N73-32745
NASA CR-2298

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BALLISTIC MODE MERCURY ORBITER MISSION OPPORTUNITY HANDBOOK

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Prepared by
MARTIN MARIETTA CORPORATION
Denver, Colo.
for Ames Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1973

1. Report No. NASA CR-2298	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Ballistic Mode Mercury Orbiter Mission Opportunity Handbook		5. Report Date August 1973
		6. Performing Organization Code
7. Author(s) G. R. Hollenbeck, D. G. Roos, P. S. Lewis		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Martin Marietta Corporation Denver, Colorado		11. Contract or Grant No. NAS 2-7268
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics & Space Administration Washington, D.C.		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Significant payloads in Mercury Orbit can be achieved through use of high-thrust, chemical propulsion systems on ballistic trajectories. Interplanetary trajectory characteristics are presented, for Venus swingbys to Mercury, were multiple revolutions about the Sun are allowed on each leg to provide low energy missions in 1977, 1980, 1985, and 1988. Guidance and navigation results are shown for each opportunity. Additionally, the use of midcourse maneuvers and multiple Venus swingbys are explored as means of further reducing the energy requirements.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Mercury, Orbiter, Trajectory, Ballistic, Navigation	UNCLASSIFIED-UNLIMITED

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
UNCLASSIFIED	UNCLASSIFIED	129	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

This document was prepared under Contract No. NAS2-7268, Study of Ballistic Mode Mercury Orbiter Missions. Interplanetary trajectory characteristics are assembled in handbook format for four specific mission opportunities corresponding to launch in 1977, 1980, 1985 and 1988. Results of investigations of alternate flight techniques applicable to the baseline cases and to other mission opportunities are also reported.

A final report for the study contract will be published in July 1973. This latter document will include parametric analyses of Mercury orbit selection considerations and a review of critical technology requirements.

Credit is due Ms. Jill Strauss whose conscientious preparation of graphic material contributed significantly to the quality of this handbook.

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I. INTRODUCTION AND SUMMARY

Advanced missions to the planet Mercury have been addressed in terms of ballistic mode flight compatible with programmed launch vehicles and conventional spacecraft propulsion technologies. Data are presented to validate the performance feasibility of this approach and provide a basis for planning an orderly program of Mercury exploration.

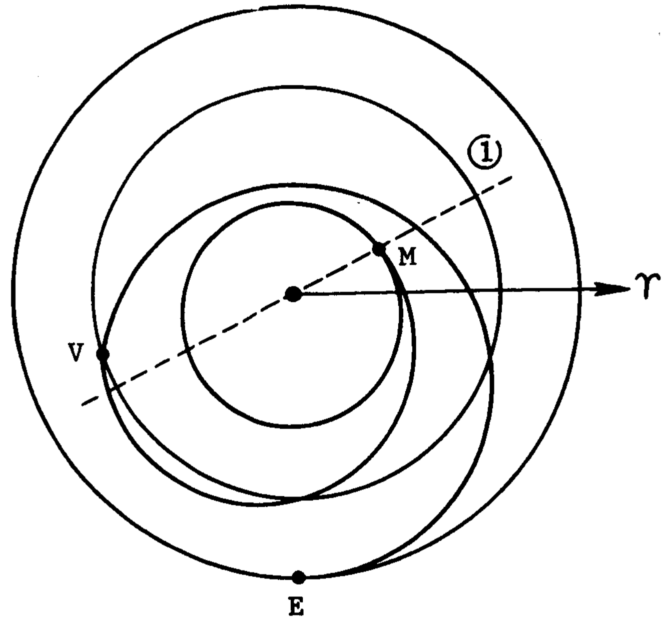
Previous investigations of the difficult Mercury orbiter mission have indicated that the ballistic mode would require a Saturn V class launch vehicle for adequate performance to support a useful mission. As a consequence, most recent effort has been oriented to use of Solar Electric Propulsion as a solution for the performance requirements.

More thorough analysis of the ballistic mode utilizing Venus gravity-assist has resulted in identification of timely, high-performance mission opportunities which are not dependent on extensive new developments. Characteristics of these mission opportunities are assembled in this document.

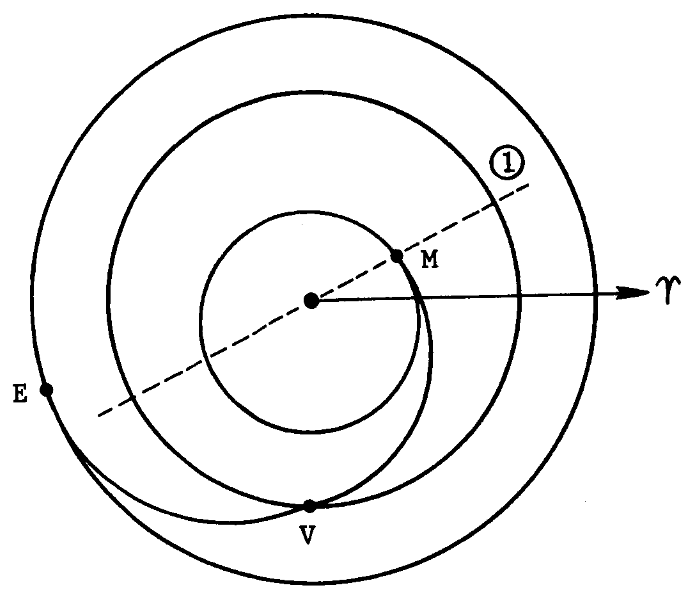
The basic technique employed for the mission opportunity search is depicted in Figure I-1. Idealized three-planet geometries corresponding to maximum utilization of Venus gravity-assist potential were determined. A basic consideration was the requirement to arrange for Mercury arrival to occur near Mercury perihelion. Moreover, arrival in proximity to the Venus-Mercury plane intersection is important to suppress the cross-plane component of encounter velocity. Two geometries satisfying the foregoing considerations are illustrated in Figure I-1. Of these, the Type I transfer case corresponds to a Venus position at swingby substantially displaced from the Mercury orbit plane. From this position, Venus gravity-assist cannot significantly remove the effects of the angle between the Venus and Mercury orbit planes (about 4.3 deg.).

The Type II transfer geometry is predicated on the same spacecraft orbit elements but with Venus closer to the Mercury orbit plane. From this position, Venus swingby can produce near-tangential encounter with Mercury. Accordingly, the search for near-ideal alignments of Earth, Venus, and Mercury was limited to the higher-potential Type II transfer geometry.

Four mission opportunities were identified in the time period following the MVM'73 flyby, namely: 1977, 1980, 1985, and 1988 launch. Of these, the latter three involve extra solar revolutions of the spacecraft to accommodate planet phasing. Resultant flight durations and event sequences are displayed in Figure I-2. Corresponding allowable spacecraft weights are presented for a



IDEALIZED TYPE II TRANSFER GEOMETRY



IDEALIZED TYPE I TRANSFER GEOMETRY

E: EARTH AT LAUNCH
V: VENUS AT SWINGBY
M: MERCURY AT ENCOUNTER
① INTERSECTION OF VENUS AND MERCURY ORBIT PLANES

Figure I-1. Mercury Orbiter Transfer Geometries consistent, conservative set of assumed conditions.

The Mercury orbiter mission opportunities depicted in Figure I-2 comprised the baseline for the study reported in this document. Trajectory characteristics and constraints for each opportunity have been defined and are presented in handbook format for use by mission analysts and spacecraft designers. Assessment of navigation requirements are included to demonstrate feasibility. The final report for this study contract will document parametric analyses of orbit selection considerations and a review of critical technology requirements.

As an adjunct to the basic study, exploratory investigations of two alternate flight techniques were conducted. These involved the use of midcourse propulsive maneuvers and multiple Venus swingby. The impact of these options is illustrated in Figure I-3 in context with the baseline mission opportunities. As shown, performance of the 1985 opportunity can be substantially improved by use of modest midcourse velocity maneuvers. Also, two new high-performance mission opportunities predicated on multiple Venus swingby have been identified for 1983 and 1988 launch. The capabilities depicted for the alternate flight techniques represent verified minimum potential without benefit of complete optimization.

CONDITIONS

TITAN IIIE/CENTAUR LAUNCH VEHICLE (MINIMUM PERFORMANCE)

15 DAY LAUNCH PERIOD

MIDCOURSE CORRECTIONS = 250 MPS TOTAL
(AUXILIARY PROPULSION SPECIFIC IMPULSE = 235 SEC)

MINIMUM VENUS SWINGBY ALTITUDE = 250 KM

MERCURY ORBIT PERIAPSIS ALTITUDE = 500 KM

MERCURY ORBIT ECCENTRICITY = 0.8 MAXIMUM

MERCURY ORBIT INSERTION PROPULSION: SINGLE STAGE SOLID
SPECIFIC IMPULSE = 290 SEC
MASS FRACTION = 0.93

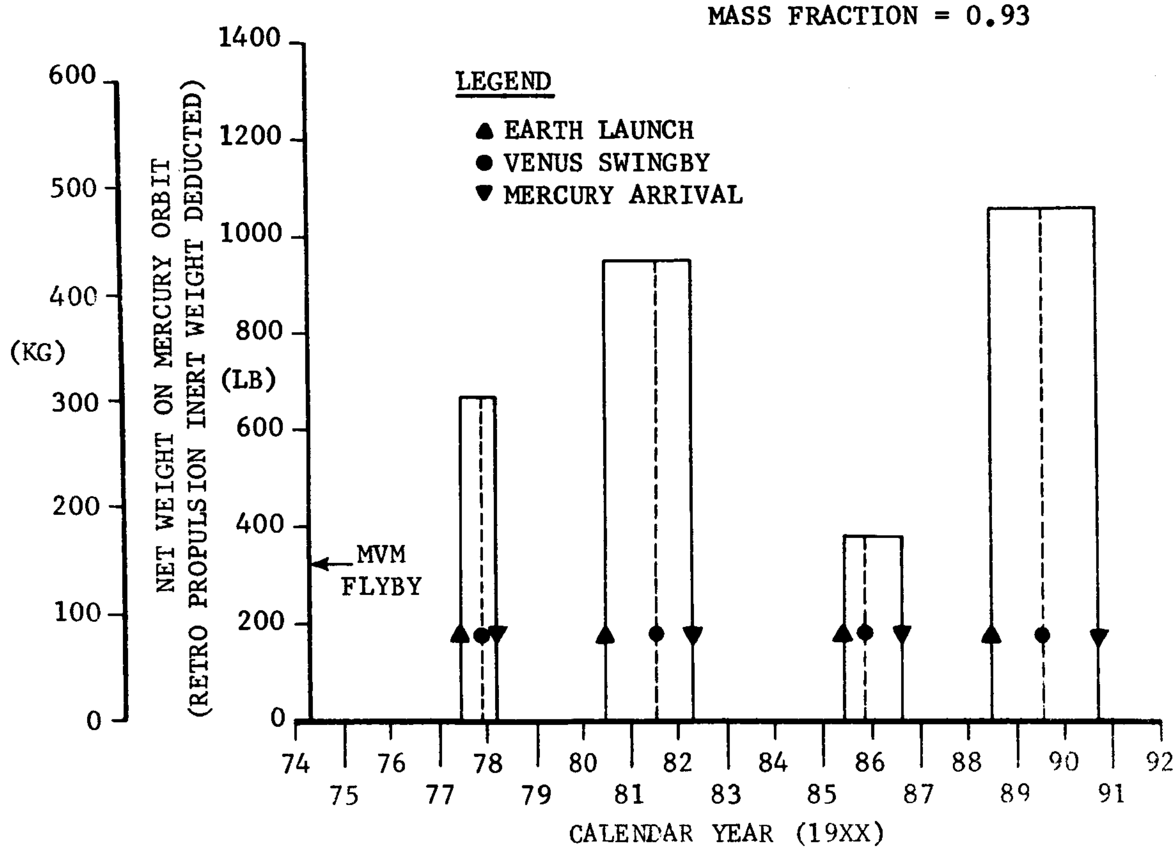


Figure 1-2. Follow-on Mercury Mission Opportunities

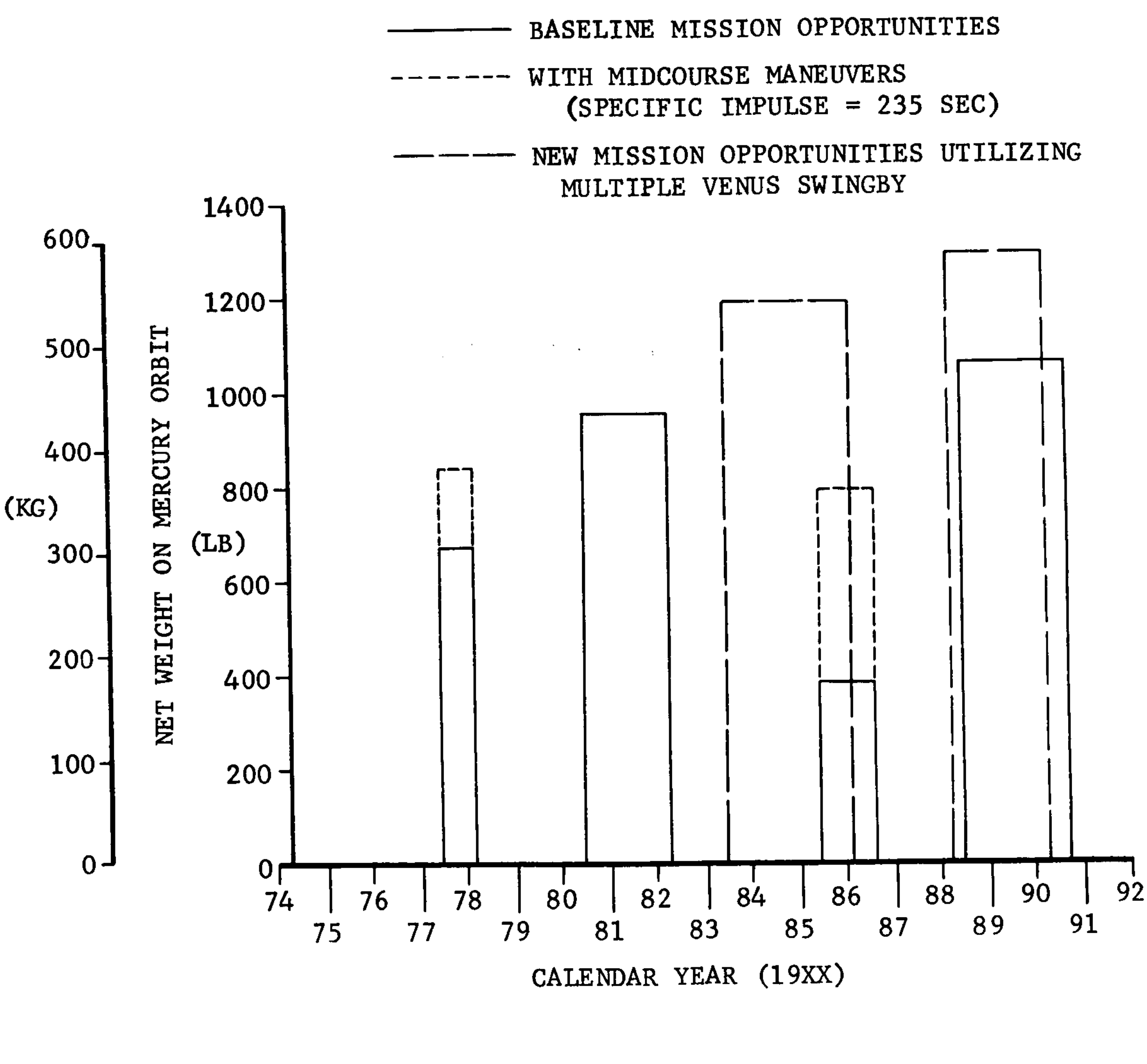


Figure I-3. Potential of Alternate Flight Techniques

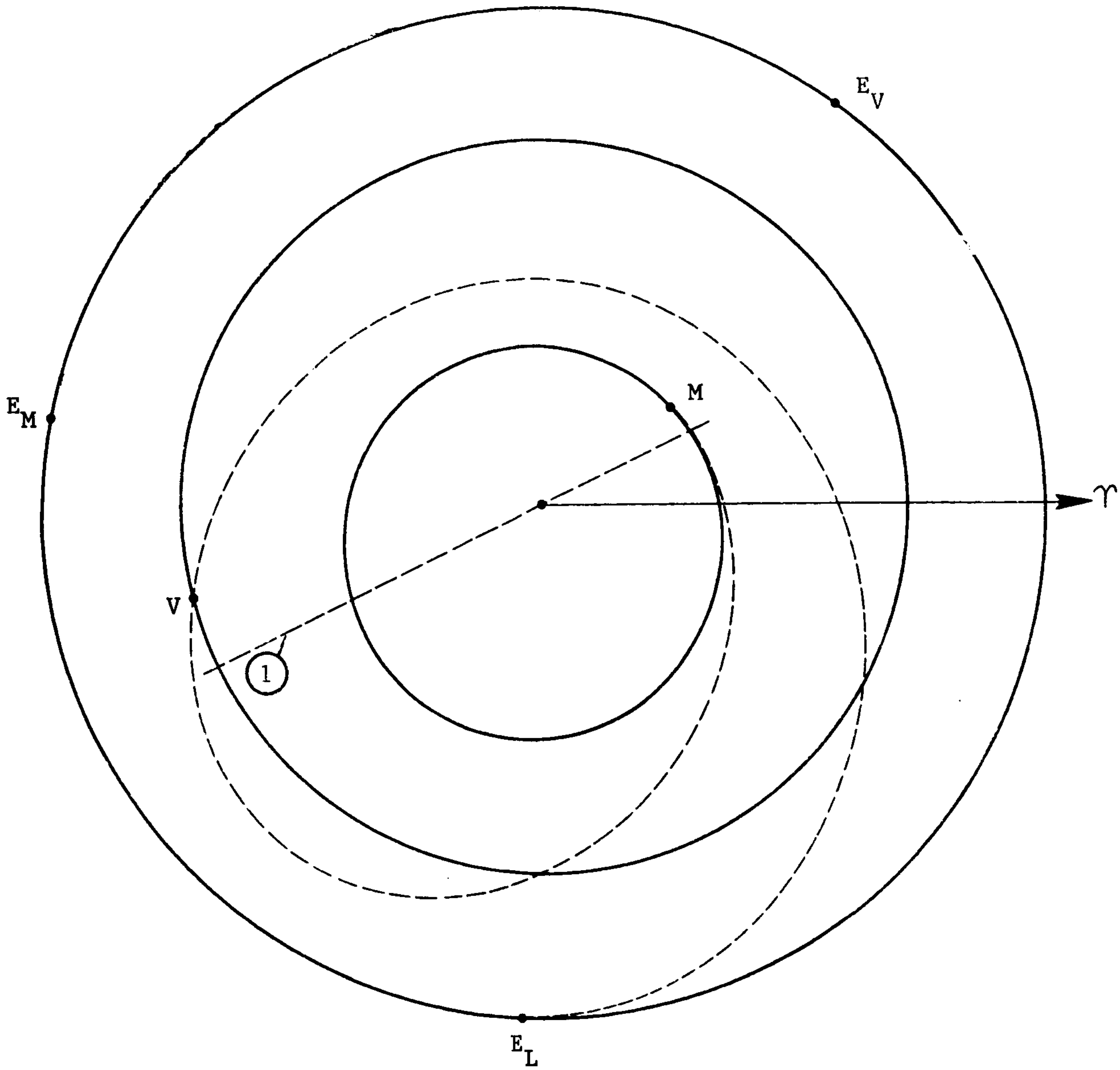
II. 1977 MISSION OPPORTUNITY

II. 1977 MISSION OPPORTUNITY

A. Heliocentric Geometry

The flight profile for this 9 month mission is presented as an ecliptic projection in Figure II-1. As shown, the basic Type II geometry for Earth-Venus transfer is employed. The Venus gravity swingby deflects the trajectory to produce Mercury encounter near Mercury perihelion and near the intersection of the Venus and Mercury orbit planes. The post-Venus trajectory is also Type II as predicted by the analytical determination of idealized transfer geometry.

Earth positions at the Venus swingby and Mercury encounter events are indicated. The significance of these relative geometries to Earth tracking and navigation requirements is discussed in subsection II.E.



E_L: EARTH AT LAUNCH, 6-19-77

E_V: EARTH AT VENUS SWINGBY, 11-16-77

E_M: EARTH AT MERCURY ENCOUNTER, 3-11-78

V: VENUS AT SWINGBY

M: MERCURY AT ENCOUNTER

1 INTERSECTION OF VENUS AND MERCURY ORBIT PLANES

Figure II-1. Heliocentric Geometry, 1977 Opportunity

B. Performance Parameters

Three-planet trajectory analyses were conducted for a range of Earth launch dates encompassing the region of minimum approach velocity at Mercury. This parameter is of paramount importance to performance of orbiter missions. Figure II-2 presents the variation in arrival conditions for a series of fixed Mercury encounter dates. Also shown is the minimum envelope to facilitate use of the data.

Corresponding launch energy requirements are presented on Figure II-3. No attempt was made to minimize this parameter due to the over-riding significance of Mercury approach velocity. Determination of best performance for a particular launch vehicle and orbit insertion propulsion type does involve some second-order tradeoffs between launch requirements and Mercury arrival conditions. Sufficient data are provided to accommodate such optimizations. For convenience, launch energy corresponding to minimum Mercury approach velocity for each Earth launch date is indicated. Also, the maximum value of DLA (declination of the launch asymptote) is noted for the range of Earth launch dates and lowest Mercury arrival velocities.

Associated Venus swingby altitudes are shown on Figure II-4. To facilitate interpretation, conditions for minimum relative velocity at Mercury are superimposed. As shown, the entire region of high performance launch dates corresponds to acceptable altitude clearance considering the extent of the Venus atmosphere.

