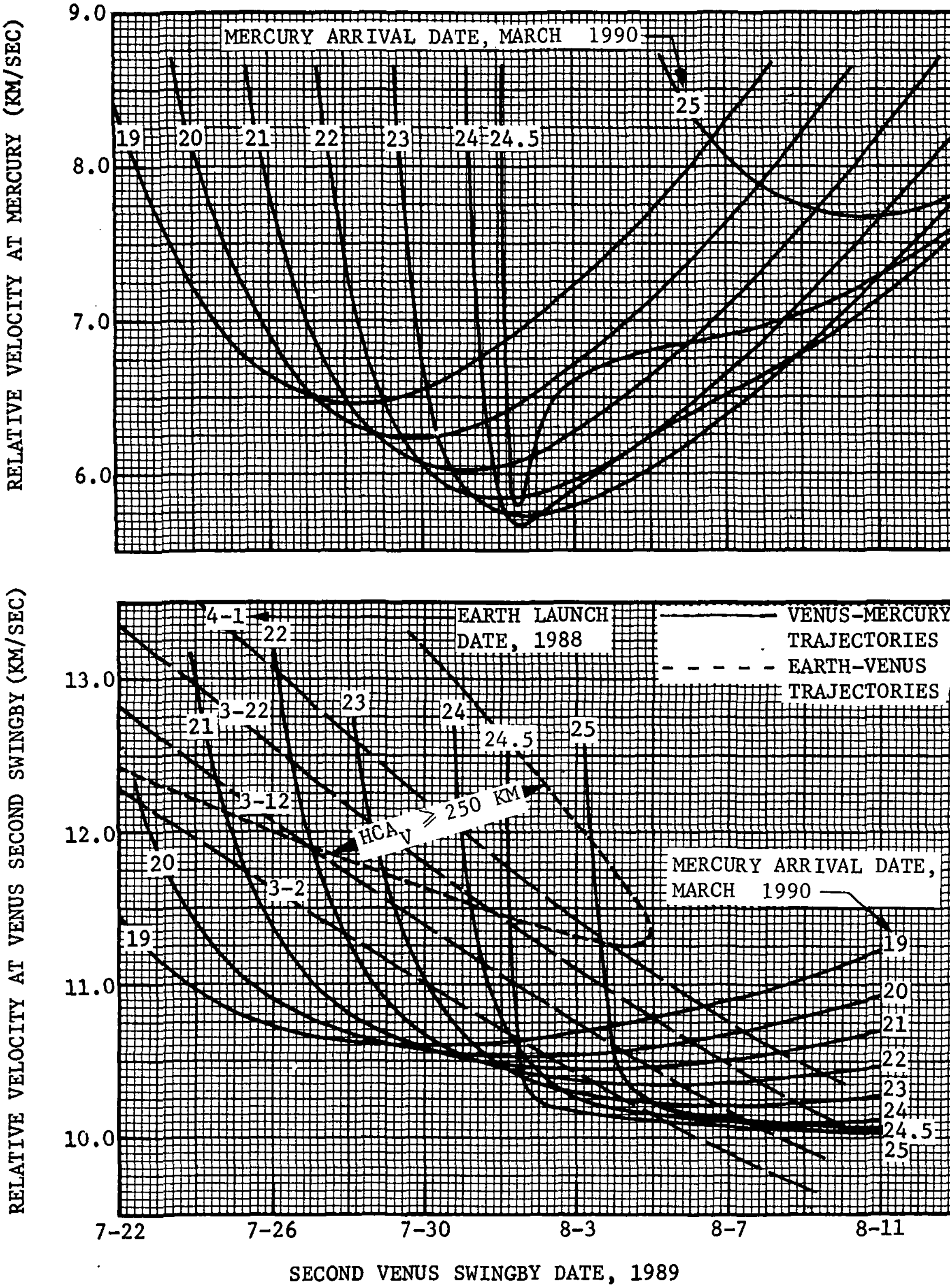

Figure A-5 Venus Arrival/Departure Characteristics, 1988 Multiple Venus Swingby Opportunity (Type I Venus-Mercury Transfer)

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