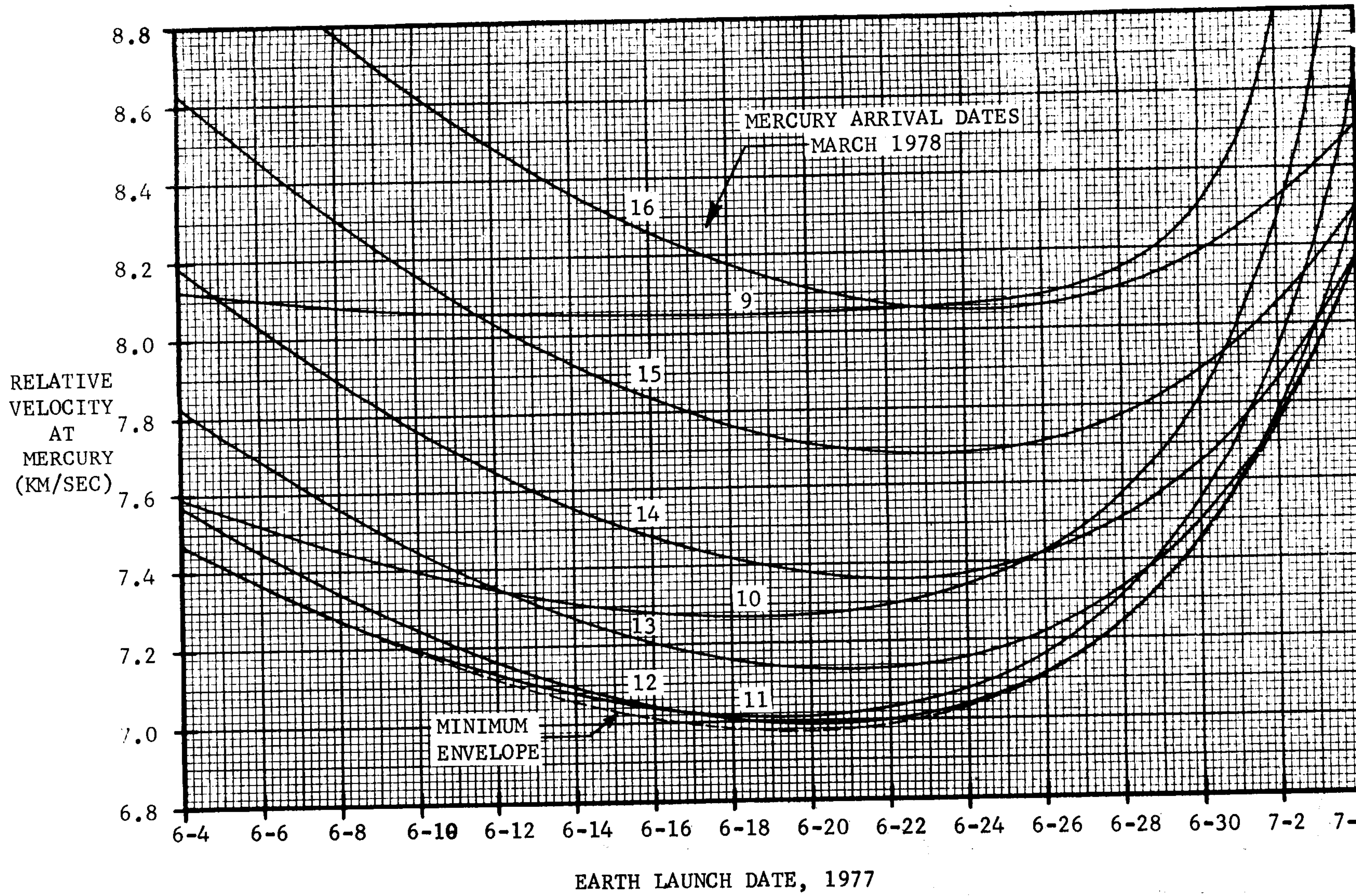


Figure II-2. Relative Velocity at Mercury vs. Launch/Arrival Date, 1977 Opportunity

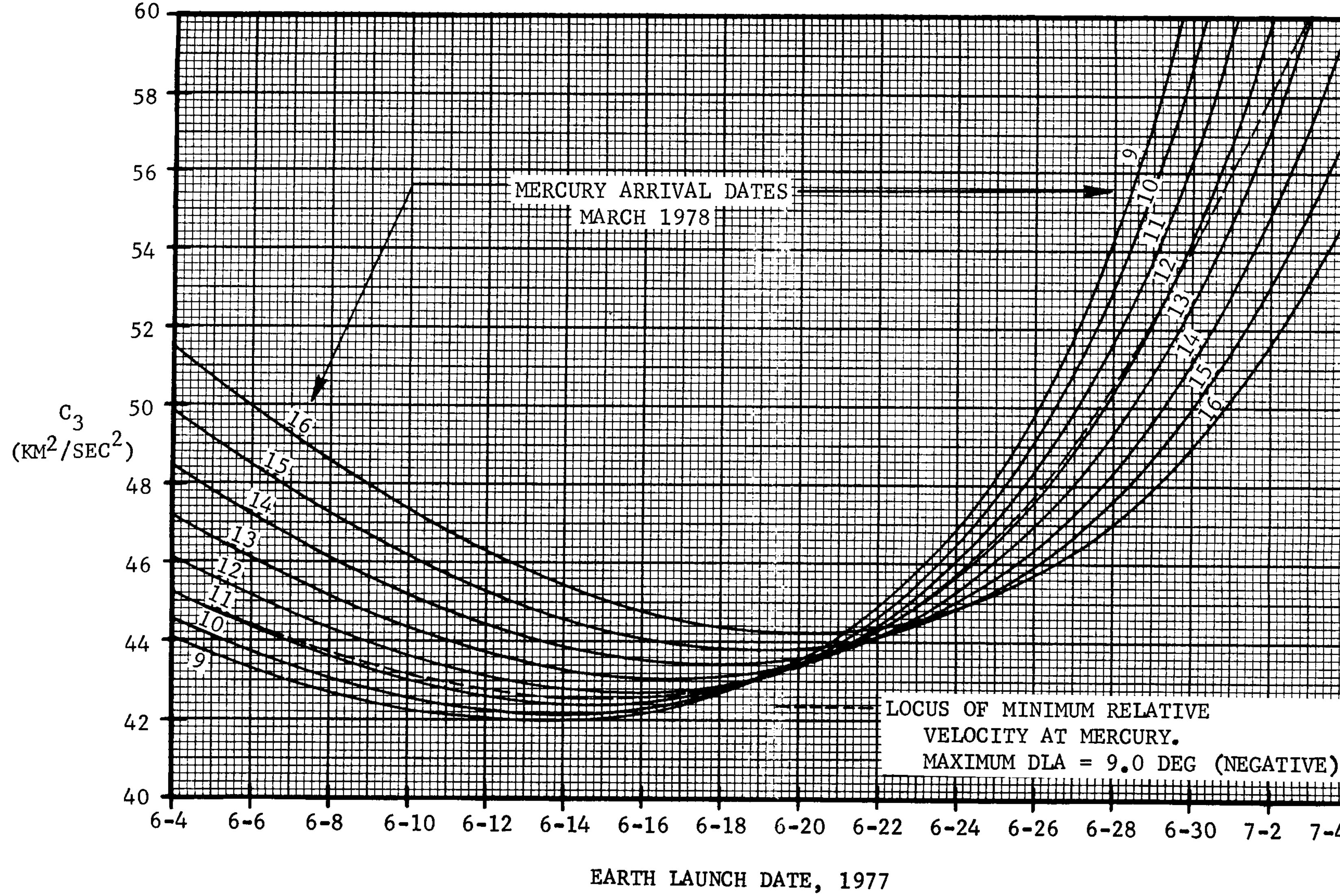


Figure II-3. C_3 vs. Launch/Arrival Date, 1977 Opportunity

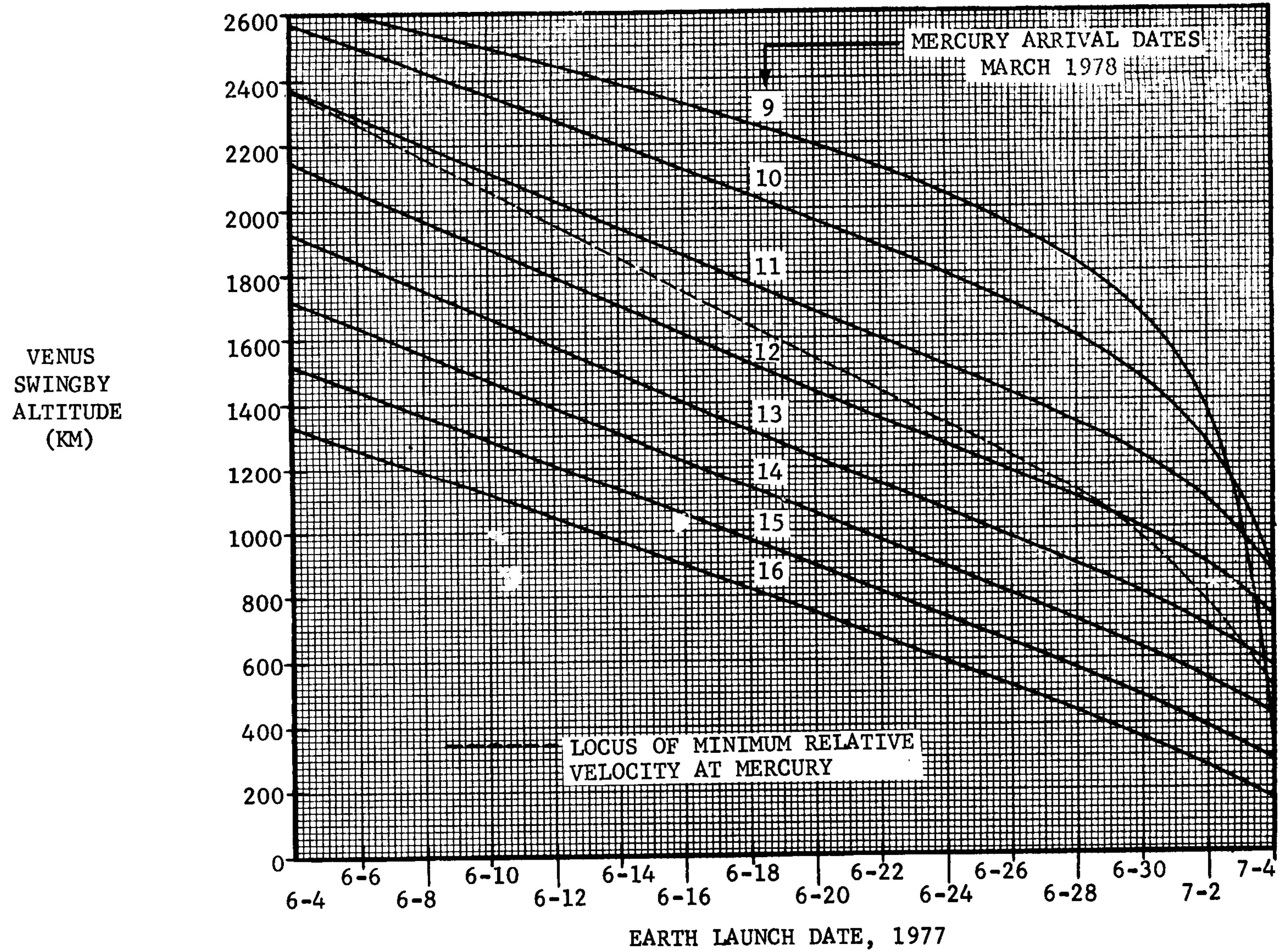


Figure II-4. Venus Swingby Altitude vs. Launch/Arrival Date, 1977 Opportunity

C. Trajectory Data

Tabulated details for three representative trajectories from the 1977 opportunity are listed in Tables II-1 through II-3. The Earth launch dates (6-12, 6-19, and 6-26) are approximately centered on the best performance 15-day launch period. Venus swingby dates and Mercury encounter dates are selected to provide ballistic trajectories with minimum Mercury arrival velocity for each launch date. The print key which defines each listed parameter appears in Section 1 of the Appendix.

```
JD=2443306.500    C3=  42.774  FLT TIM= 156.709   JUN 12 1977  0, 0, 0.
ECLIPTIC           X                    Y                    Z                    TOTAL
R EARTH    -2.5775915E+07    -1.4971446E+08     9.4887386E+03     1.5191714E+08
V EARTH     2.8869587E+01    -5.1566575E+00     1.4314616E-04     2.9326510E+01
VEL S/C     2.2526173E+01    -4.2561701E+00    -1.3128100E+00     2.2962293E+01
VHE        -6.3434145E+00     9.0048743E-01    -1.3129531E+00     6.5401552E+00
RAA=171.920 DECA=-11.581        SEVHE= 88.346
EQUATORIAL         X                    Y                    Z                    TOTAL
R EARTH    -2.5775915E+07    -1.3736155E+08    -5.9618702E+07     1.5191714E+08
V EARTH     2.8869587E+01    -4.7311097E+00    -1.9742803E+00     2.9326510E+01
VEL S/C     2.2526173E+01    -3.3826296E+00    -2.8375526E+00     2.2962293E+01
VHE        -6.3434145E+00     1.3484801E+00    -8.6327231E-01     6.5401552E+00
RAA=167.999 DECA= -7.582 RP= 65631308.01 APO=151947539.51
A=108789423.76 E= .39671 I=  3.278 NODE=260.294 W=178.524
TH1= 178.6    TH2= 472.2    DTH= 293.7    TYPE    II


JD=2443463.209 VHA= 14.041 VHD= 14.041  NOV 15 1977 17,  0, 14.410
ECLIPTIC           X                    Y                    Z                    TOTAL
R VENUS    -1.0455608E+08    -2.5931109E+07     5.6522968E+06     1.0787189E+08
V VENUS     8.1985716E+00    -3.4146469E+01    -9.5675034E-01     3.5129949E+01
V S/C A    -5.7976705E+00    -3.4742510E+01    -8.1772299E-03     3.5222934E+01
VHA        -1.3996242E+01    -5.9604094E-01     9.4857311E-01     1.4041006E+01
V S/C D    -5.2546743E+00    -3.0136150E+01    -1.2349461E+00     3.0615752E+01
VHD        -1.3453246E+01     4.0103187E+00    -2.7819571E-01     1.4041007E+01
RCA=  7997.0   BTH=194.4     B*T=     -9205     B*R=     -2360     HCA=   1947.0
RAA= 182.4 DECA=    3.9 SPA= 168.5 EPA= 146.0 CPA=   90.9    TYPE II
RAE=  36.4 DECE=   -1.3 RAS=   13.9 DECS=   -3.0
AH=       1647.8 EH=  5.85317 I= 165.1 NODE= 347.7 W= 154.9 TAU=   80.2
A= 87125519.1 E=     .456381 I=    4.9 NODE= 411.9 W= 359.8 TURN=  19.7
THI= 142.2 THF= 346.7 DTH= 204.5 FLT TIM= 115.625
PERIHELION= 47363110.5  APHELION=126887927.8

JD=2443578.834     VHP=  7.118    MAR 11 1978  8, 0,31.998
ECLIPTIC           X                    Y                    Z                    TOTAL
R MERCURY  3.7447507E+07     2.9637734E+07    -9.5228875E+05     4.7766284E+07
V MERCURY -3.9787121E+01     4.0418009E+01     6.9553556E+00     5.7140243E+01
V S/C      -4.2711386E+01     4.6699756E+01     5.3273417E+00     6.3509923E+01
VHP        -2.9242658E+00     6.2817471E+00    -1.6280138E+00     7.1177318E+00
RAA= 115.0    DECA= -13.2     SPA= 103.3    EPA=  66.7    CPA=  62.9
RAE= 180.9    DECE=     .3    RAS=-141.6    DECS=    1.1
EQUATORIAL         X                    Y                    Z                    TOTAL
R MERCURY  4.7187350E+07     7.4143055E+06     7.4505806E-09     4.7766284E+07
V MERCURY -1.4992697E+01     5.5138248E+01    -2.8421709E-14     5.7140243E+01
V S/C      -1.4383847E+01     6.1813265E+01    -2.3949037E+00     6.3509923E+01
VHP         6.0884983E-01     6.6750164E+00    -2.3949037E+00     7.1177318E+00
RAA=  84.8   DECA= -19.7  RAS=-171.1   DECS=     -.0  RAE= 151.8   DECE=  -4.8
MERCURY OP         X                    Y                    Z                    TOTAL
R MERCURY  4.7175429E+07    -7.4897803E+06     7.4505806E-09     4.7766284E+07
V MERCURY  2.7307661E+00     5.7074953E+01    -2.8421709E-14     5.7140243E+01
V S/C      5.3672219E+00     6.3237391E+01    -2.3949037E+00     6.3509923E+01
VHP        2.6364557E+00     6.1624381E+00    -2.3949037E+00     7.1177318E+00
RAA=  66.8   DECA= -19.7  RAS= 171.0   DECS=     -.0  RAE= 133.8   DECE=  -4.8
```

TABLE II-1 TRAJECTORY PRINTOUT, 6-12-77 LAUNCH

```
JD=2443313.500    C3=  43.035  FLT TIM= 150.518   JUN 19 1977  0, 0, 0.
ECLIPTIC          X                 Y                 Z                 TOTAL
R EARTH    -8.1782594E+06   -1.5179143E+08    9.5161853E+03    1.5201159E+08
V EARTH     2.9258360E+01   -1.7049969E+00   -7.4401312E-05    2.9307997E+01
VEL S/C     2.2971934E+01   -3.0987199E-01   -1.2527950E+00    2.3008157E+01
VHE        -6.2864264E+00    1.3951249E+00   -1.2527206E+00    6.5600945E+00
RAA=167.487 DECA=-11.009        SEVHE= 99.254
EQUATORIAL        X                 Y                 Z                 TOTAL
R EARTH    -8.1782594E+06   -1.3926712E+08   -6.0398007E+07    1.5201159E+08
V EARTH     2.9258360E+01   -1.5642454E+00   -6.0026591E-01    2.9307997E+01
VEL S/C     2.2971934E+01    2.1408574E-01   -1.2113627E+00    2.3008157E+01
VHE        -6.2864264E+00    1.7783312E+00   -6.1109681E-01    6.5600945E+00
RAA=164.205 DECA= -5.344 RP= 65948957.57 APO=152201035.95
A=109074996.76 E= .39538 I=  3.124 NODE=266.982 W=183.472
TH1= 183.5   TH2= 471.8   DTH= 288.3   TYPE   II


JD=2443464.018 VHA= 13.999 VHD= 13.999  NOV 16 1977 12, 25, 42.688
ECLIPTIC          X                 Y                 Z                 TOTAL
R VENUS    -1.0395579E+08   -2.8312002E+07    5.5839376E+06    1.0788678E+08
V VENUS     8.9692446E+00   -3.3945984E+01   -9.9828037E-01    3.5125115E+01
V S/C A    -4.9471537E+00   -3.4914272E+01    1.6927888E-01    3.5263428E+01
VHA        -1.3916398E+01   -9.6828788E-01    1.1675593E+00    1.3998818E+01
V S/C D    -4.5100918E+00   -3.0187907E+01   -1.3873233E+00    3.0554465E+01
VHD        -1.3479336E+01    3.7580764E+00   -3.8904294E-01    1.3998821E+01
RCA=  7633.6    BTH=197.6    B*T=      -8714    B*R=      -2767    HCA=  1583.6
RAA= 184.0 DECA=   4.8 SPA= 168.6 EPA= 146.5 CPA=  92.1   TYPE II
RAE=  37.4 DECE=  -1.3 RAS=  15.2 DECS=  -3.0
AH=      1657.7 EH=  5.60485 I= 161.8 NODE= 349.3 W= 154.3 TAU=  79.7
A= 86930948.1 E=     .456265 I=    5.1 NODE= 410.8 W=    1.8 TURN=  20.6
THI= 142.5 THF= 346.9 DTH= 204.4 FLT TIM= 115.023
PERIHELION= 47267426.8  APHELION=126594469.3

JD=2443579.041     VHP=  6.977   MAR 11 1978 12,59,12.000
ECLIPTIC          X                 Y                 Z                 TOTAL
R MERCURY  3.6727230E+07    3.0356169E+07   -8.2747030E+05    4.7655756E+07
V MERCURY -4.0599272E+01    3.9761109E+01    6.9748410E+00    5.7252905E+01
V S/C      -4.3676646E+01    4.5869576E+01    5.5965422E+00    6.3584500E+01
VHP        -3.0773741E+00    6.1084666E+00   -1.3782988E+00    6.9773422E+00
RAA= 116.7   DECA= -11.4    SPA= 102.8    EPA=  65.2    CPA=  64.8
RAE= 181.3   DECE=     .3   RAS=-140.4    DECS=   1.0
EQUATORIAL        X                 Y                 Z                 TOTAL
R MERCURY  4.7084463E+07    7.3569335E+06   -3.7252903E-09    4.7655756E+07
V MERCURY -1.4798259E+01    5.5307383E+01    5.6843419E-14    5.7252905E+01
V S/C      -1.4270286E+01    6.1925274E+01   -2.1466412E+00    6.3584500E+01
VHP         5.2797314E-01    6.6178909E+00   -2.1466412E+00    6.9773422E+00
RAA=  85.4  DECA= -17.9  RAS=-171.1  DECS=     .0  RAE= 150.9  DECE=  -4.8
MERCURY OP        X                 Y                 Z                 TOTAL
R MERCURY  4.7215117E+07   -6.4655897E+06   -3.7252903E-09    4.7655756E+07
V MERCURY  1.6972477E+00    5.7227742E+01    5.6843419E-14    5.7252905E+01
V S/C       4.1023152E+00    6.3415705E+01   -2.1466412E+00    6.3584500E+01
VHP         2.4050675E+00    6.1879630E+00   -2.1466412E+00    6.9773422E+00
RAA=  68.8  DECA= -17.9  RAS= 172.2  DECS=     .0  RAE= 134.2  DECE=  -4.8
```

TABLE II-2 TRAJECTORY PRINTOUT, 6-19-77 LAUNCH

```
JD=2443320.500    C3=  47.730   FLT TIM= 143.053    JUN 26 1977   0, 0, 0.
ECLIPTIC           X                  Y                  Z                   TOTAL
R EARTH      9.5323511E+06    -1.5177308E+08     9.4122065E+03     1.5207214E+08
V EARTH      2.9242923E+01     1.7649147E+00    -2.9089292E-04     2.9296134E+01
VEL S/C      2.2827112E+01     4.0162883E+00    -1.2243015E+00     2.3210053E+01
VHE         -6.4158104E+00     2.2513735E+00    -1.2240106E+00     6.9085545E+00
RAA=160.664 DECA=-10.205         SEVHE=112.548
EQUATORIAL         X                  Y                  Z                   TOTAL
R EARTH      9.5323511E+06    -1.3925024E+08    -6.0343517E+07     1.5207214E+08
V EARTH      2.9242923E+01     1.6193633E+00     7.7993168E-01     2.9296134E+01
VEL S/C      2.2827112E+01     4.1718513E+00     5.3544635E-01     2.3210053E+01
VHE         -6.4158104E+00     2.5524880E+00    -2.4448533E-01     6.9086545E+00
RAA=158.305 DECA= -2.028 RP= 66404162.06 APO=153558469.83
A=109981315.95 E= .39622 I=   3.042 NODE=273.661 W=189.834
TH1= 189.9    TH2= 470.8    DTH= 280.9    TYPE    II


JD=2443463.553 VHA= 14.061 VHD= 14.061  NOV 16 1977  1, 16, 51.315
ECLIPTIC           X                  Y                  Z                   TOTAL
R VENUS     -1.0430688E+08    -2.6947334E+07     5.6235237E+06     1.0787821E+08
V VENUS      8.5275409E+00    -3.4063183E+01    -9.7451038E-01     3.5127896E+01
V S/C A     -5.4351180E+00    -3.4986069E+01     4.0697065E-01     3.5408066E+01
VHA         -1.3962659E+01    -9.2288622E-01     1.3814810E+00     1.4061154E+01
V S/C D     -4.9719457E+00    -3.0149754E+01    -1.3807417E+00     3.0588141E+01
VHD         -1.3499487E+01     3.9134289E+00    -4.0623128E-01     1.4061155E+01
RCA=  7282.5    BTH=199.5       B*T=     -8268     B*R=     -2935     HCA=  1232.5
RAA= 183.8 DECA=    5.6 SPA= 169.0 EPA= 146.8 CPA=   92.9    TYPE II
RAE=  36.8 DECE=   -1.3 RAS=   14.5 DECS=  -3.0
AH=     1643.1 EH=  5.43226 I= 159.7 NODE= 348.3 W= 153.0 TAU=  79.4
A= 87037200.8 E=    .457095 I=    5.1 NODE= 410.2 W=    1.8 TURN=  21.2
THI= 142.3 THF= 348.9 DTH= 206.6 FLT TIM= 115.726
PERIHELION= 47252910.4  APHELION=126821491.3

JD=2443579.279     VHP=  7.114    MAR 11 1978 18,41,35.999
ECLIPTIC           X                  Y                  Z                   TOTAL
R MERCURY   3.5883704E+07     3.1165074E+07    -6.8397692E+05     4.7532829E+07
V MERCURY  -4.1517450E+01     3.8983137E+01     6.9939515E+00     5.7378559E+01
V S/C      -4.4400348E+01     4.5343871E+01     5.6390368E+00     6.3712293E+01
VHP        -2.8828973E+00     6.3607345E+00    -1.3549146E+00     7.1137777E+00
RAA= 114.4    DECA= -11.0    SPA= 106.4    EPA=  67.9    CPA=  65.1
RAE= 181.8    DECE=     .2   RAS=-139.0    DECS=     .8
EQUATORIAL         X                  Y                  Z                   TOTAL
R MERCURY   4.6969295E+07     7.2976169E+06    -7.4505806E-09     4.7532829E+07
V MERCURY  -1.4576767E+01     5.5496098E+01     2.8421709E-14     5.7378559E+01
V S/C      -1.3582392E+01     6.2211354E+01    -2.1265913E+00     6.3712293E+01
VHP         9.9437509E-01     6.7152559E+00    -2.1265913E+00     7.1137777E+00
RAA=  81.6   DECA= -17.4  RAS=-171.2  DECS=     .0  RAE= 149.9  DECE=   -4.8
MERCURY OP         X                  Y                  Z                   TOTAL
R MERCURY   4.7237734E+07    -5.2883201E+06    -1.1175871E-08     4.7532829E+07
V MERCURY   5.0284601E-01     5.7376355E+01     2.8421709E-14     5.7378559E+01
V S/C       3.2251819E+00     6.3595063E+01    -2.1265913E+00     6.3712293E+01
VHP         2.7223359E+00     6.2187081E+00    -2.1265913E+00     7.1137777E+00
RAA=  66.4   DECA= -17.4  RAS= 173.6  DECS=     .0  RAE= 134.7  DECE=   -4.8
```

TABLE II-3 TRAJECTORY PRINTOUT, 6-26-77 LAUNCH

D. Flight Characteristics

Time histories of four parameters; Earth-Spacecraft range, Sun-Spacecraft range, Sun-Earth-Spacecraft angle, and Spacecraft equatorial declination are presented in Figure II-5. These plots are based on the second reference trajectory (Table II-2) for this opportunity. Three of these parameters have significant impact on the navigation analysis. The Earth-Spacecraft range during the pre-Venus tracking arc is over 200 million kilometers. The S/C equatorial declination during the pre-Venus tracking arc ranges from +5 to -10 degrees. Finally, the small Sun-Earth-Spacecraft angle just before Mercury encounter implies that the last midcourse maneuver must be executed 30 days before encounter rather than the standard 3 days before encounter.

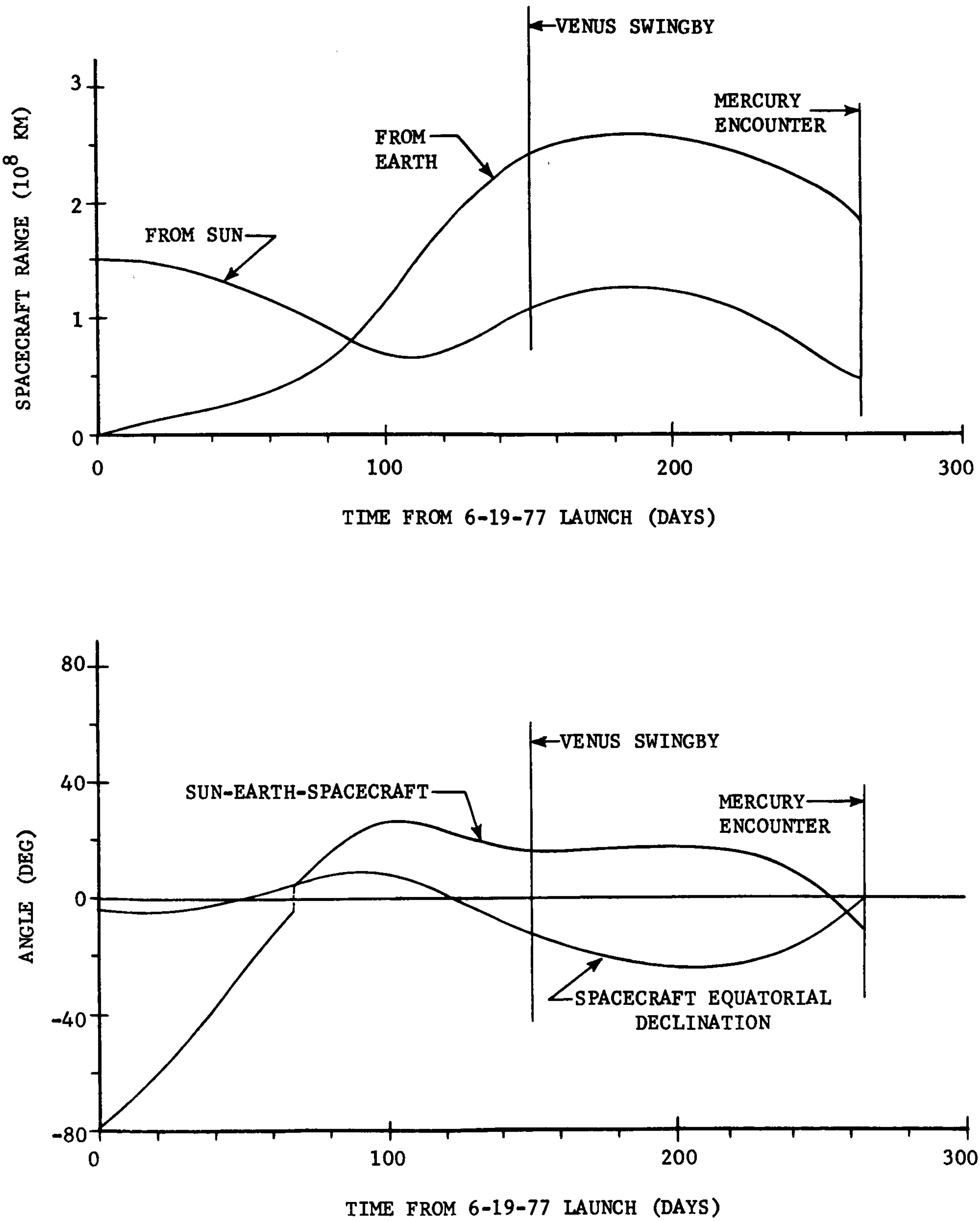


Figure II-5. Typical Time Histories, 1977 Opportunity

E. Navigation Requirements

Four midcourse maneuvers are required for this opportunity. A navigation analysis of the second reference trajectory (Table II-2) indicates total corrective ΔV requirements of 226.5 m/s (Table II-4). The navigation and orbit determination assumptions on which this analysis is based are discussed in Section VI. Geometries of the two critical tracking phases are indicated in the heliocentric profile presented in Figure II-6.

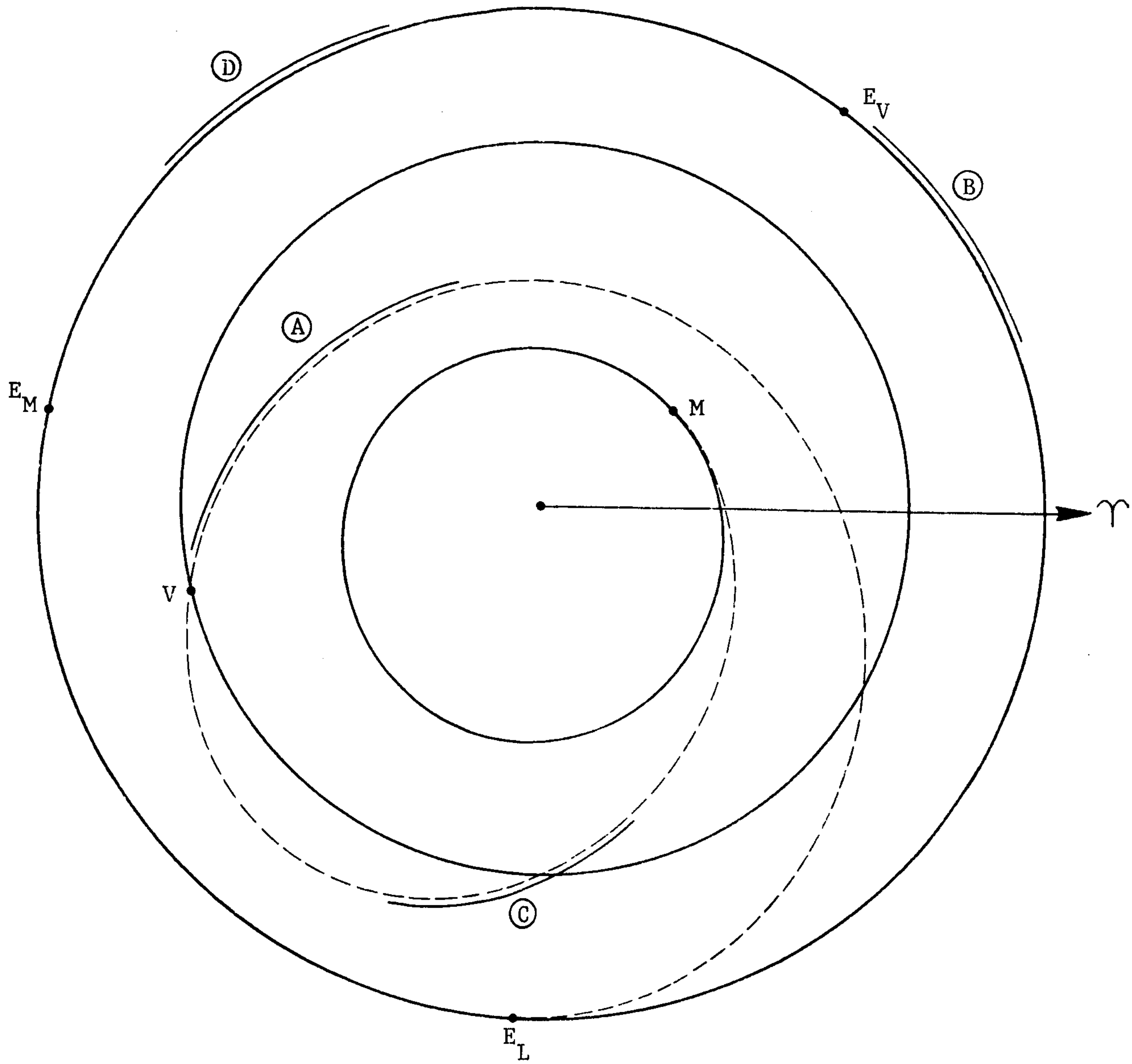
TABLE II-4

1977 MANEUVER SCHEDULE AND STATISTICAL DESCRIPTION

MANEUVER TIME (days)	MEAN ΔV (m/s)	SIGMA ΔV (m/s)		MEAN PLUS THREE SIGMA (m/s)
E+10	6.90	4.57		20.6
V-3	3.94	2.76		12.2
V+2	62.15	41.40		186.4
M-30	2.26	1.68		7.3
			TOTAL	226.5

A maneuver is required 10 days after launch to remove injection errors. The small but critical second maneuver is required three days before Venus encounter. Large out-of-ecliptic, Z, knowledge errors at the time of this maneuver result from the large Earth-Spacecraft range and zero equatorial declination during the pre-maneuver tracking arc. Pre-Venus errors are amplified drastically by the gravity-assist. Consequently, the mean plus three sigma ΔV requirement for the post-Venus maneuver (V+2) is 186 m/s. Finally, a small maneuver thirty days before Mercury encounter shapes the approach trajectory. Solar interference of the doppler signal between M-30 and M-3 prohibits later execution of the maneuver as shown by Figure II-6. Resulting Mercury B-plane dispersions are dominated on the R-axis by a 60 km ephemeris error and along the T-axis by the mapping of pre-maneuver knowledge errors through a 30-day arc. These effects are discussed further in Section VI. Applying the Lee-Boain analytical technique to the ΔV covariance at V+2 indicates a cumulative probability of .99 for 170 m/s and .999 for 212 m/s.

Dispersions at Venus closest approach are not a problem for this mission because the nominal swingby altitude is about 1600 km.



Ⓐ SPACECRAFT DURING PRE-VENUS TRACKING PERIOD

Ⓑ EARTH DURING PRE-VENUS TRACKING PERIOD

Ⓒ SPACECRAFT DURING PRE-MERCURY TRACKING PERIOD

Ⓓ EARTH DURING PRE-MERCURY TRACKING PERIOD

Figure II-6. Critical Tracking Geometries, 1977 Opportunity

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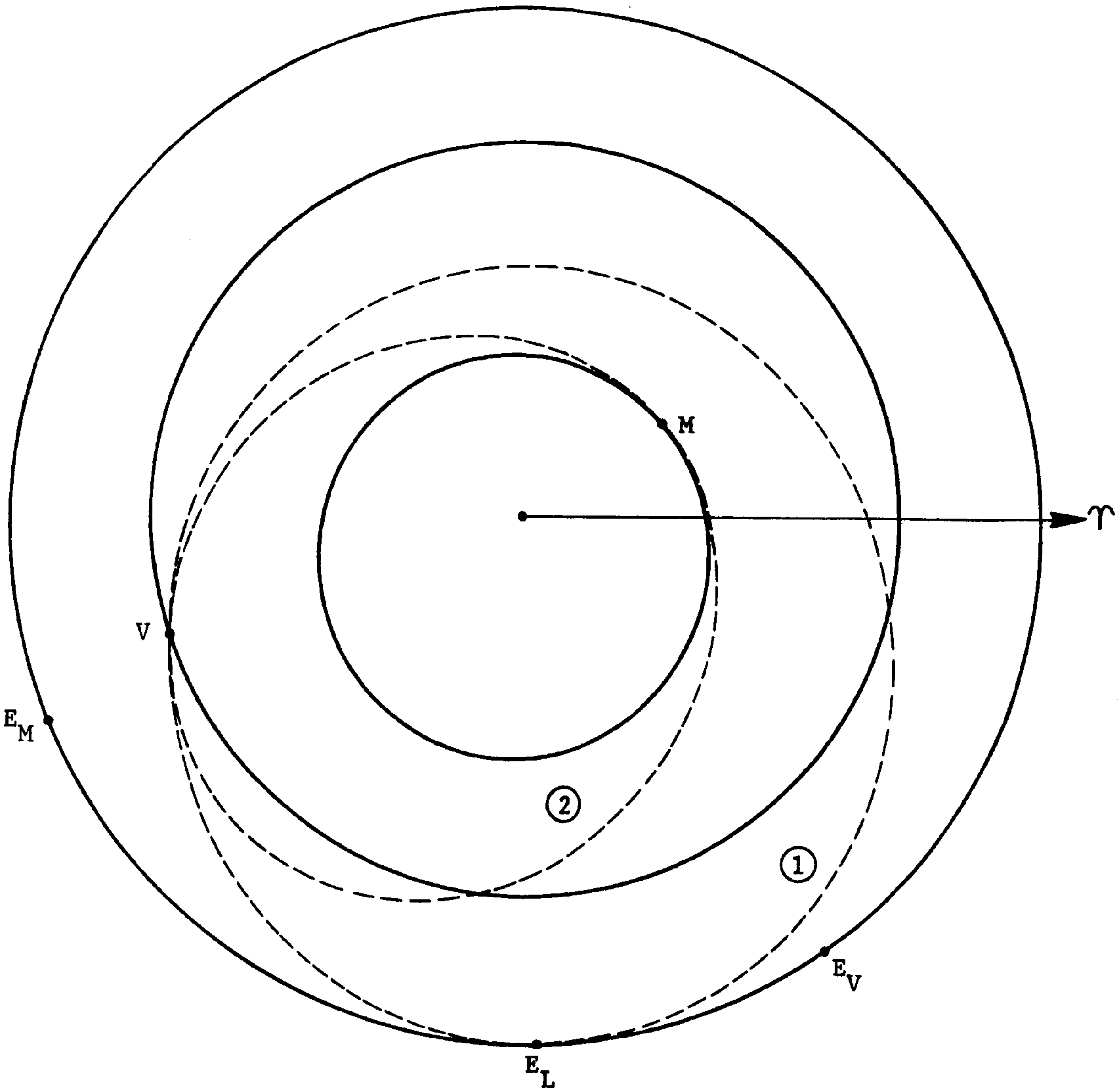
III. 1980 MISSION OPPORTUNITY

III. 1980 MISSION OPPORTUNITY

A. Heliocentric Geometry

The 1980 flight profile involves the same basic Type II geometry as the 1977 opportunity. However, extra solar revolutions of the spacecraft are required to accommodate planet phasing. As shown on Figure III-1, one complete phasing orbit is utilized for Earth-Venus transfer and a second phasing orbit is employed for the Venus-Mercury trajectory.

A result of the 22 month flight duration is reflected in the Earth positions at the Venus swingby and Mercury encounter times. Subsection III.E and Section VI relate these modified geometries to Earth tracking and navigation requirements.



E_L: EARTH AT LAUNCH, 6-24-80

E_V: EARTH AT VENUS SWINGBY, 7-29-81

E_M: EARTH AT MERCURY ENCOUNTER, 4-14-82

V: VENUS AT SWINGBY

M: MERCURY AT ENCOUNTER

① ONE COMPLETE SOLAR REVOLUTION BEFORE VENUS SWINGBY

② ONE COMPLETE SOLAR REVOLUTION BEFORE MERCURY ENCOUNTER

Figure III-1. Heliocentric Geometry, 1980 Opportunity

B. Performance Parameters

Planetary geometries for the 1980 mission opportunity are near ideal for utilization of Venus gravity-assist potential. As a result, performance is considerably better than for the similar 1977 opportunity. A second result of the high utilization of Venus is reflected in the low Venus swingby altitudes corresponding to best performance. In contrast to the 1977 opportunity, it is necessary to limit Venus altitude and optimize performance within the constraints.

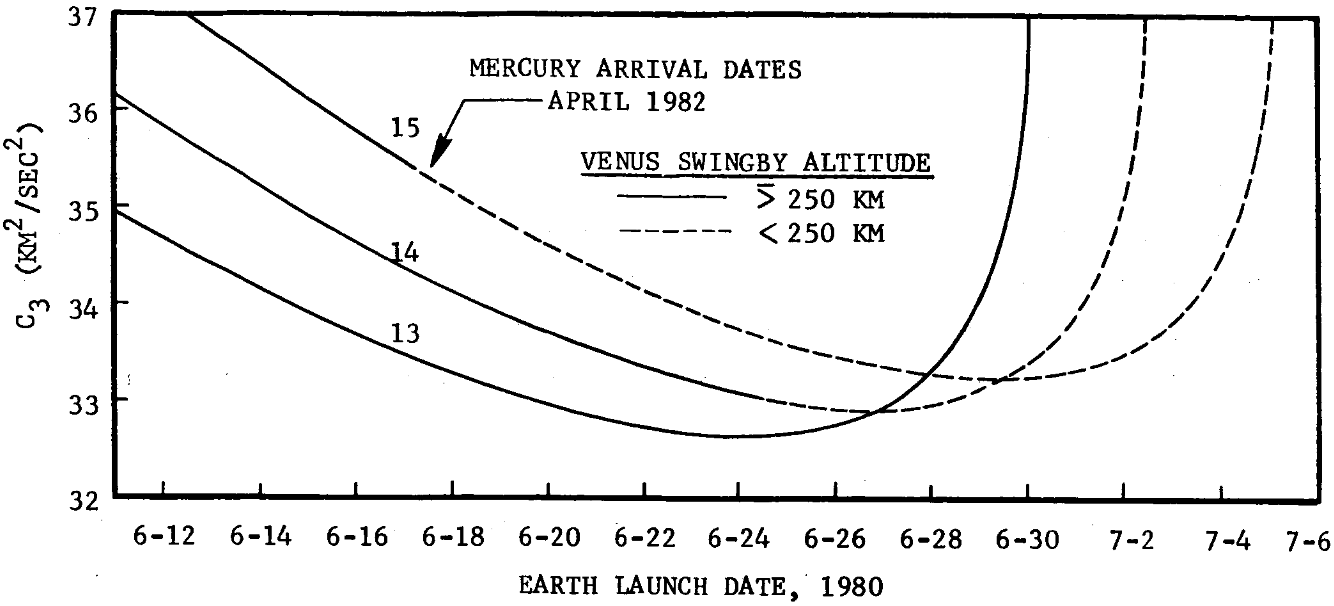
Figure III-2 presents the 1980 performance parameters for representative Mercury arrival dates. As shown, best values of Mercury approach velocity are limited by Venus altitude. Also, the variation with Earth launch date shows pronounced asymmetry with or without Venus altitude constraints. The reasons for this behavior are involved with the conditions at Venus swingby which are discussed in Section 2 of the Appendix.

Due to the interactions with Venus altitude, and the small range of Mercury arrival dates corresponding to best Mercury arrival conditions, data were generated for the special case of minimum relative velocity at Mercury. Performance parameters are presented on Figure III-3 for optimized Mercury arrival dates in the range of April 13.7 to 15. Three criteria for the Venus altitude constraint are shown for unpowered Venus swingby, i.e., no velocity maneuver at Venus. Subsection IIIE and Section VI discuss the implications of navigation requirements on the selection of safe Venus swingby altitude. The altitudes shown on Figure III-3 are sufficient to cover the probable range of a final determination of Venus swingby constraints.

The effects of Venus altitude limits on performance are not large. As shown by the Figure, higher minimum altitudes increase relative velocity at Mercury somewhat but this effect is partially compensated by corresponding reduction of launch energy requirements.

Also shown on Figure III-3 are the improvements in Mercury approach velocity which can be produced with modest velocity maneuvers near Venus. If these maneuvers are applied at Venus departure in conjunction with the post-Venus statistical navigation midcourse corrections, the net cost of the maneuvers are considerably less than the nominal maneuver magnitude. This effect is further discussed in Subsection III.E and Section VI.

The basic reasons for the improvements resulting from velocity maneuvers at Venus are discussed in Appendix 2 in context with the Venus swingby conditions.



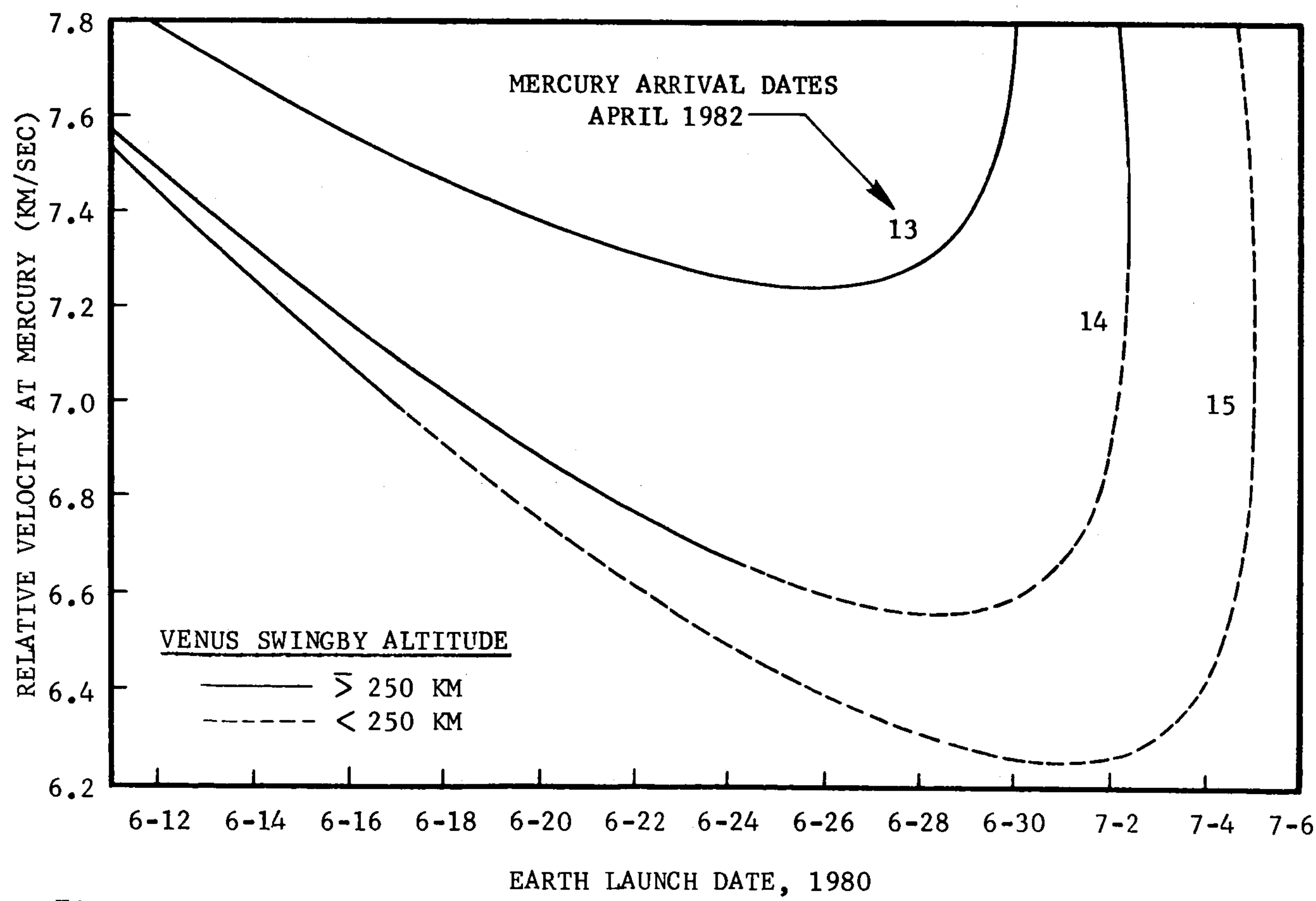


Figure III-2. Relative Velocity at Mercury and C_3 vs. Launch/Arrival Date, 1980 Opportunity

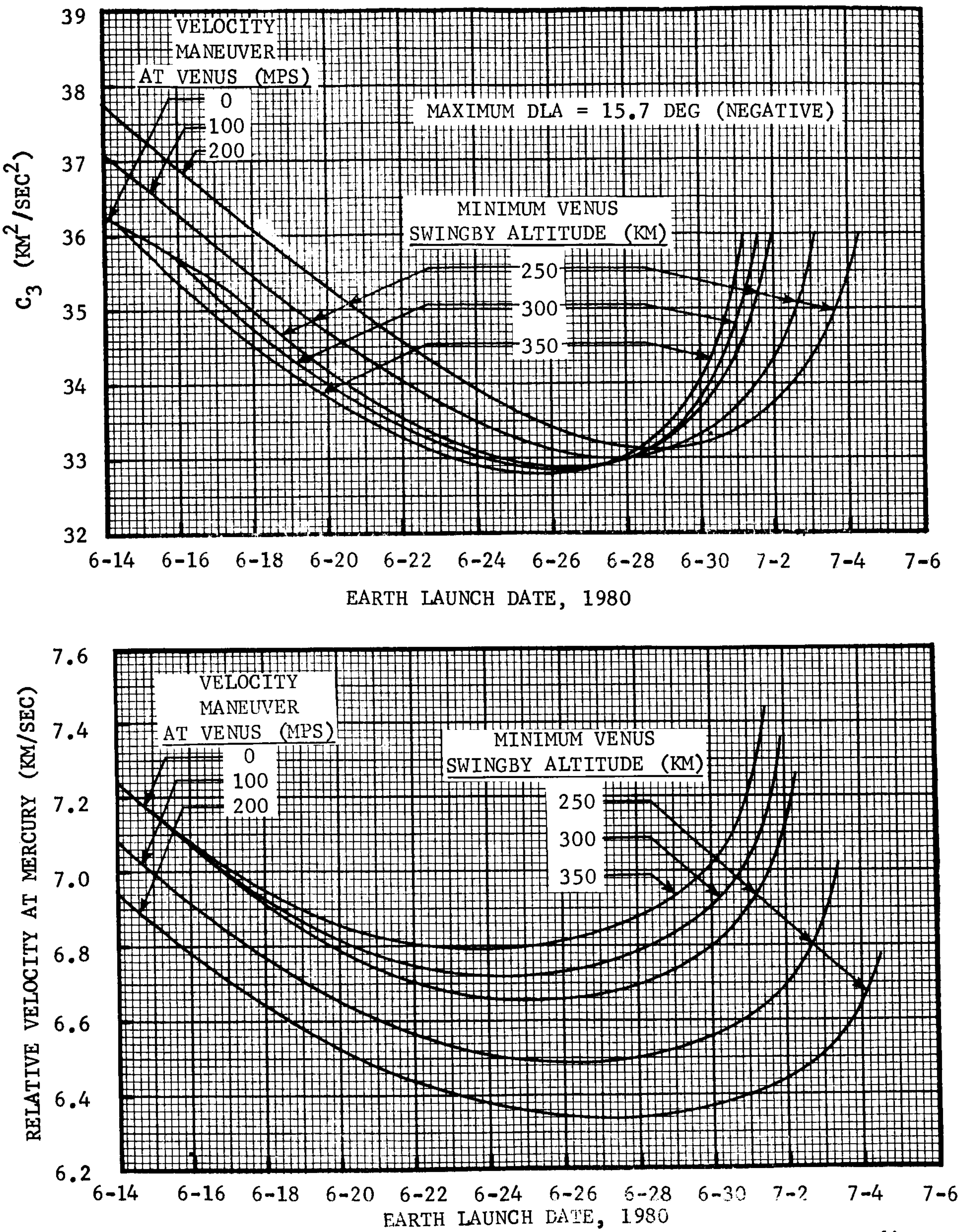


Figure III-3. Minimum Relative Velocity at Mercury and Corresponding C_3 vs. Launch Date, 1980 Opportunity

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C. Trajectory Data

Tabulated details for three unpowered Venus swingby trajectories for the 1980 opportunity are listed in Tables III-1 through III-3. The Earth launch dates (6-17, 6-24, and 7-1) are approximately centered on the best performance 15 day ballistic launch period. The corresponding Mercury encounter dates are selected to provide minimum Mercury arrival velocity. The print key which defines each listed parameter appears in Section 1 of the Appendix.

```
JD=2444407.500   C3=  35.419  FLT TIM= 405.685   JUN 17 1980  0, 0, 0.
ECLIPTIC           X                   Y                   Z                 TOTAL
R EARTH    -1.2734852E+07    -1.5145613E+08     1.0561826E+04     1.5199058E+08
V EARTH     2.9196749E+01    -2.5980599E+00    -2.0585542E-05     2.9312114E+01
VEL S/C     2.3447617E+01    -3.4237641E+00    -1.2970858E+00     2.3731737E+01
VHE        -5.7492829E+00    -8.2634992E-01    -1.2970434E+00     5.9514225E+00
RAA=188.179 DECA=-12.588        SEVHE= 77.333
EQUATORIAL         X                   Y                   Z                 TOTAL
R EARTH    -1.2734852E+07    -1.3896042E+08    -6.0278268E+07     1.5199058E+08
V EARTH     2.9196749E+01    -2.3836299E+00    -9.4713688E-01     2.9312114E+01
VEL S/C     2.3447617E+01    -2.6252039E+00    -2.4826334E+00     2.3731737E+01
VHE        -5.7492829E+00    -2.4217515E-01    -1.5357338E+00     5.9514225E+00
RAA=182.412 DECA=-14.943 RP= 71840686.52 APO=152500671.34
A=112170678.93 E= .35954 I=  3.139 NODE=265.266 W=173.659
TH1= 173.7   TH2= 465.3   DTH= 291.6   TYPE   IV    I


JD=2444813.185 VHA= 12.693 VHD= 12.693  JUL 27 1981 16, 26, 23.575
ECLIPTIC           X                   Y                   Z                 TOTAL
R VENUS    -1.0317236E+08    -3.1123489E+07     5.4982849E+06     1.0790477E+08
V VENUS     9.8790370E+00    -3.3684884E+01    -1.0472727E+00     3.5119276E+01
V S/C A    -2.6215273E+00    -3.5634325E+01    -1.7995540E-02     3.5730629E+01
VHA        -1.2500564E+01    -1.9494413E+00     1.0292772E+00     1.2693457E+01
V S/C D    -2.1606095E+00    -2.9700344E+01    -1.5730047E+00     2.9820346E+01
VHD        -1.2039646E+01     3.9845399E+00    -5.2573194E-01     1.2692755E+01
RCA=  6304.2    BTH=194.0      B*T=     -7834     B*R=      -1946     HCA=    254.2
RAA= 188.9 DECA=    4.7 SPA= 171.9 EPA= 144.1 CPA=  93.2   TYPE IV     I
RAE= 333.1 DECE=  -1.5 RAS=  16.8 DECS=  -2.9
AH=      2016.2 EH=  4.12674 I= 165.3 NODE= 350.8 W= 147.3 TAU=  76.0
A= 84500389.2 E=    .438551 I=   5.2 NODE= 410.6 W= 359.1 TURN=  28.0
THI= 146.9 THF= 349.4 DTH= 202.5 FLT TIM= 261.269
PERIHELION= 47442640.1  APHELION=121558138.2

JD=2445074.454    VHP=  6.989   APR 14 1982 22,53,19.999
ECLIPTIC           X                   Y                   Z                 TOTAL
R MERCURY  3.6955899E+07     3.0131687E+07    -8.6624849E+05     4.7690748E+07
V MERCURY -4.0345163E+01     3.9968906E+01     6.9687123E+00     5.7217205E+01
V S/C     -4.2395178E+01     4.6530343E+01     5.7066670E+00     6.3205933E+01
VHP       -2.0500148E+00     6.5614373E+00    -1.2620453E+00     6.9891186E+00
RAA= 107.4   DECA= -10.4    SPA= 111.7    EPA= 100.1    CPA=  65.4
RAE= 207.5   DECE=     .3    RAS=-140.8    DECS=    1.0
EQUATORIAL         X                   Y                   Z                 TOTAL
R MERCURY -4.6523873E+07    -1.0485070E+07    -3.7252903E-09     4.7690748E+07
V MERCURY  1.8494181E+01    -5.4145857E+01     5.6843419E-14     5.7217205E+01
V S/C      1.7337747E+01    -6.0749393E+01    -1.9757925E+00     6.3205933E+01
VHP       -1.1564332E+00    -6.6035358E+00    -1.9757925E+00     6.9891186E+00
RAA= 260.1   DECA= -16.4   RAS=  12.7   DECS=      .0   RAE=    1.2   DECE=  -2.2
MERCURY OP         X                   Y                   Z                 TOTAL
R MERCURY  4.7212474E+07    -6.7371886E+06    -1.1175871E-08     4.7690748E+07
V MERCURY  1.9604761E+00     5.7183609E+01     2.8421709E-14     5.7217205E+01
V S/C      5.3886915E+00     6.2944803E+01    -1.9757925E+00     6.3205933E+01
VHP        3.4282155E+00     5.7611945E+00    -1.9757925E+00     6.9891186E+00
RAA=  59.2   DECA= -16.4   RAS= 171.9   DECS=      .0   RAE= 160.4   DECE=  -2.2
```

TABLE III-1 TRAJECTORY PRINTOUT, 6-17-80 LAUNCH

```
JD=2444414.500    C3=  33.105  FLT TIM= 399.644    JUN 24 1980  0, 0, 0.
ECLIPTIC            X                  Y                  Z                 TOTAL
R EARTH     4.9700338E+06     -1.5197858E+08     1.0483108E+04      1.5205983E+08
V EARTH     2.9285580E+01      8.7150966E-01    -2.6131094E-04      2.9298545E+01
VEL S/C     2.3683515E+01      4.3957468E-01    -1.2389783E+00      2.3719974E+01
VHE        -5.6021184E+00     -4.3259210E-01    -1.2386863E+00      5.7537127E+00
RAA=184.416 DECA=-12.432        SEVHE= 87.518
EQUATORIAL          X                  Y                  Z                 TOTAL
R EARTH     4.9700338E+06     -1.3943973E+08    -6.0433761E+07      1.5205983E+08
V EARTH     2.9285580E+01      7.9968662E-01     4.3317781E-01      2.9298545E+01
VEL S/C     2.3683515E+01      8.9617194E-01    -8.9171740E-01      2.3719974E+01
VHE        -5.6021184E+00      9.5870253E-02    -1.3251287E+00      5.7537127E+00
RAA=179.020 DECA=-13.306 RP= 72299057.27 APO=152087275.63
A=112193166.45 E= .35558 I=  2.994 NODE=271.949 W=178.459
TH1= 178.5   TH2= 465.0   DTH= 286.4    TYPE   IV     I


JD=2444814.144 VHA= 12.550 VHD= 12.549  JUL 28 1981 15, 27, 57.720
ECLIPTIC            X                  Y                  Z                 TOTAL
R VENUS    -1.0231611E+08     -3.3904134E+07     5.4094873E+06      1.0792284E+08
V VENUS     1.0778512E+01     -3.3400243E+01    -1.0950191E+00      3.5113411E+01
V S/C A    -1.4970927E+00     -3.5696522E+01     1.4176208E-01      3.5728183E+01
VHA        -1.2275605E+01     -2.2962792E+00     1.2367811E+00      1.2549622E+01
V S/C D    -1.2134687E+00     -2.9718968E+01    -1.4460724E+00      2.9778863E+01
VHD        -1.1991981E+01      3.6812749E+00    -3.5105329E-01      1.2549208E+01
RCA=  6300.0   BTH=193.9     B*T=     -7866    B*R=     -1951    HCA=    250.0
RAA= 190.6 DECA=    5.7 SPA= 171.8 EPA= 143.5 CPA=   94.6    TYPE IV      I
RAE= 334.2 DECE=  -1.5 RAS=  18.3 DECS=  -2.9
AH=      2062.7 EH=  4.05426 I= 165.0 NODE= 348.9 W= 143.4 TAU=  75.7
A= 84389679.9 E=     .436528 I=    5.0 NODE= 413.6 W= 357.4 TURN=  28.6
THI= 147.2 THF= 342.8 DTH= 195.6 FLT TIM= 259.390
PERIHELION= 47551241.0  APHELION=121228118.8

JD=2445073.534    VHP=  6.662   APR 14 1982  0,49,38.718
ECLIPTIC            X                  Y                  Z                 TOTAL
R MERCURY  4.0015076E+07      2.6846337E+07    -1.4157063E+06      4.8207222E+07
V MERCURY -3.6662653E+01      4.2696327E+01     6.8596555E+00      5.6693751E+01
V S/C      -3.9283246E+01      4.8606091E+01     5.2513779E+00      6.2716046E+01
VHP        -2.6205926E+00      5.9097635E+00    -1.6082776E+00      6.6617841E+00
RAA= 113.9    DECA= -14.0     SPA= 100.1    EPA=  91.7    CPA=   62.1
RAE= 205.6    DECE=     .4    RAS=-146.1    DECS=    1.7
EQUATORIAL          X                  Y                  Z                 TOTAL
R MERCURY -4.6977348E+07     -1.0819660E+07     1.4901161E-08      4.8207222E+07
V MERCURY  1.9312506E+01     -5.3302988E+01     2.8421709E-14      5.6693751E+01
V S/C      1.9556364E+01     -5.9543938E+01    -2.3174195E+00      6.2716046E+01
VHP        2.4385845E-01     -6.2409509E+00    -2.3174195E+00      6.6617841E+00
RAA= 272.2   DECA= -20.4   RAS=  13.0   DECS=    -.0   RAE=    4.9   DECE=  -2.2
MERCURY OP          X                  Y                  Z                 TOTAL
R MERCURY  4.6876789E+07     -1.1247354E+07     1.4901161E-08      4.8207222E+07
V MERCURY  6.4630616E+00      5.6324153E+01     2.8421709E-14      5.6693751E+01
V S/C      9.0257626E+00      6.2019897E+01    -2.3174195E+00      6.2716046E+01
VHP        2.5627009E+00      5.6957439E+00    -2.3174195E+00      6.6617841E+00
RAA=  65.8   DECA= -20.4   RAS= 166.5   DECS=    -.0   RAE= 158.4   DECE=  -2.2
```

TABLE III-2 TRAJECTORY PRINTOUT, 6-24-80 LAUNCH

```
JD=2444421.500   C3=  34.421  FLT TIM= 391.654   JUL  1 1980  0, 0, 0.
ECLIPTIC            X                   Y                   Z                   TOTAL
R EARTH     2.2606421E+07    -1.5040512E+08     1.0259619E+04     1.5209455E+08
V EARTH     2.8970609E+01     4.3255124E+00    -4.9848778E-04     2.9291744E+01
VEL S/C     2.3261913E+01     4.9047628E+00    -1.2238257E+00     2.3804853E+01
VHE        -5.7086965E+00     5.7925041E-01    -1.2233272E+00     5.8669649E+00
RAA=174.206 DECA=-12.035          SEVHE=104.021
EQUATORIAL          X                   Y                   Z                   TOTAL
R EARTH     2.2606421E+07    -1.3799605E+08    -5.9755756E+07     1.5209455E+08
V EARTH     2.8970609E+01     3.9687197E+00     1.8061066E+00     2.9291744E+01
VEL S/C     2.3261913E+01     4.9868136E+00     8.9726080E-01     2.3804853E+01
VHE        -5.7086965E+00     1.0180938E+00    -9.0884577E-01     5.8669649E+00
RAA=169.888 DECA= -8.908 RP= 72656335.99 APO=152573944.11
A=112615140.05 E= .35483 I=  2.952 NODE=278.623 W=186.062
TH1= 186.1   TH2= 464.3   DTH= 278.2   TYPE   IV    I


JD=2444813.154 VHA= 12.537 VHD= 12.537  JUL 27 1981 15, 42, 25.809
ECLIPTIC            X                   Y                   Z                   TOTAL
R VENUS    -1.0319838E+08    -3.1034624E+07     5.5010453E+06     1.0790420E+08
V VENUS     9.8502863E+00    -3.3693544E+01    -1.0457404E+00     3.5119462E+01
V S/C A    -2.4389745E+00    -3.5710663E+01     4.0041216E-01     3.5796095E+01
VHA        -1.2289261E+01    -2.0171196E+00     1.4461525E+00     1.2537387E+01
V S/C D    -2.0439788E+00    -2.9734103E+01    -1.1789040E+00     2.9827580E+01
VHD        -1.1894265E+01     3.9594405E+00    -1.3316370E-01     1.2536684E+01
RCA=  6300.0   BTH=193.6     B*T=    -7880     B*R=    -1907     HCA=   250.0
RAA= 189.3 DECA=   6.6 SPA= 171.7 EPA= 143.5 CPA=  95.2   TYPE IV    I
RAE= 333.1 DECE=  -1.5 RAS=  16.7 DECS=  -2.9
AH=      2066.7 EH=  4.04830 I= 164.9 NODE= 343.8 W= 139.4 TAU=  75.7
A= 84522912.0 E=    .435660 I=   4.6 NODE= 416.4 W= 353.2 TURN=  28.6
THI= 147.0 THF= 342.5 DTH= 195.5 FLT TIM= 260.095
PERIHELION= 47699638.0  APHELION=121346186.0

JD=2445073.250    VHP=  6.903   APR 13 1982 17,59,53.413
ECLIPTIC            X                   Y                   Z                   TOTAL
R MERCURY  4.0902056E+07     2.5787183E+07    -1.5838280E+06     4.8378357E+07
V MERCURY -3.5490505E+01     4.3458807E+01     6.8162084E+00     5.6521718E+01
V S/C     -3.7893209E+01     4.9579857E+01     4.7166660E+00     6.2580384E+01
VHP       -2.4027042E+00     6.1210503E+00    -2.0995424E+00     6.9027765E+00
RAA= 111.4    DECA= -17.7     SPA= 100.9    EPA=  93.5    CPA=  58.2
RAE= 205.0    DECE=    .5     RAS=-147.8    DECS=   1.9
EQUATORIAL          X                   Y                   Z                   TOTAL
R MERCURY -4.7123693E+07    -1.0946368E+07    -7.4505806E-09     4.8378357E+07
V MERCURY  1.9569565E+01    -5.3025811E+01     2.8421709E-14     5.6521718E+01
V S/C      1.9699914E+01    -5.9332645E+01    -2.8027107E+00     6.2580384E+01
VHP        1.3034854E-01    -6.3068332E+00    -2.8027107E+00     6.9027765E+00
RAA= 271.2  DECA= -24.0  RAS=  13.1  DECS=     .0  RAE=    6.1  DECE=  -2.2
MERCURY OP          X                   Y                   Z                   TOTAL
R MERCURY  4.6701186E+07    -1.2627933E+07    -7.4505806E-09     4.8378357E+07
V MERCURY  7.8186542E+00     5.5978328E+01     2.8421709E-14     5.6521718E+01
V S/C      1.0684879E+01     6.1597749E+01    -2.8027107E+00     6.2580384E+01
VHP        2.8662245E+00     5.6194210E+00    -2.8027107E+00     6.9027765E+00
RAA=  63.0  DECA= -24.0  RAS= 164.9  DECS=     .0  RAE= 157.8  DECE=  -2.2
```

TABLE III-3 TRAJECTORY PRINTOUT, 7-1-80 LAUNCH

D. Flight Characteristics

Time histories of four geometry parameters for this opportunity are depicted in Figure III-4. Again, the Earth-spacecraft range during the pre-Venus tracking arc is over two hundred million kilometers, although the position of Earth is significantly different (Figure III-5). The different position of Earth gets away from the zero equatorial declination problem during the pre-Venus tracking arc as may be seen in Figure III-4. Unfortunately, a different geometry problem occurs to degrade the Orbit Determination process. As can be seen in Figure III-4, the Earth-spacecraft range is very constant during the pre-Venus tracking arc. This leads to the plane-of-the-sky problem which prohibits good determination of Z and $\dot{Z}$. The zero declination problem does occur during the pre-Mercury tracking arc for this trajectory.

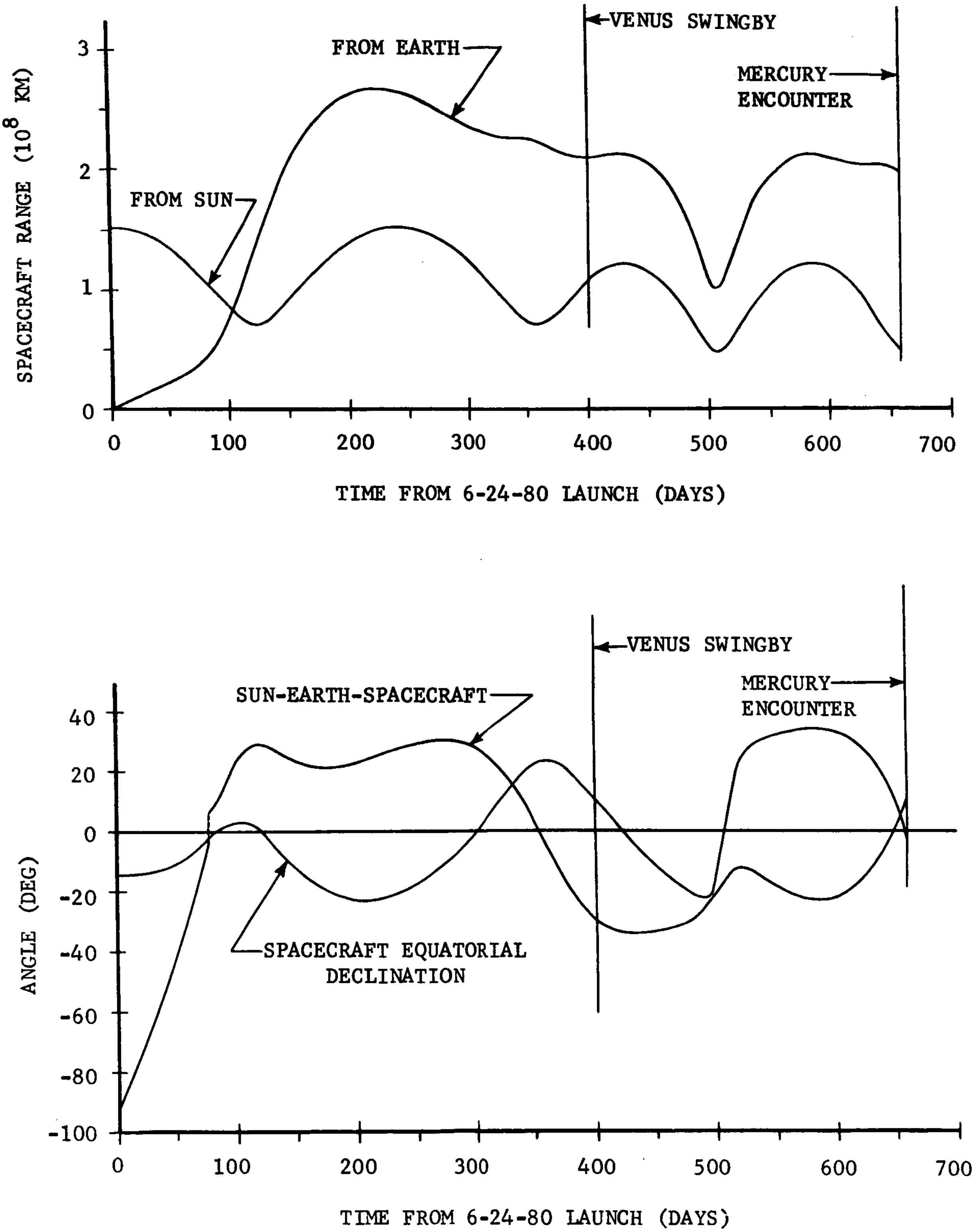


Figure III-4. Typical Time Histories, 1980 Opportunity

E. Navigation Requirements

The standard four midcourse maneuvers plus one each for the two extra solar revolutions are required for this opportunity. The pre-Venus Orbit determination errors are larger than normal (for pre-Venus tracking arcs) due to the large Earth-spacecraft range and the plane-of-the-sky problem. The total (mean + three sigma) ΔV requirements for all six statistical midcourse maneuvers described in Table III-4 is 240 mps. As explained in Section VI, a 100 mps planned maneuver can be combined with the large V+2 maneuver for a statistical penalty of 26 mps.

The final Mercury B-plane dispersions (Figure VI-7) are dominated by ephemeris errors on the T-axis and approach orbit determination uncertainties on the R-axis. That results from the zero equatorial declination problem during the pre-Mercury tracking arc.

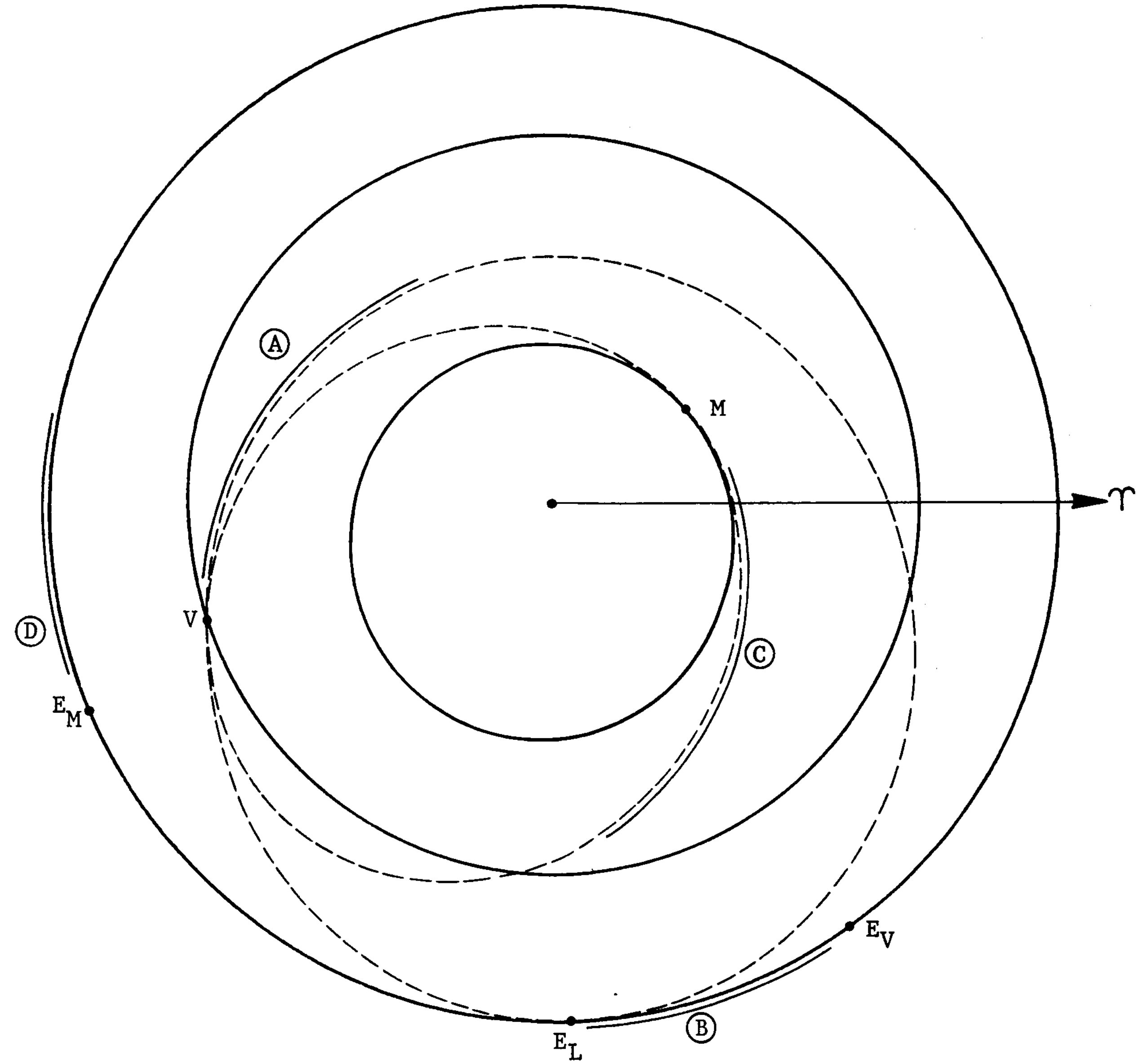
TABLE III-4

1980 MANEUVER SCHEDULE AND STATISTICAL DESCRIPTION

MANEUVER TIME (days)	MEAN ΔV (m/s)	SIGMA ΔV (m/s)	MEAN PLUS THREE SIGMA (m/s)
E+10	7.53	5.12	22.9
E+260	.06	.04	.2
V-3	1.08	.72	3.2
V+2	66.04	41.84	206.6*
M-100	.98	.58	2.7
M-3	1.32	.99	4.3
		TOTAL	239.9

* 233 mps when combined with 100 mps planned velocity maneuver at Venus.

Three sigma uncertainties in Venus swingby altitude are listed as 87 kilometers in Section VI. This result is a function of the assumptions also listed in that section. Raising the nominal Venus swingby radius from 6300 km to 6350 km could be accomplished with small velocity maneuvers at Venus or constrained with unpowered swingby for the penalties indicated in Figure III-3.



(A) SPACECRAFT DURING PRE-VENUS TRACKING PERIOD
(B) EARTH DURING PRE-VENUS TRACKING PERIOD
(C) SPACECRAFT DURING PRE-MERCURY TRACKING PERIOD
(D) EARTH DURING PRE-MERCURY TRACKING PERIOD

Figure III-5. Critical Tracking Geometries, 1980 Opportunity

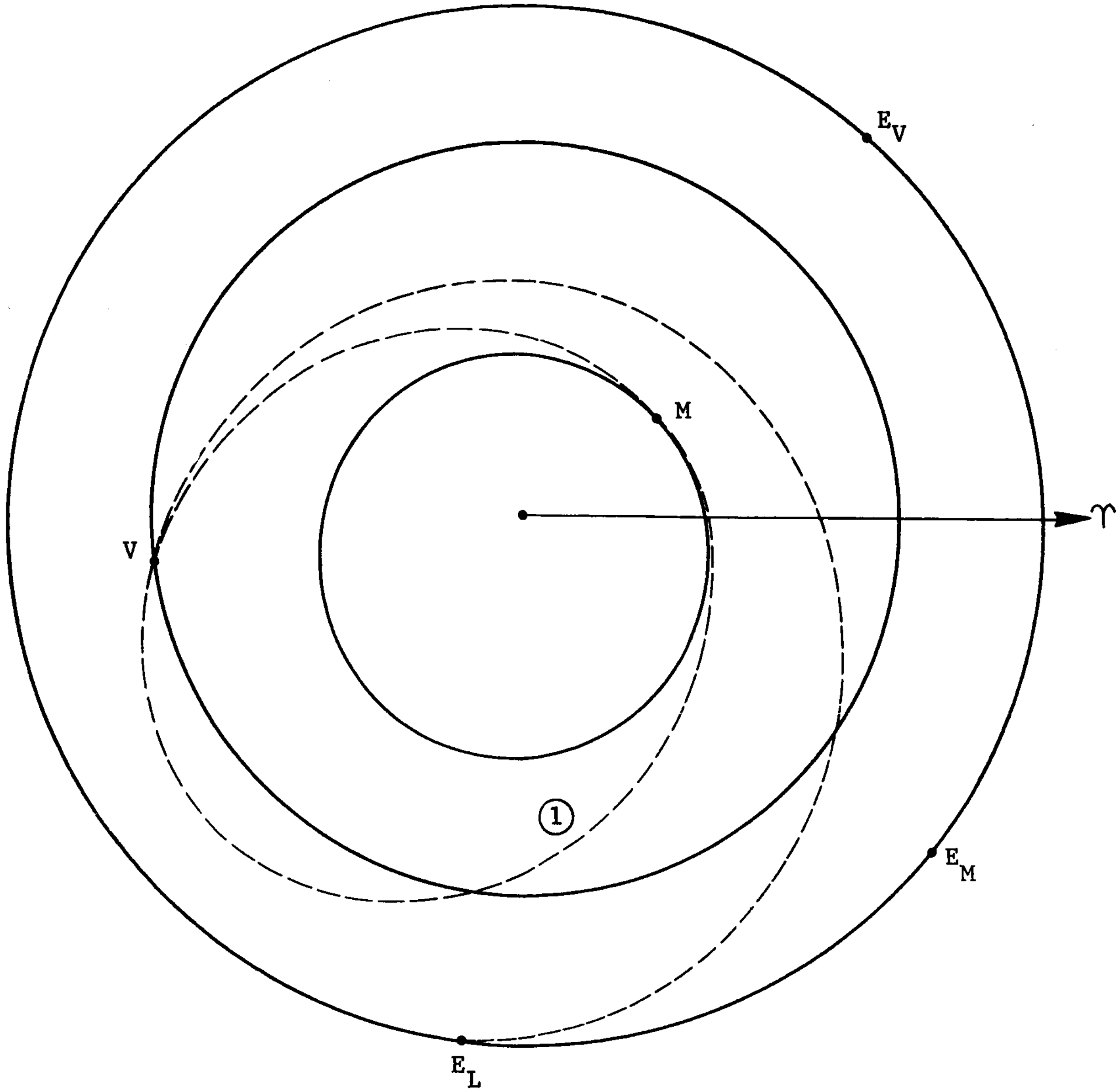
IV. 1985 MISSION OPPORTUNITY

IV. 1985 MISSION OPPORTUNITY

A. Heliocentric Geometry

Figure IV-1 shows the flight profile for the 13 month 1985 opportunity. This mission is similar to 1977 through Venus swingby, i.e., no phasing orbits are employed for the Earth-Venus transfer. However, the Venus-Mercury trajectory is similar to the 1980 opportunity in that one complete solar revolution of the spacecraft is required for phasing with Mercury.

Earth position at Venus swingby is similar to the 1977 opportunity. Relative geometry during the Mercury encounter is,however, different from both the 1977 and 1980 cases. The implications to Earth tracking and navigation requirements are discussed in Subsection IV.E and Section VI.



E_L: EARTH AT LAUNCH, 6-15-85

E_V: EARTH AT VENUS SWINGBY, 11-11-85

E_M: EARTH AT MERCURY ENCOUNTER, 8-15-86

V: VENUS AT SWINGBY

M: MERCURY AT ENCOUNTER

① ONE COMPLETE SOLAR REVOLUTION BEFORE MERCURY ENCOUNTER

Figure IV-1. Heliocentric Geometry, 1985 Opportunity

B. Performance Parameters

Planetary geometries for the 1985 opportunity depart significantly from the ideal conditions for ballistic flight with Venus gravity-assist. Consequently, performance is relatively poor.

Figure IV-2 illustrates the primary performance limitation. As shown, relative velocities at Mercury exceed those for the 1977 and 1980 opportunities by over one km/sec. The reasons for this condition involve conflicts of Venus swingby timing as discussed in Appendix 2.

Since the 1985 opportunity represents the only identified simple ballistic mission option for the mid 1980's and since larger capability launch vehicles such as Shuttle/Centaur may be available, complete parametric analyses were conducted. Figure IV-3 presents launch energy requirements with conditions for minimum Mercury approach velocity indicated. For this parameter, similarities to the 1977 opportunity requirements are exhibited.

Another similarity to the 1977 mission involves the relatively large Venus swingby altitude values shown on Figure IV-4. As was the case for 1977, this altitude clearance is the result of imperfect planet alignments limiting the extent of the Venus swingby contribution to performance.

All data presented in this section apply to the ballistic flight mode. Section VII presents potential performance improvements available with a mid-course maneuver flight technique. On the basis of preliminary investigation, this alternate flight technique appears basic to a useful 1985 Mercury orbiter mission.

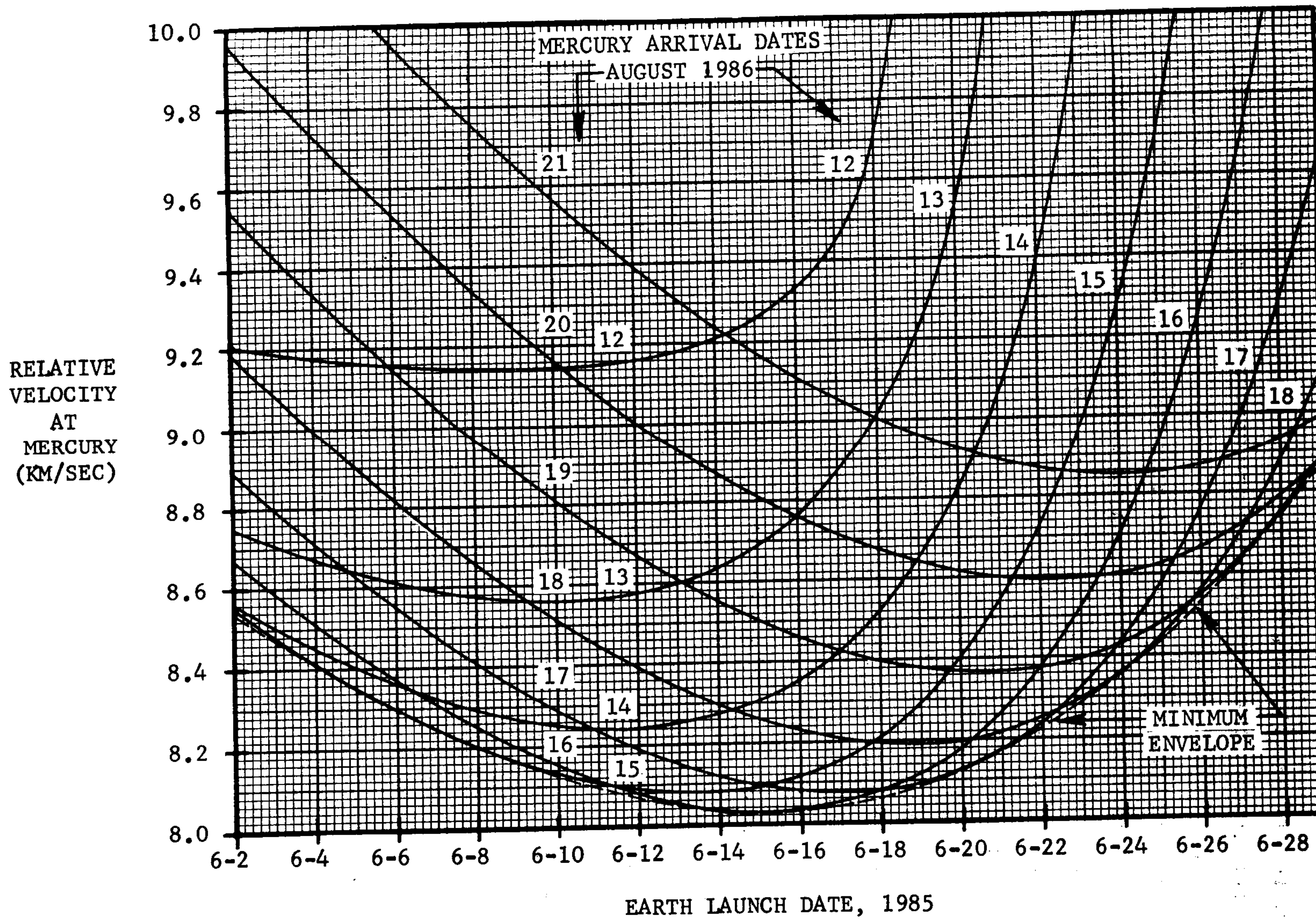


Figure IV-2. Relative Velocity at Mercury vs. Launch/Arrival Date, 1985 Opportunity

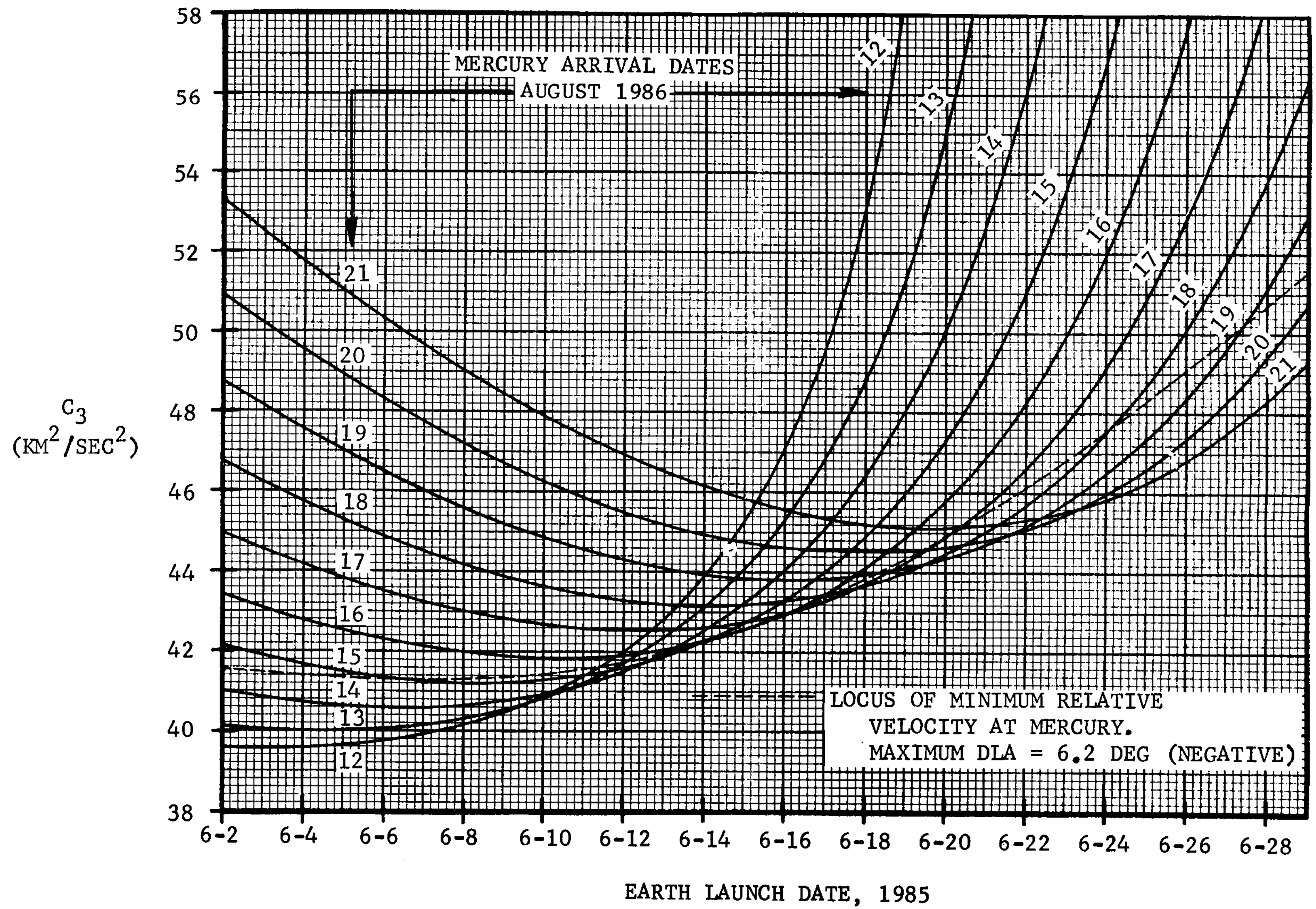


Figure IV-3. C_3 vs. Launch/Arrival Date, 1985 Opportunity

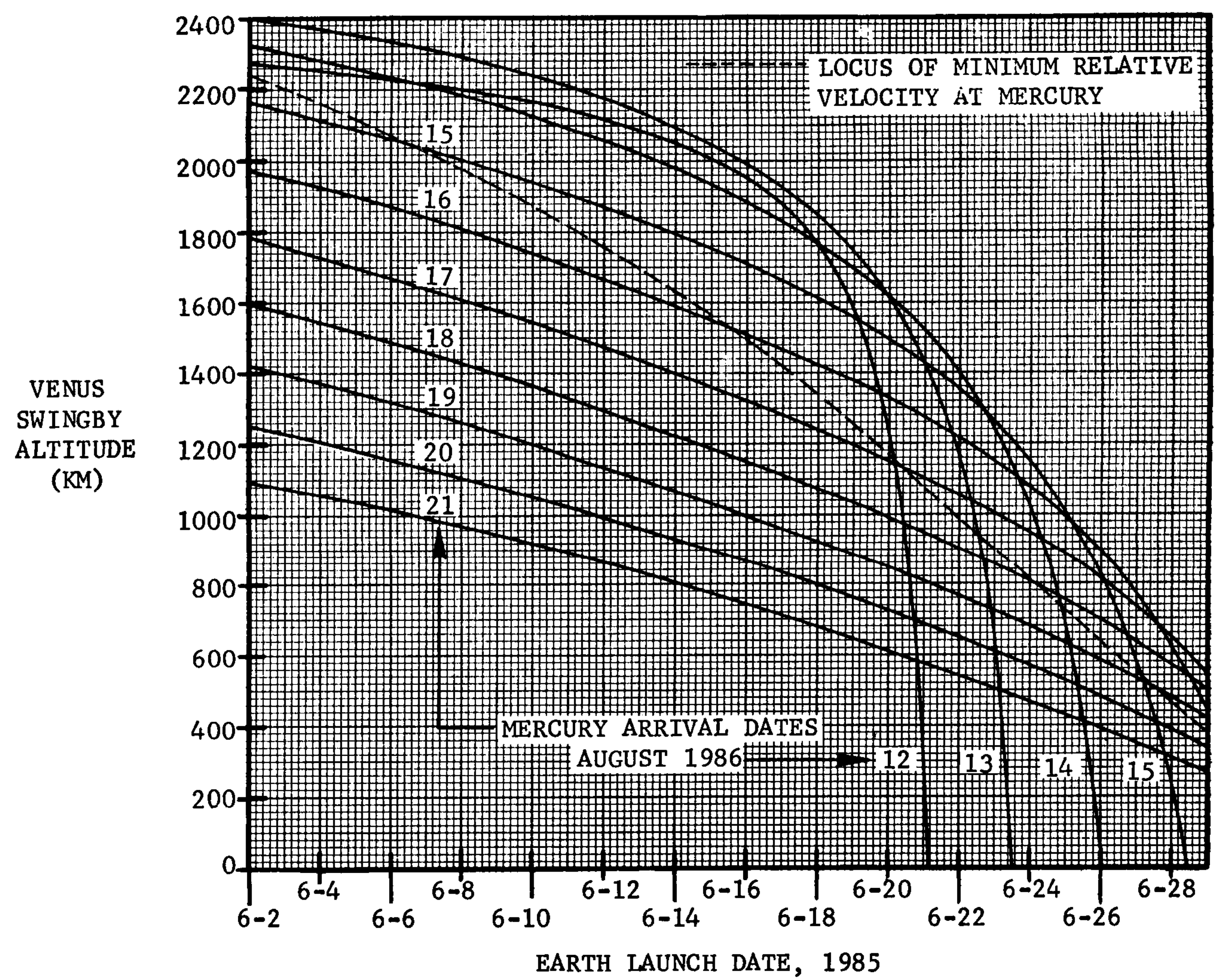


Figure IV-4. Venus Swingby Altitude vs. Launch/Arrival Date, 1985 Opportunity

C. Trajectory Data

Tabulated details for three representative trajectories for the 1985 opportunity are listed in Tables IV-1 through IV-3. The Earth launch dates (6-8, 6-15, and 6-22) are approximately centered on the best performance 15 day launch period. Mercury encounter 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=2446224.500   C3=  41.284  FLT TIM= 155.772   JUN  8 1985   0, 0, 0.
ECLIPTIC            X                  Y                  Z                 TOTAL
R EARTH     -3.6043312E+07    -1.4750678E+08     1.2155036E+04     1.5184653E+08
V EARTH      2.8450121E+01    -7.1726728E+00     3.4955099E-04     2.9340359E+01
VEL S/C      2.2401174E+01    -5.4910344E+00    -1.3657779E+00     2.3104748E+01
VHE         -6.0489475E+00     1.6816384E+00    -1.3661275E+00     6.4252609E+00
RAA=164.464 DECA=-12.276           SEVHE= 91.765
EQUATORIAL          X                  Y                  Z                 TOTAL
R EARTH     -3.6043312E+07    -1.3533852E+08    -5.8790027E+07     1.5184653E+08
V EARTH      2.8450121E+01    -6.5808826E+00    -2.7549663E+00     2.9340359E+01
VEL S/C      2.2401174E+01    -4.4945840E+00    -3.3602281E+00     2.3104748E+01
VHE         -6.0489475E+00     3.0862986E+00    -6.0526180E-01     6.4252609E+00
RAA=160.971 DECA= -5.404 RP= 66762671.48 APO=151846595.14
A=109304633.31 E= .38921 I=  3.389 NODE=256.346 W=179.857
TH1= 179.9   TH2= 471.0   DTH= 291.1   TYPE   II

JD=2446380.272 VHA= 13.793 VHD= 13.793  NOV 10 1985 18, 31, 50.504
ECLIPTIC            X                  Y                  Z                 TOTAL
R VENUS     -1.0674139E+08    -1.3849650E+07     5.9485923E+06     1.0780039E+08
V VENUS      4.2847590E+00    -3.4883158E+01    -7.4258782E-01     3.5153169E+01
V S/C A     -9.4585259E+00    -3.4037753E+01     6.8483663E-02     3.5327568E+01
VHA         -1.3743285E+01     8.4540408E-01     8.1107148E-01     1.3793130E+01
V S/C D     -8.3735347E+00    -2.9404544E+01    -7.9393698E-01     3.0583879E+01
VHD         -1.2658294E+01     5.4786133E+00    -5.1349165E-02     1.3793123E+01
RCA=  8032.7   BTH=189.8      B*T=     -9448     B*R=     -1639    HCA=  1982.7
RAA= 176.5 DECA=    3.4 SPA= 169.1 EPA= 145.8 CPA=  89.0   TYPE IV    I
RAE=  30.7 DECE=  -1.4 RAS=   7.4 DECS=  -3.2
AH=     1707.5 EH=  5.70427 I= 169.6 NODE= 337.8 W= 150.9 TAU=  79.9
A= 86921084.1 E=    .450974 I=    4.3 NODE= 414.1 W= 350.7 TURN=  20.2
THI= 142.5 THF= 352.7 DTH= 210.2 FLT TIM= 277.347
PERIHELION= 47721968.1  APHELION=126120200.0

JD=2446657.619    VHP=  8.200   AUG 15 1986  2,51,12.000
ECLIPTIC            X                  Y                  Z                 TOTAL
R MERCURY  3.7925749E+07     2.9147575E+07    -1.0351063E+06     4.7843652E+07
V MERCURY -3.9234848E+01     4.0847051E+01     6.9402283E+00     5.7061560E+01
V S/C     -4.0427453E+01     4.8630531E+01     4.6512831E+00     6.3410898E+01
VHP       -1.1926056E+00     7.7834801E+00    -2.2889451E+00     8.2002524E+00
RAA=  98.7    DECA= -16.2     SPA= 118.0    EPA= 151.5    CPA=  59.7
RAE= 302.7    DECE=     .4    RAS=-142.5    DECS=   1.2
EQUATORIAL          X                  Y                  Z                 TOTAL
R MERCURY -4.5801677E+07    -1.3828282E+07     3.7252903E-09     4.7843652E+07
V MERCURY  2.2484453E+01    -5.2444933E+01     0.                5.7061560E+01
V S/C      2.0705427E+01    -5.9859158E+01    -3.0180234E+00     6.3410898E+01
VHP       -1.7790268E+00    -7.4142254E+00    -3.0180234E+00     8.2002524E+00
RAA= 256.5  DECA= -21.6  RAS=  16.8  DECS=    -.0  RAE= 102.0  DECE=   7.2
MERCURY OP          X                  Y                  Z                 TOTAL
R MERCURY  4.7157502E+07    -8.0737234E+06     3.7252903E-09     4.7843652E+07
V MERCURY  3.2938282E+00     5.6966414E+01     0.                5.7061560E+01
V S/C      8.1957022E+00     6.2806560E+01    -3.0180234E+00     6.3410898E+01
VHP        4.9018740E+00     5.8401460E+00    -3.0180234E+00     8.2002524E+00
RAA=  50.0  DECA= -21.6  RAS= 170.3  DECS=    -.0  RAE= 255.4  DECE=   7.2
```

TABLE IV-1 TRAJECTORY PRINTOUT, 6-8-85 LAUNCH

```
JD=2446231.500    C3=  42.559  FLT TIM= 150.410   JUN 15 1985  0, 0, 0.
ECLIPTIC            X                  Y                  Z                 TOTAL
R EARTH    -1.8627542E+07    -1.5081413E+08    1.2288497E+04    1.5196015E+08
V EARTH     2.9076829E+01    -3.7533540E+00    6.9493269E-05    2.9318077E+01
VEL S/C     2.2993075E+01    -1.7936540E+00   -1.3062086E+00    2.3099889E+01
VHE        -6.0837543E+00     1.9597000E+00   -1.3062781E+00    6.5237146E+00
RAA=162.149 DECA=-11.551        SEVHE=100.593
EQUATORIAL          X                  Y                  Z                 TOTAL
R EARTH    -1.8627542E+07    -1.3837300E+08   -6.0045614E+07    1.5196015E+08
V EARTH     2.9076829E+01    -3.4436339E+00   -1.3928319E+00    2.9318077E+01
VEL S/C     2.2993075E+01    -1.1260287E+00   -1.8327043E+00    2.3099889E+01
VHE        -6.0837543E+00     2.3176052E+00   -4.3987235E-01    6.5237146E+00
RAA=159.146 DECA= -3.865 RP= 66603657.24 APO=152200678.45
A=109402167.84 E= .39120 I=  3.245 NODE=263.041 W=183.940
TH1= 184.0    TH2= 471.1    DTH= 287.1    TYPE   II

JD=2446381.910 VHA= 13.864 VHD= 13.864  NOV 12 1985  9, 49, 41.577
ECLIPTIC            X                  Y                  Z                 TOTAL
R VENUS    -1.0602233E+08    -1.8768182E+07    5.8372708E+06    1.0782881E+08
V VENUS     5.8787746E+00    -3.4638791E+01   -8.3088742E-01    3.5143936E+01
V S/C A    -7.9439841E+00    -3.4428466E+01    2.1054319E-01    3.5333701E+01
VHA        -1.3822759E+01     2.1032565E-01    1.0414306E+00    1.3863530E+01
V S/C D    -7.0553213E+00    -2.9658189E+01   -1.1472972E+00    3.0507410E+01
VHD        -1.2934096E+01     4.9806019E+00   -3.1640978E-01    1.3863526E+01
RCA=  7610.8    BTH=195.1     B*T=     -8829     B*R=     -2386     HCA=  1560.8
RAA= 179.1 DECA=    4.3 SPA= 169.0 EPA= 146.3 CPA=   90.5    TYPE IV     I
RAE=   32.8 DECE=   -1.4 RAS=   10.0 DECS=   -3.1
AH=      1690.2 EH=  5.50277 I= 164.3 NODE= 343.6 W= 153.4 TAU=  79.5
A= 86692683.5 E=     .453728 I=    4.8 NODE= 410.1 W= 357.0 TURN=  20.9
THI= 142.8 THF= 355.3 DTH= 212.5 FLT TIM= 276.549
PERIHELION= 47357771.8  APHELION=126027595.3

JD=2446658.459     VHP=  8.028    AUG 15 1986 23, 0,48.000
ECLIPTIC            X                  Y                  Z                 TOTAL
R MERCURY  3.4959191E+07     3.2015035E+07   -5.2862249E+05    4.7406613E+07
V MERCURY -4.2486403E+01     3.8117357E+01    7.0098988E+00    5.7507965E+01
V S/C      -4.4061852E+01     4.5806925E+01    5.3237796E+00    6.3781375E+01
VHP        -1.5754484E+00     7.6895687E+00   -1.6861192E+00    8.0283561E+00
RAA= 101.6    DECA= -12.1    SPA= 120.3    EPA= 154.9    CPA=   63.7
RAE= 303.9    DECE=     .2    RAS=-137.5    DECS=      .6
EQUATORIAL          X                  Y                  Z                 TOTAL
R MERCURY -4.5425970E+07    -1.3559804E+07    3.7252903E-09    4.7406613E+07
V MERCURY  2.1799561E+01    -5.3216023E+01    0.               5.7507965E+01
V S/C       1.9773939E+01    -6.0589354E+01   -2.4465002E+00    6.3781375E+01
VHP        -2.0256216E+00    -7.3733300E+00   -2.4465002E+00    8.0283561E+00
RAA= 254.6   DECA= -17.7   RAS=   16.6   DECS=     -.0   RAE=   97.9   DECE=    7.0
MERCURY OP          X                  Y                  Z                 TOTAL
R MERCURY  4.7244451E+07    -3.9177644E+06    3.7252903E-09    4.7406613E+07
V MERCURY -9.1848772E-01     5.7500630E+01    0.               5.7507965E+01
V S/C       3.6536618E+00     6.3629625E+01   -2.4465002E+00    6.3781375E+01
VHP         4.5721495E+00     6.1289956E+00   -2.4465002E+00    8.0283561E+00
RAA=   53.3   DECA= -17.7   RAS= 175.3   DECS=     -.0   RAE= 256.6   DECE=    7.0
```

TABLE IV-2 TRAJECTORY PRINTOUT, 6-15-85 LAUNCH

```
JD=2446238.500   C3=  46.154  FLT TIM= 145.032   JUN 22 1985  0, 0, 0.
ECLIPTIC            X                  Y                  Z                 TOTAL
R EARTH    -9.5430160E+05    -1.5203756E+08    1.2252199E+04     1.5204056E+08
V EARTH     2.9300898E+01    -2.8875076E-01   -2.1129142E-04     2.9302320E+01
VEL S/C     2.3019470E+01     1.9759439E+00   -1.2526491E+00     2.3138053E+01
VHE        -6.2814272E+00     2.2646946E+00   -1.2524378E+00     6.7936566E+00
RAA=160.174 DECA=-10.623        SEVHE=109.121
EQUATORIAL          X                  Y                  Z                 TOTAL
R EARTH    -9.5430160E+05    -1.3949545E+08   -6.0471432E+07     1.5204056E+08
V EARTH     2.9300898E+01    -2.6483739E-01   -1.4070139E-02     2.9302320E+01
VEL S/C     2.3019470E+01     2.3111752E+00   -2.8391383E-01     2.3138053E+01
VHE        -6.2814272E+00     2.5760126E+00   -2.6984370E-01     6.7936566E+00
RAA=157.701 DECA= -2.276 RP= 66248777.88 APO=153041531.80
A=109645154.84 E= .39579 I=  3.116 NODE=269.725 W=188.045
TH1= 188.1   TH2= 471.1   DTH= 283.0   TYPE   II

JD=2446383.532 VHA= 14.039 VHD= 14.039  NOV 14 1985  0, 45, 45.807
ECLIPTIC            X                  Y                  Z                 TOTAL
R VENUS    -1.0508843E+08    -2.3602106E+07    5.7147829E+06     1.0785776E+08
V VENUS     7.4445404E+00    -3.4324544E+01   -9.1656713E-01     3.5134536E+01
V S/C A    -6.5306205E+00    -3.4752398E+01    3.4644835E-01     3.5362383E+01
VHA        -1.3975161E+01    -4.2785319E-01    1.2630155E+00     1.4038639E+01
V S/C D    -5.8376668E+00    -2.9820976E+01   -1.5366484E+00     3.0425815E+01
VHD        -1.3282207E+01     4.5035685E+00   -6.2008131E-01     1.4038649E+01
RCA=  7044.5   BTH=200.1     B*T=     -8013     B*R=     -2938    HCA=    994.5
RAA= 181.8 DECA=    5.2 SPA= 168.9 EPA= 146.8 CPA=   92.0    TYPE IV    I
RAE=   34.8 DECE=   -1.4 RAS=   12.7 DECS=  -3.0
AH=       1648.3 EH=   5.27370 I= 159.2 NODE= 348.0 W= 154.4 TAU=   79.1
A= 86449222.2 E=     .458879 I=    5.4 NODE= 406.7 W=    2.7 TURN=  21.9
THI= 143.2 THF= 361.7 DTH= 218.6 FLT TIM= 276.357
PERIHELION= 46779521.5  APHELION=126118922.8

JD=2446659.889    VHP=  8.224   AUG 17 1986   9,20,   .001
ECLIPTIC            X                  Y                  Z                 TOTAL
R MERCURY  2.9390357E+07     3.6401099E+07    3.3975341E+05     4.6786200E+07
V MERCURY -4.7546776E+01     3.2731850E+01    7.0243093E+00     5.8149900E+01
V S/C      -4.9470233E+01     4.0669375E+01    6.0576770E+00     6.4327268E+01
VHP        -1.9234570E+00     7.9375242E+00   -9.6663229E-01     8.2242541E+00
RAA= 103.6    DECA=  -6.7    SPA= 127.1    EPA= 156.7    CPA=   69.1
RAE= 305.9    DECE=   -.1    RAS=-128.9    DECS=    -.4
EQUATORIAL          X                  Y                  Z                 TOTAL
R MERCURY -4.4857209E+07    -1.3295838E+07    1.8626451E-09     4.6786200E+07
V MERCURY  2.0650253E+01    -5.4359708E+01    5.6843419E-14     5.8149900E+01
V S/C       1.7688403E+01    -6.1821799E+01   -1.7840961E+00     6.4327268E+01
VHP        -2.9618505E+00    -7.4620907E+00   -1.7840961E+00     8.2242541E+00
RAA= 248.4   DECA= -12.5   RAS=  16.5   DECS=     -.0   RAE=  91.2   DECE=    6.7
MERCURY OP          X                  Y                  Z                 TOTAL
R MERCURY  4.6676546E+07     3.2013453E+06    1.8626451E-09     4.6786200E+07
V MERCURY -8.3063021E+00     5.7553305E+01    5.6843419E-14     5.8149900E+01
V S/C      -3.7915435E+00     6.4190643E+01   -1.7840961E+00     6.4327268E+01
VHP         4.5167586E+00     6.6373374E+00   -1.7840961E+00     8.2242541E+00
RAA=  55.8   DECA= -12.5   RAS=-176.1   DECS=     -.0   RAE= 258.6   DECE=    6.7
```

TABLE IV-3 TRAJECTORY PRINTOUT, 6-22-85 LAUNCH

D. Flight Characteristics

Time-histories of four geometry parameters are presented in Figure IV-5. These plots are based on the second reference trajectory for this opportunity. The Earth-Venus leg of this trajectory is very similar to the Earth-Venus leg of the 1977 reference trajectory. As is true for all of these missions, the Earth-spacecraft range during the pre-Venus tracking arc is over two hundred million kilometers. The pre-Venus trajectory is generally in the Earth equatorial plane. Neither spacecraft equatorial declination nor the Sun-Earth-spacecraft angle is near zero during the last half of the pre-Mercury tracking arc.

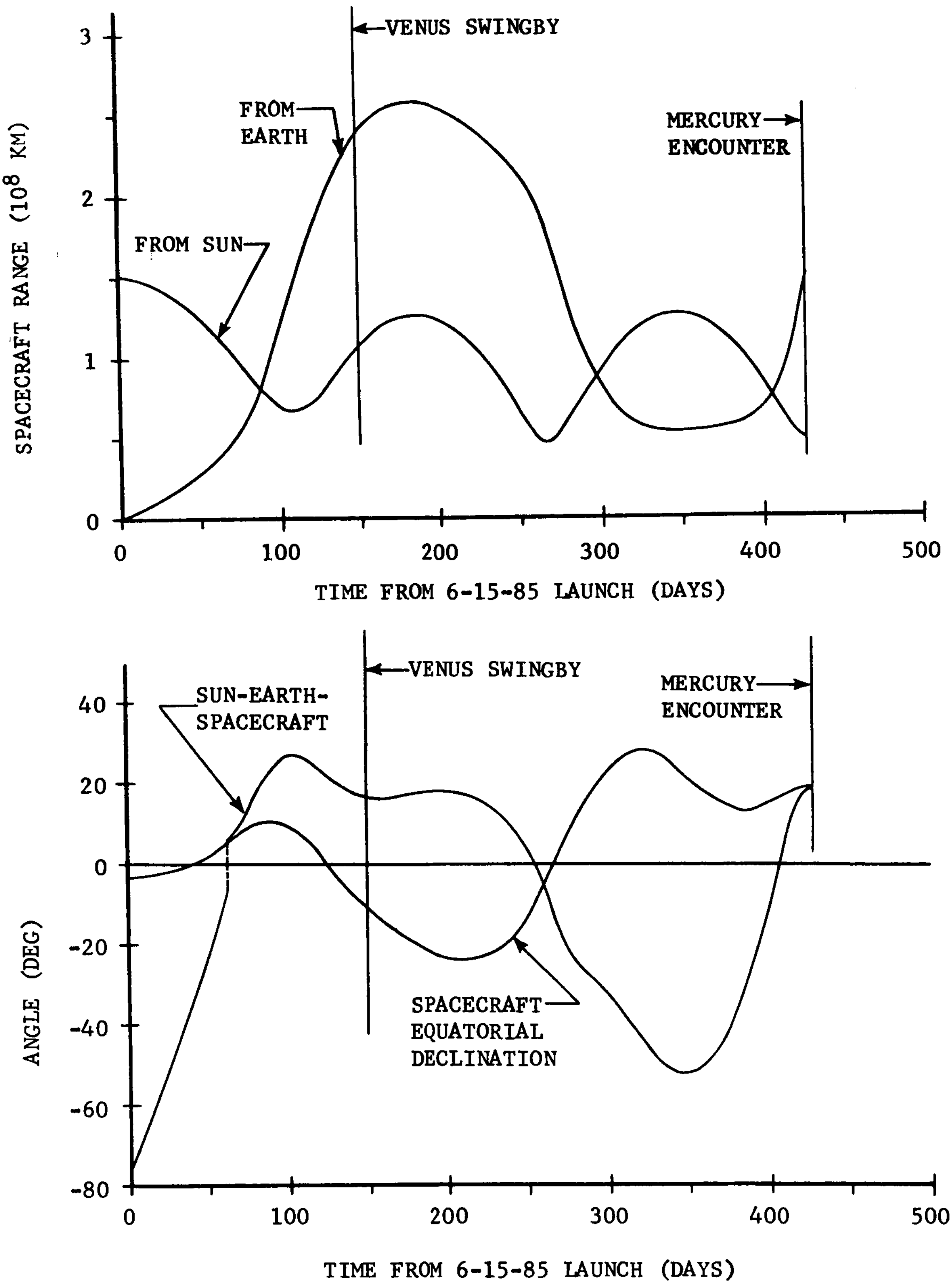


Figure IV-5. Typical Time Histories, 1985 Opportunity

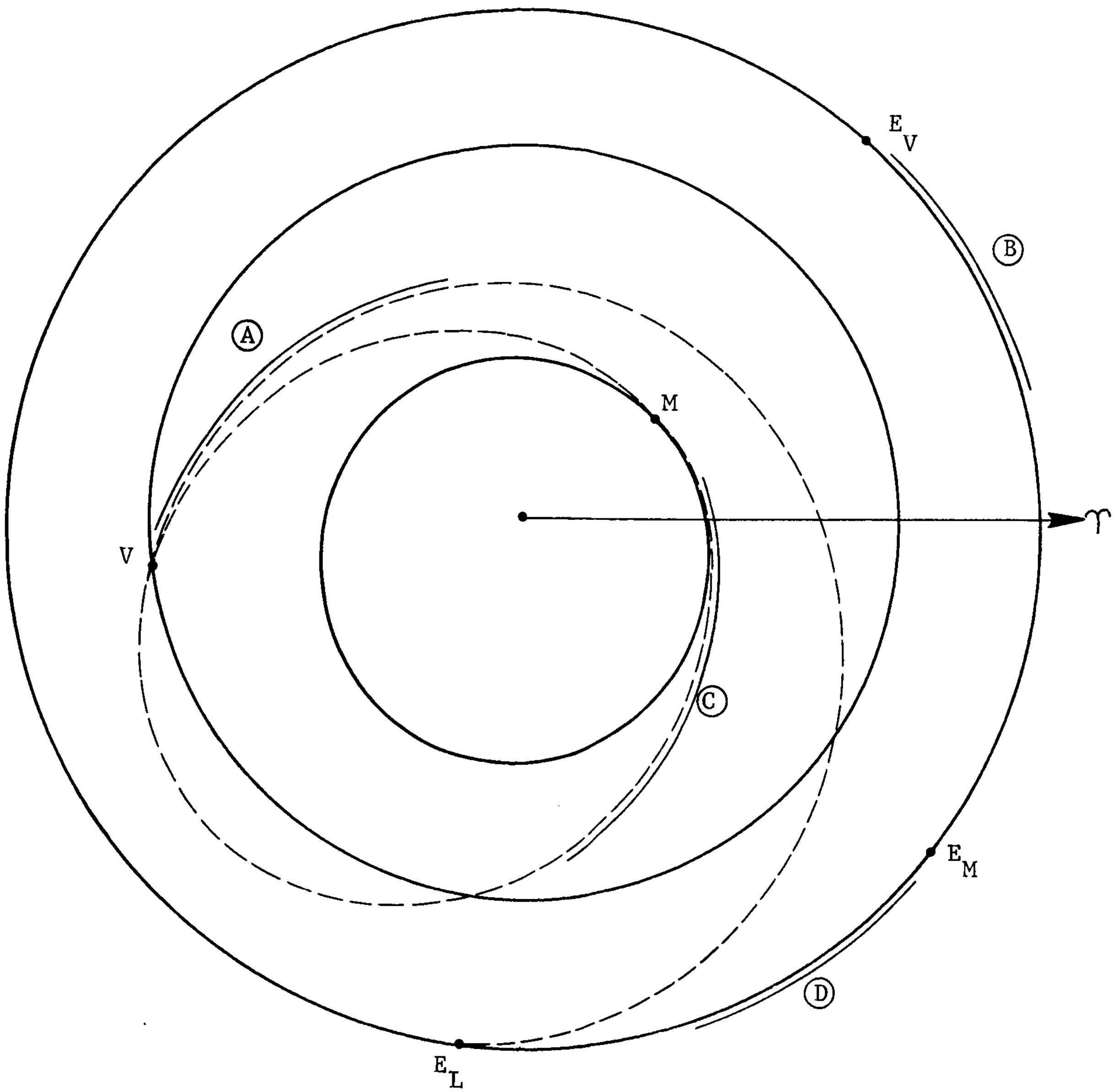
E. Navigation Requirements

The standard four midcourse maneuvers plus one extra for the extra solar revolution on the Venus-Mercury leg are required for this opportunity. A parametric analysis of the pre-Venus tracking arc and the resulting V+2 midcourse maneuver is presented in Section VI. As can be seen in Figure IV-6, the Earth-spacecraft geometry during the pre-Venus tracking arc is very similar to that for the 1977 trajectory. Although some data is lost during the middle of the pre-Mercury tracking arc from solar interference, good Earth-spacecraft geometry during the last several days allows good orbit-determination for the pre-Mercury maneuver. The resulting B-plane dispersions (Figure VI-7) are dominated by the 60 km ephemeris error. A statistical description of the ΔV requirements for the most reasonable set of assumptions is listed in Table IV-4. Applying the Lee-Boain analytical technique to the V+2 covariance indicated a cumulative probability of .99 for 193 m/s and a cumulative probability of .999 for 243 m/s, as compared with 211.1 m/s for the mean plus three sigma from the Hoffman-Young approximation.

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	6.95	4.61	20.8
V-3	1.23	.71	3.4
V+2	69.04	47.34	211.1
M-100	1.20	.78	3.8
M-3	1.00	.75	3.2
		TOTAL	242.3



(A) SPACECRAFT DURING PRE-VENUS TRACKING PERIOD

(B) EARTH DURING PRE-VENUS TRACKING PERIOD

(C) SPACECRAFT DURING PRE-MERCURY TRACKING PERIOD

(D) EARTH DURING PRE-MERCURY TRACKING PERIOD

Figure IV-6. Critical Tracking Geometries, 1985 Opportunity

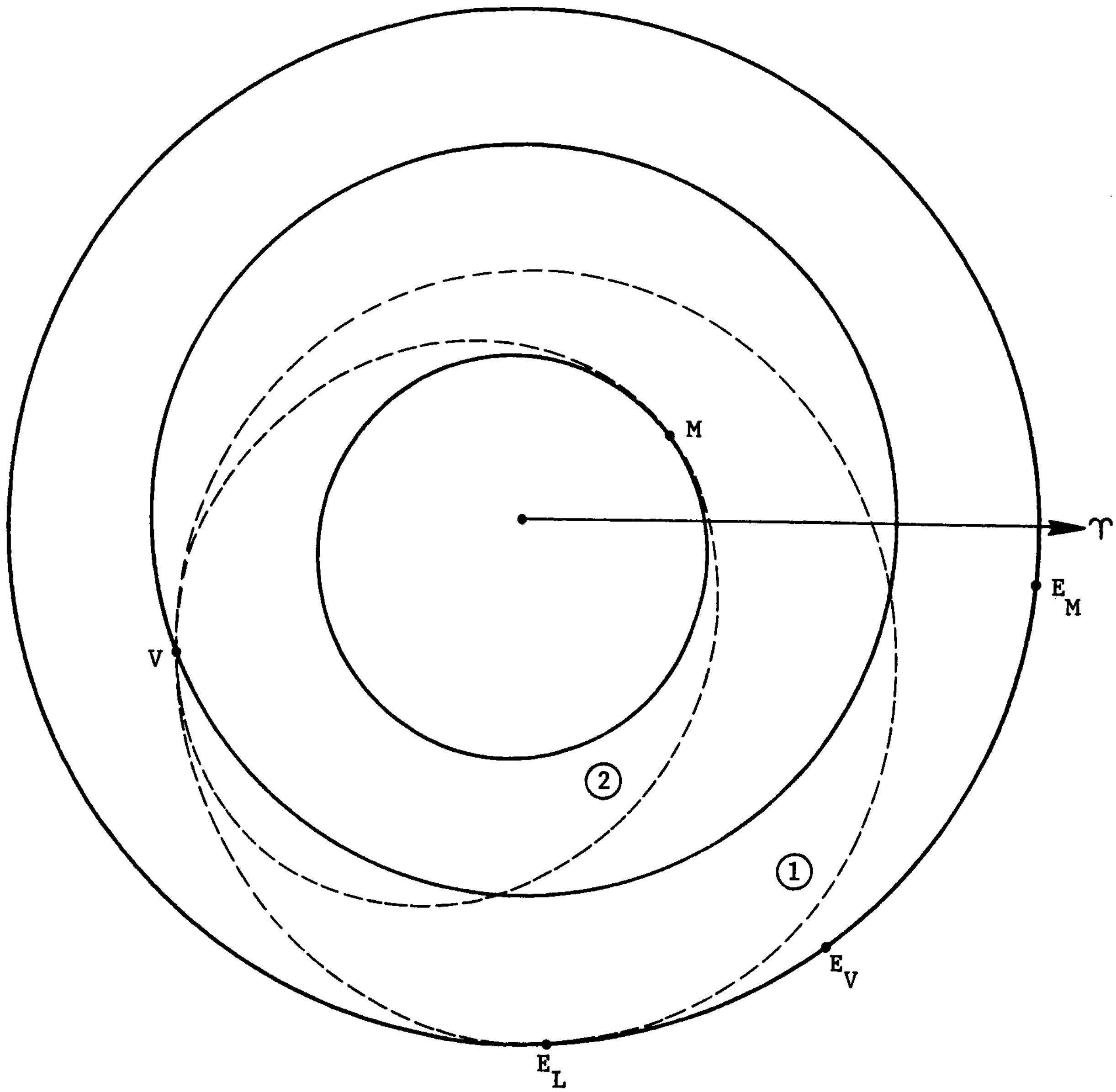
V. 1988 MISSION OPPORTUNITY

V. 1988 MISSION OPPORTUNITY

A. Heliocentric Geometry

The 1988 opportunity involves the longest flight duration of the four baseline mission cases. As shown on Figure V-1, an extra solar revolution is employed during the Earth-Venus transfer producing similarities to the 1980 opportunity. However, two complete revolutions are required for phasing with Mercury with resultant total flight time of about 27 months

Earth position at Mercury encounter is advanced from 1980 mission conditions as a consequence of the additional spacecraft orbit. Subsection V.E and Section VI relate the modified tracking conditions to navigation requirements.



E_L: EARTH AT LAUNCH, 6-26-88

E_V: EARTH AT VENUS SWINGBY, 7-30-89

E_M: EARTH AT MERCURY ENCOUNTER, 9-17-90

V: VENUS AT SWINGBY

M: MERCURY AT ENCOUNTER

1 ONE COMPLETE SOLAR REVOLUTION BEFORE VENUS SWINGBY

2 TWO COMPLETE SOLAR REVOLUTIONS BEFORE MERCURY ENCOUNTER

Figure V-1. Heliocentric Geometry, 1988 Opportunity

B. Performance Parameters

Of the four baseline mission opportunities, the 1988 geometry is the most complex. The nature of the complications is discussed in Appendix 2 in terms of the multiple solutions possible for the Venus swingby phase. Resolution of these complexities has resulted in the highest performance of the baseline mission opportunities.

Figure V-2 illustrates the unique 1988 geometry effects on the primary performance parameters. The representative Mercury arrival dates shown exhibit a region of Earth launch dates for which no usable trajectories exist. This indication of an interruption in the launch period is true for the case of unpowered Venus swingby.

Assessment of the cause of the Earth launch date gap necessitated inspection of the Venus swingby conditions (see Appendix 2). As a result, it was determined that a small (75 mps) velocity maneuver at Venus departure was effective in producing launch period continuity over a region of high performance conditions.

Minimum achievable Mercury approach velocity for the 1988 opportunity is presented in Figure V-3 for optimized Mercury arrival dates in the range of September 17 to 19. These results and the corresponding launch energy requirements are dependent on the 75 mps velocity maneuver at Venus. Combined with the post-Venus navigation correction maneuver, the actual cost of the programmed velocity increment is considerably less than the nominal value. Subsection V.E and Section VI further discuss this statistical benefit.

A range of Venus swingby altitudes is presented on Figure V-3 to permit interpretation for altitude constraints which may result from more thorough analysis of specific navigation system characteristics.

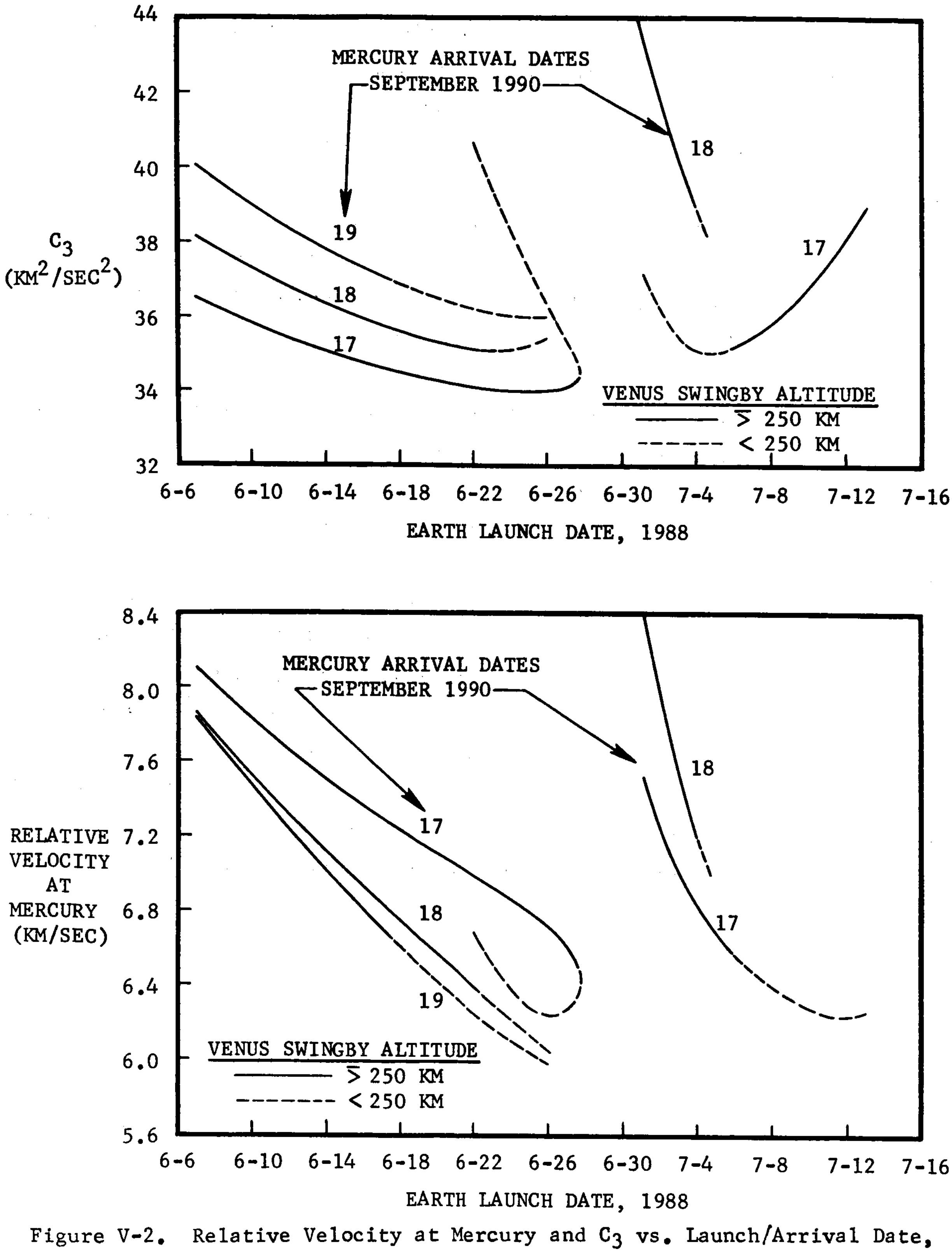


Figure V-2. Relative Velocity at Mercury and C_3 vs. Launch/Arrival Date, 1988 Opportunity

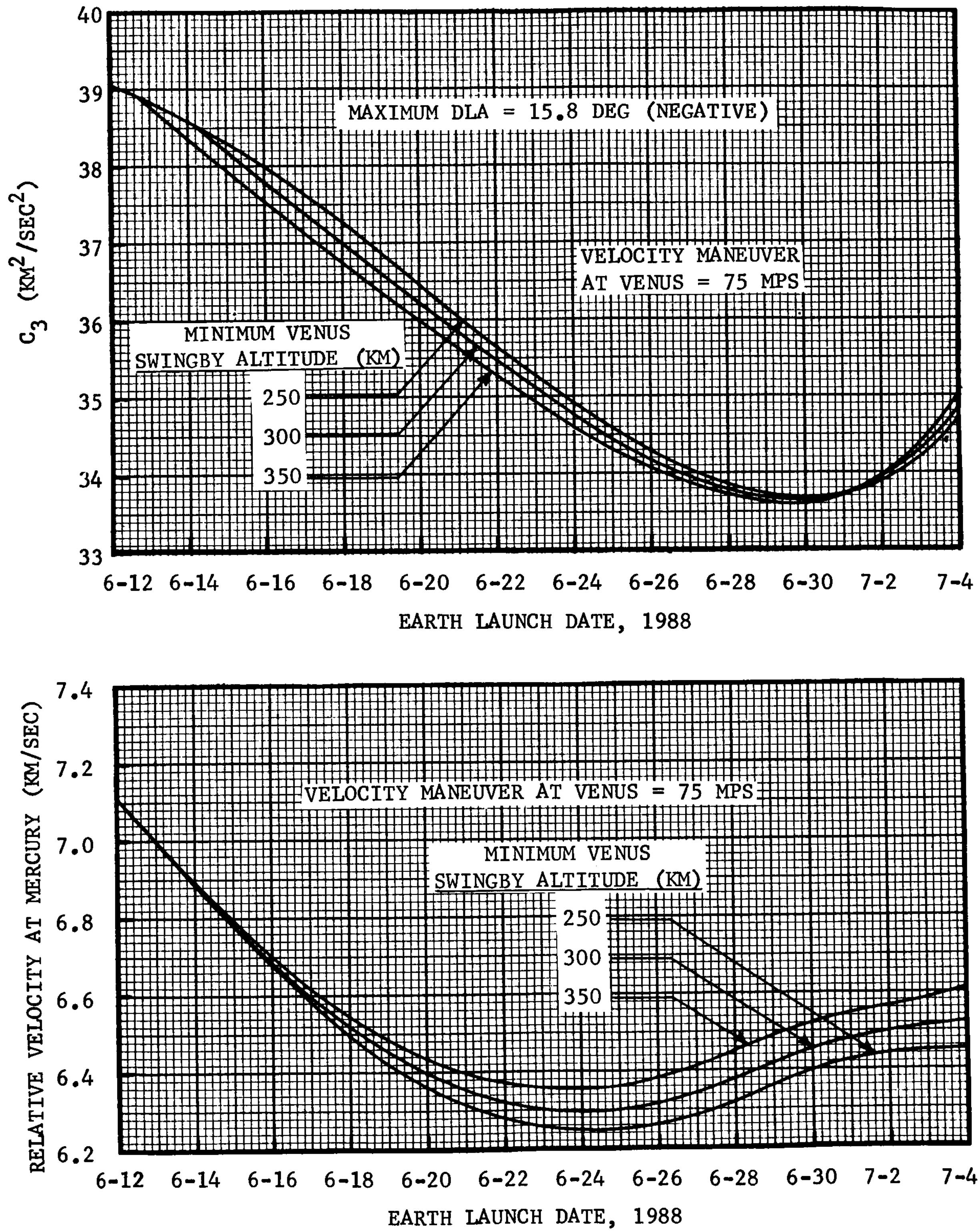


Figure V-3. Minimum Relative Velocity at Mercury and Corresponding C_3 vs. Launch Date, 1988 Opportunity

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C. Trajectory Data

Tabulated details of three reference trajectories for the 1988 opportunity appear in Tables V-1 through V-3. All of these trajectories include a 75 m/s Venus sphere exit maneuver (ΔV_V) and a Venus swingby radius constraint of 6300 km. The Mercury encounter date for each Earth launch date is selected to minimize Mercury approach velocity within the constraint. The Earth launch dates (6-19, 6-26, and 7-3) are approximately centered on the best performance 15 day launch period.

```
JD=2447331.500    C3=  36.815  FLT TIM= 404.837   JUN 19 1988  0, 0, 0.
ECLIPTIC            X                   Y                   Z                 TOTAL
R EARTH     -8.0498153E+06    -1.5179922E+08     1.3326247E+04     1.5201251E+08
V EARTH      2.9259681E+01    -1.6790338E+00    -1.0766646E-04     2.9307816E+01
VEL S/C      2.3442322E+01    -2.8561604E+00    -1.2590227E+00     2.3649213E+01
VHE         -5.8174959E+00    -1.1777894E+00    -1.2588894E+00     6.0675571E+00
RAA±191.445 DECA=-11.975          SEVHE= 75.842
EQUATORIAL          X                   Y                   Z                 TOTAL
R EARTH     -8.0498153E+06    -1.3927776E+08    -6.0401087E+07     1.5201251E+08
V EARTH      2.9259681E+01    -1.5404339E+00    -5.5863975E-01     2.9307816E+01
VEL S/C      2.3442322E+01    -2.1196426E+00    -2.2036412E+00     2.3649213E+01
VHE         -5.8174959E+00    -5.7982703E-01    -1.6452421E+00     6.0675571E+00
RAA=185.692 DECA=-15.717 RP= 71013739.20 APO=152636117.95
A=111824928.58 E= .36496 I=  3.059 NODE=267.058 W=173.056
TH1= 173.1   TH2= 466.2   DTH= 293.1   TYPE    IV    I


JD=2447736.337 VHA= 12.888 VHD= 12.824  JUL 28 1989 20,  5, 45.260
ECLIPTIC            X                   Y                   Z                 TOTAL
R VENUS     -1.0126140E+08    -3.7011225E+07     5.3031299E+06     1.0794362E+08
V VENUS      1.1783263E+01    -3.3050171E+01    -1.1485468E+00     3.5106670E+01
V S/C A     -7.9108353E-01    -3.5658177E+01    -5.5571852E-02     3.5666994E+01
VHA         -1.2574346E+01    -2.6080054E+00     1.0929750E+00     1.2888385E+01
V S/C D     -6.0120824E-01    -2.9783194E+01    -1.7890760E+00     2.9842937E+01
VHD         -1.2384471E+01     3.2669776E+00    -6.4052920E-01     1.2824139E+01
RCA=  6300.0     BTH=195.7      B*T=      -7720      B*R=      -2176     HCA=    250.0
RAA= 191.7 DECA=    4.5 SPA= 171.4 EPA= 143.1 CPA=   94.1    TYPE VI     I
RAE= 334.9 DECE=   -1.5 RAS=  20.1 DECS=  -2.8
AH=      1955.7 EH=  4.22137 I= 163.5 NODE= 355.0 W= 148.9 TAU=  76.3
A= 84620709.9 E=     .441007 I=    5.5 NODE= 410.6 W=    2.7 TURN=  27.4
THI= 146.7 THF= 343.7 DTH= 197.1 FLT TIM= 416.679
PERIHELION= 47302392.8  APHELION=121939027.0

RCA CONSTRAINED AT    6300.0
DV          -7.1853309E-02    -1.8954970E-02     7.4378067E-03     7.4682728E-02
ACTUAL RCA USED IS    6300.0

JD=2448153.016     VHP=   6.423    SEP 18 1990 12,23,27.998
ECLIPTIC            X                   Y                   Z                 TOTAL
R MERCURY   3.8197817E+07     2.8863154E+07    -1.0827721E+06     4.7888697E+07
V MERCURY  -3.8915077E+01     4.1089906E+01     6.9310628E+00     5.7015816E+01
V S/C      -4.1936254E+01     4.6683918E+01     6.0150042E+00     6.3041398E+01
VHP        -3.0211767E+00     5.5940114E+00    -9.1605853E-01     6.4233663E+00
RAA= 118.4    DECA=  -8.2    SPA=   98.8    EPA= 139.3    CPA=   68.1
RAE= 338.5    DECE=     .5   RAS=-142.9    DECS=    1.3
EQUATORIAL          X                   Y                   Z                 TOTAL
R MERCURY   4.4818681E+07     1.6870481E+07    -1.4901161E-08     4.7888697E+07
V MERCURY  -2.5976738E+01     5.0754432E+01     2.8421709E-14     5.7015816E+01
V S/C      -2.7217484E+01     5.6839555E+01    -1.6405697E+00     6.3041398E+01
VHP        -1.2407460E+00     6.0851225E+00    -1.6405697E+00     6.4233663E+00
RAA= 101.5  DECA= -14.8  RAS=-159.4  DECS=      .0  RAE= 322.3  DECE=    7.1
MERCURY OP          X                   Y                   Z                 TOTAL
R MERCURY   4.7142928E+07    -8.4185295E+06    -7.4505806E-09     4.7888697E+07
V MERCURY   3.6278035E+00     5.6900284E+01     2.8421709E-14     5.7015816E+01
V S/C       5.6729843E+00     6.2764191E+01    -1.6405697E+00     6.3041398E+01
VHP         2.0451808E+00     5.8639067E+00    -1.6405697E+00     6.4233663E+00
RAA=  70.8  DECA= -14.8  RAS= 169.9  DECS=      .0  RAE= 291.6  DECE=    7.1
```

TABLE V-1 TRAJECTORY PRINTOUT, 6-19-88 LAUNCH

```
JD=2447338.500    C3=  34.316  FLT TIM= 399.259   JUN 26 1988  0, 0, 0.
ECLIPTIC            X                 Y                Z               TOTAL
R EARTH     9.6607057E+06   -1.5176517E+08   1.3175911E+04   1.5207233E+08
V EARTH     2.9241308E+01    1.7908380E+00  -4.1072948E-04   2.9296095E+01
VEL S/C     2.3578102E+01    8.8060952E-01  -1.1903304E+00   2.3624548E+01
VHE        -5.6632053E+00   -9.1022847E-01  -1.1899196E+00   5.8580132E+00
RAA=189.131 DECA=-11.720        SEVHE= 84.627
EQUATORIAL          X                 Y                Z               TOTAL
R EARTH     9.6607057E+06   -1.3924646E+08  -6.0321463E+07   1.5207233E+08
V EARTH     2.9241308E+01    1.6432181E+00   8.2132571E-01   2.9296095E+01
VEL S/C     2.3578102E+01    1.2814370E+00  -6.5364113E-01   2.3624548E+01
VHE        -5.6632053E+00   -3.6178103E-01  -1.4749668E+00   5.8580132E+00
RAA=183.655 DECA=-14.570 RP= 71394794.49 APO=152164817.21
A=111779805.85 E= .36129 I=  2.889 NODE=273.741 W=177.244
TH1= 177.3   TH2= 466.0   DTH= 288.7   TYPE   IV    I

JD=2447737.759 VHA= 12.755 VHD= 12.789  JUL 30 1989  6, 12, 31.812
ECLIPTIC            X                 Y                Z               TOTAL
R VENUS    -9.9734180E+07   -4.1039484E+07   5.1578997E+06   1.0797106E+08
V VENUS     1.3085207E+01   -3.2544604E+01  -1.2163083E+00   3.5097767E+01
V S/C A     7.8041995E-01   -3.5642885E+01   7.8055151E-02   3.5651513E+01
VHA        -1.2304787E+01   -3.0982813E+00   1.2943634E+00   1.2754705E+01
V S/C D     6.2473387E-01   -2.9727860E+01  -1.8152065E+00   2.9789779E+01
VHD        -1.2460473E+01    2.8167433E+00  -5.9889824E-01   1.2788906E+01
RCA=  6300.0   BTH=196.9     B*T=    -7706     B*R=    -2339    HCA=   250.0
RAA= 194.1 DECA=   5.8 SPA= 171.2 EPA= 142.3 CPA=  95.6   TYPE VI    I
RAE= 336.6 DECE=  -1.4 RAS=  22.4 DECS=  -2.7
AH=      1996.9 EH=  4.15490 I= 162.2 NODE= 355.6 W= 146.7 TAU=  76.1
A= 84483618.0 E=    .441481 I=   5.5 NODE= 412.0 W=    3.3 TURN=  27.9
THI= 146.9 THF= 336.8 DTH= 189.9 FLT TIM= 414.415
PERIHELION= 47185736.1  APHELION=121781499.9

RCA CONSTRAINED AT   6300.0
DV          1.8586112E-02   -6.9225760E-02   2.1747903E-02   7.4904077E-02
ACTUAL RCA USED IS   6300.0

JD=2448152.174    VHP=  6.263   SEP 17 1990 16,10,39.998
ECLIPTIC            X                 Y                Z               TOTAL
R MERCURY   4.0905680E+07    2.5784886E+07  -1.5831740E+06   4.8380177E+07
V MERCURY  -3.5487957E+01    4.3458601E+01   6.8156526E+00   5.6519893E+01
V S/C      -3.9309446E+01    4.8329056E+01   5.8683661E+00   6.2572901E+01
VHP        -3.8214882E+00    4.8704551E+00  -9.4728647E-01   6.2627835E+00
RAA= 128.1   DECA=  -8.7    SPA=  84.5   EPA= 148.8   CPA=  68.4
RAE= 338.4   DECE=    .8    RAS=-147.8   DECS=   1.9
EQUATORIAL          X                 Y                Z               TOTAL
R MERCURY   4.5193338E+07    1.7268575E+07   7.4505806E-09   4.8380177E+07
V MERCURY  -2.6616574E+01    4.9860367E+01   2.8421709E-14   5.6519893E+01
V S/C      -2.9323292E+01    5.5251022E+01  -1.6843316E+00   6.2572901E+01
VHP        -2.7067186E+00    5.3906547E+00  -1.6843316E+00   6.2627835E+00
RAA= 116.7  DECA= -15.6  RAS=-159.1  DECS=   -.0  RAE= 327.4  DECE=   7.3
MERCURY OP          X                 Y                Z               TOTAL
R MERCURY   4.6729957E+07   -1.2528074E+07   7.4505806E-09   4.8380177E+07
V MERCURY   7.6956368E+00    5.5993530E+01   2.8421709E-14   5.6519893E+01
V S/C       8.6660787E+00    6.1946994E+01  -1.6843316E+00   6.2572901E+01
VHP         9.7044187E-01    5.9534634E+00  -1.6843316E+00   6.2627835E+00
RAA=  80.7  DECA= -15.6  RAS= 165.0  DECS=   -.0  RAE= 291.5  DECE=   7.3
```

TABLE V-2 TRAJECTORY PRINTOUT, 6-26-88 LAUNCH

```
JD=2447345.500    C3=  34.213  FLT TIM= 391.902   JUL  3 1988  0, 0, 0.
ECLIPTIC            X                    Y                    Z                  TOTAL
R EARTH     2.7238064E+07   -1.4963866E+08    1.2843664E+04    1.5209747E+08
V EARTH     2.8819910E+01    5.2331229E+00   -7.0817648E-04    2.9291172E+01
VEL S/C     2.3087780E+01    5.1451378E+00   -1.1615528E+00    2.3682636E+01
VHE        -5.7321291E+00   -8.7985079E-02   -1.1608447E+00    5.8491543E+00
RAA=180.879 DECA=-11.447       SEVHE= 99.249
EQUATORIAL          X                    Y                    Z                  TOTAL
R EARTH     2.7238064E+07   -1.3729530E+08   -5.9410094E+07    1.5209747E+08
V EARTH     2.8819910E+01    4.8015575E+00    2.1888145E+00    2.9291172E+01
VEL S/C     2.3087780E+01    5.1826011E+00    1.0673296E+00    2.3682636E+01
VHE        -5.7321291E+00    3.8104360E-01   -1.1214850E+00    5.8491543E+00
RAA=176.197 DECA=-11.046 RP= 71826036.11 APO=152306787.00
A=112066411.56 E= .35908 I=  2.813 NODE=280.415 W=183.918
TH1= 184.0    TH2= 465.5    DTH= 281.5    TYPE   IV    I


JD=2447737.402 VHA= 12.687 VHD= 12.750  JUL 29 1989 21, 39, 20.907
ECLIPTIC            X                    Y                    Z                  TOTAL
R VENUS    -1.0013209E+08   -4.0035373E+07    5.1950926E+06    1.0796414E+08
V VENUS     1.2760742E+01   -3.2676221E+01   -1.1995010E+00    3.5100011E+01
V S/C A     5.2791040E-01   -3.5691184E+01    2.9153929E-01    3.5696278E+01
VHA        -1.2232832E+01   -3.0149626E+00    1.4910403E+00    1.2686819E+01
V S/C D     3.5360021E-01   -2.9760075E+01   -1.5452196E+00    2.9802262E+01
VHD        -1.2407142E+01    2.9161461E+00   -3.4571851E-01    1.2749925E+01
RCA=  6300.0    BTH=196.1      B*T=     -7752     B*R=     -2241     HCA=   250.0
RAA= 193.8 DECA=   6.7 SPA= 171.1 EPA= 142.1 CPA=  96.4   TYPE VI    I
RAE= 336.2 DECE=  -1.4 RAS=  21.8 DECS=  -2.8
AH=      2018.3 EH=  4.12140 I= 162.6 NODE= 351.7 W= 142.9 TAU=  76.0
A= 84515164.9 E=    .441004 I=   5.1 NODE= 414.8 W=    .0 TURN=  28.1
THI= 146.9 THF= 335.5 DTH= 188.6 FLT TIM= 414.444
PERIHELION= 47243656.9  APHELION=121786672.8

RCA CONSTRAINED AT   6300.0
DV          5.2332617E-02   -5.1905498E-02    1.3775948E-02    7.4984400E-02
ACTUAL RCA USED IS   6300.0

JD=2448151.846     VHP=  6.440   SEP 17 1990  8,18, 7.999
ECLIPTIC            X                    Y                    Z                  TOTAL
R MERCURY   4.1892491E+07    2.4540847E+07   -1.7756387E+06    4.8583813E+07
V MERCURY  -3.4120902E+01    4.4289578E+01    6.7602016E+00    5.6316099E+01
V S/C      -3.7980470E+01    4.9221761E+01    5.2593834E+00    6.2393582E+01
VHP        -3.8595681E+00    4.9321834E+00   -1.5008182E+00    6.4401207E+00
RAA= 128.0    DECA= -13.5    SPA=  83.0    EPA= 147.4    CPA=   63.7
RAE= 338.4    DECE=     .9   RAS=-149.6    DECS=    2.1
EQUATORIAL          X                    Y                    Z                  TOTAL
R MERCURY   4.5341512E+07    1.7450907E+07    2.2351742E-08    4.8583813E+07
V MERCURY  -2.6867661E+01    4.9493755E+01    2.8421709E-14    5.6316099E+01
V S/C      -2.9747519E+01    5.4799786E+01   -2.2422333E+00    6.2393582E+01
VHP        -2.8798577E+00    5.3060309E+00   -2.2422333E+00    6.4401207E+00
RAA= 118.5   DECA= -20.4  RAS=-158.9  DECS=     -.0  RAE= 329.4   DECE=    7.4
MERCURY OP          X                    Y                    Z                  TOTAL
R MERCURY   4.6489883E+07   -1.4109489E+07    2.2351742E-08    4.8583813E+07
V MERCURY   9.2348215E+00    5.5553767E+01    2.8421709E-14    5.6316099E+01
V S/C       1.0225259E+01    6.1509150E+01   -2.2422333E+00    6.2393582E+01
VHP         9.9043795E-01    5.9553822E+00   -2.2422333E+00    6.4401207E+00
RAA=  80.6   DECA= -20.4  RAS= 163.1  DECS=     -.0  RAE= 291.5   DECE=    7.4
```

TABLE V-3 TRAJECTORY PRINTOUT, 7-3-88 LAUNCH

D. Flight Characteristics

Time-histories of four geometry parameters are presented in Figure V-4. The Earth-Venus leg of this trajectory is very similar to the Earth-Venus leg of the 1980 trajectory. Once again, the pre-Venus Earth-spacecraft range is over two hundred million kilometers. The Sun-Earth spacecraft angle goes through zero late in the pre-Mercury tracking arc.

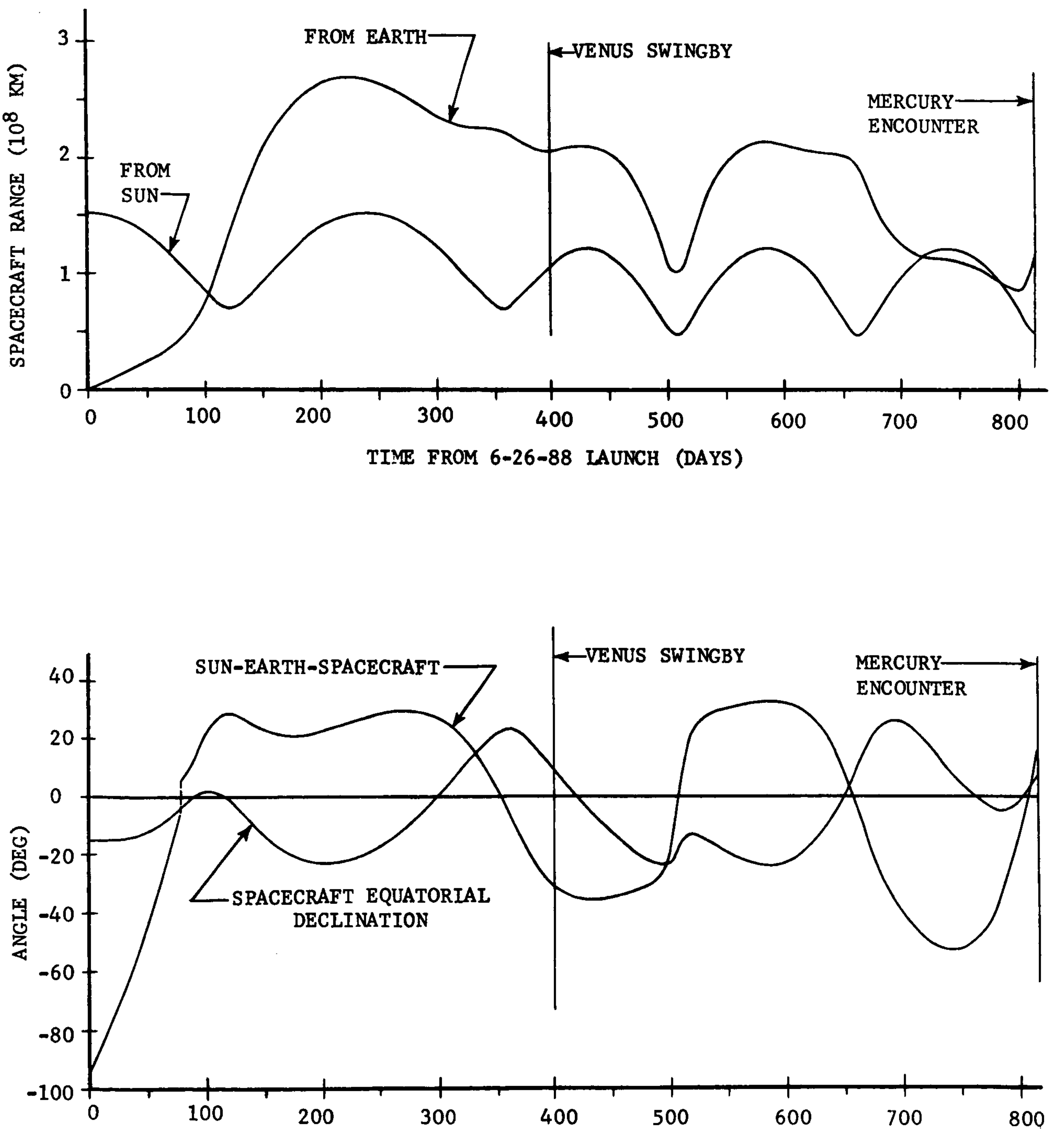


Figure V-4. Typical Time Histories, 1988 Opportunity

E. Navigation Requirements

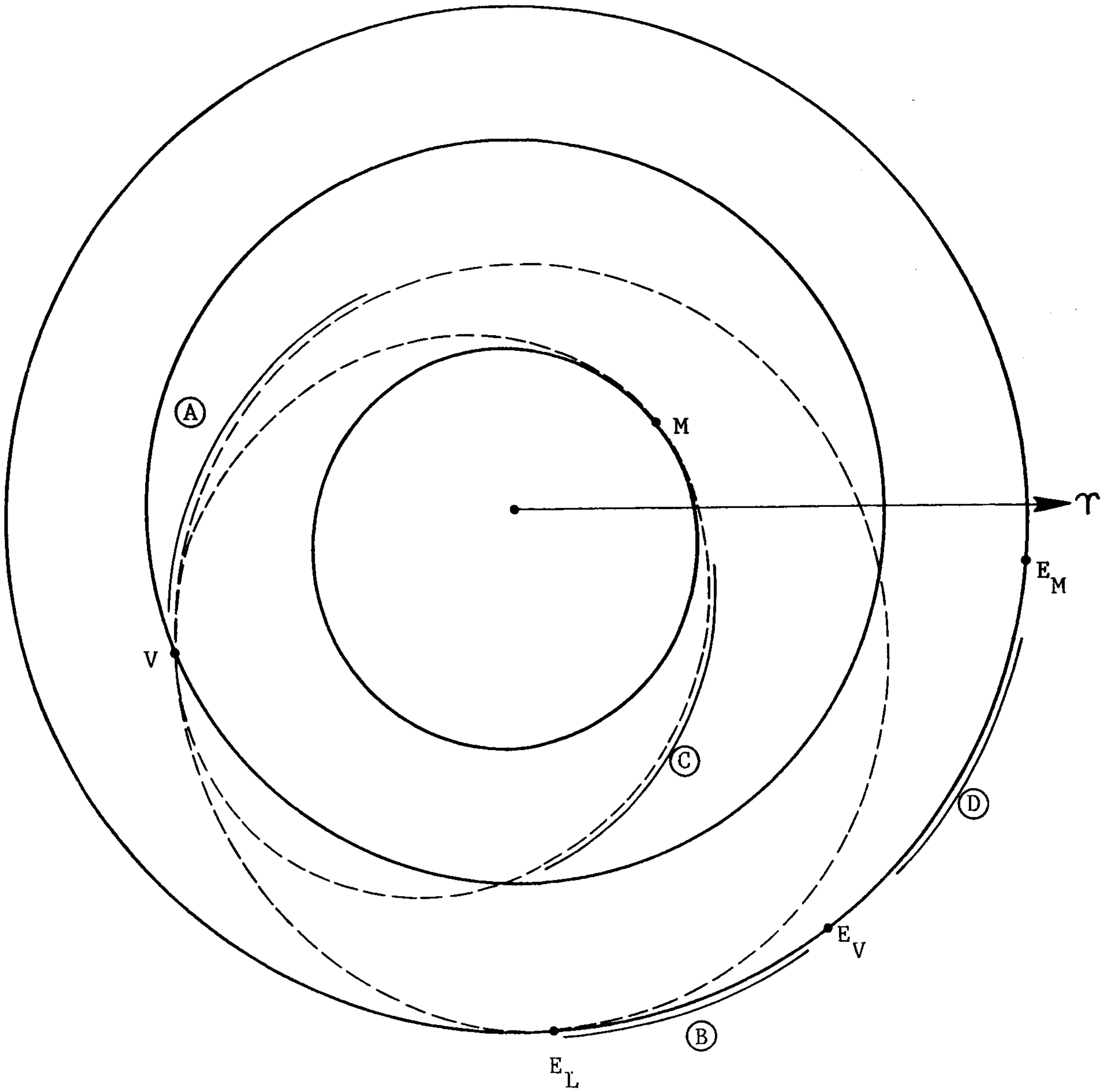
The navigation analysis for this trajectory included seven maneuvers due to three extra solar revolutions. Total ΔV requirements for seven statistical maneuvers and a 75 m/s planned maneuver are 281.9 m/s as shown in Table V-4. Pre-Venus tracking geometry for this trajectory (Figure V-5) is almost identical with that of the 1980 trajectory except that approach velocity is slightly higher. Mercury encounter dispersions are dominated by the 60 km ephemeris error (Figure VI-7) even though the final maneuver is executed at M-8 to avoid solar interference. A statistical description of the ΔV requirements resulting from this analysis follows.

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	7.45	5.05	22.6
E+260	.06	.04	.2
V-3	1.23	.84	3.8
V+2	71.70	51.43	226.0*
M-290	1.16	.67	3.2
M-100	.43	.28	1.3
M-8	2.40	1.82	7.8
		TOTAL	264.9*

* Statistical combination of 226 mps midcourse correction maneuver and 75 mps planned velocity maneuver at Venus results in 243 mps at V+2 and 281.9 mps equivalent total.



(A) SPACECRAFT DURING PRE-VENUS TRACKING PERIOD

(B) EARTH DURING PRE-VENUS TRACKING PERIOD

(C) SPACECRAFT DURING PRE-MERCURY TRACKING PERIOD

(D) EARTH DURING PRE-MERCURY TRACKING PERIOD

Figure V-5. Critical Tracking Geometries, 1988 Opportunity

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VI. NAVIGATION ANALYSIS

VI. NAVIGATION ANALYSIS

A. Introduction

A single navigation analysis has been accomplished for each of the four opportunities. (Subsection VI-B.) A parametric analysis of the critical Venus swingby conditions has been included for the 1980 and 1985 opportunities. (Subsection VI-C.) One Earth launch date (ELD), Mercury encounter date (MED) combination was selected to define a trajectory for each opportunity. Each trajectory requires four key correction maneuvers. A maneuver is required ten days after launch (E+10) to remove injection errors. The expected magnitude of this maneuver is the second largest for each trajectory (Mean $\Delta V \sim 7m/s$, sigma $\Delta V \sim 5m/s$). A very small but critical maneuver is required three days before Venus (V-3). The trajectory dispersions remaining after this maneuver are amplified into very large post-Venus trajectory dispersions which require a large correction maneuver two days after Venus (V+2). The fourth key corrective maneuver is required before Mercury encounter. This small maneuver nominally executed at M-3 allows an efficient orbit insertion from as accurate an approach trajectory as possible. The 1985, 1980, and 1988 trajectories include one, two, and three extra maneuvers respectively corresponding to the number of extra solar revolutions.

Because the Earth-Venus legs of the 1977 and 1985 trajectories are very similar, their navigation problems are similar (Figure VI-1). The Earth-Venus legs of the 1980 and 1988 trajectories are also similar (one extra revolution each) and their navigation problems are similar (Figure VI-1). Consequently, the majority of this discussion and the parametric analysis of the Venus swing-by phase will be limited to the 1980 and 1985 trajectories. Unless data is specifically called out for 1977 or 1988, the 1980 data applies qualitatively to the 1988 trajectory and the 1985 data applies to the 1977 trajectory.

The trajectory dispersions and resulting ΔV requirements for the Mercury Orbiter Missions are unusually large for inner planet missions. However, the increased dispersions in no way impair mission feasibility, they merely decrease useful performance a few percent.

An unusual combination of unfavorable geometric phenomena causes an abnormally large post-Venus maneuver for all of these trajectories. All four trajectories include high Venus approach velocities ($\sim$13 km/s) and large Earth-S/C ranges during the pre-Venus tracking arc ($>$ 200 million km). High

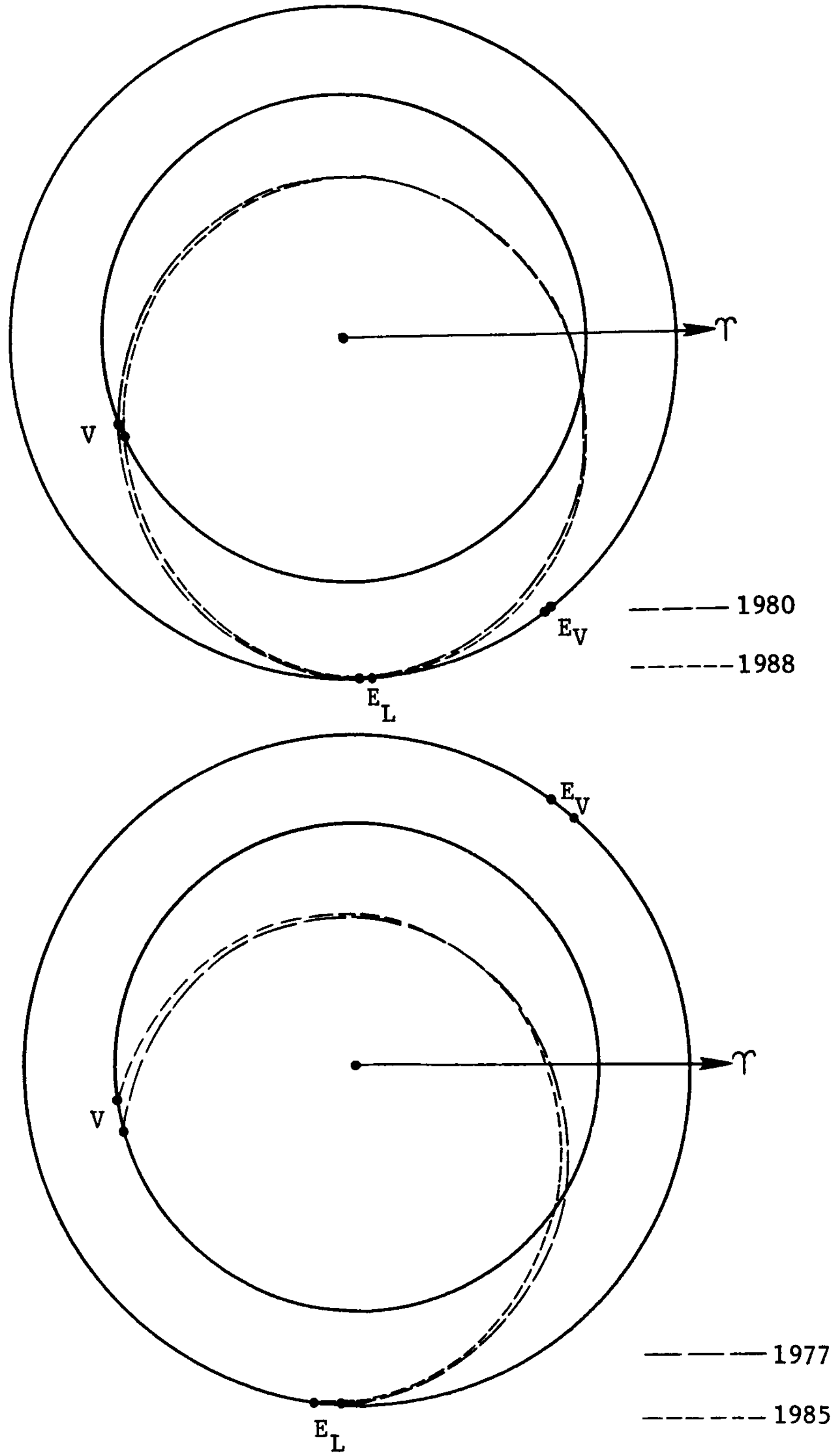


Figure VI-1. Pre-Venus Tracking Geometry Comparisions

Venus approach velocities increase expected post-Venus trajectory dispersions in two different manners. The direct effect is that the partials of post-Venus dispersions to pre-Venus dispersions are larger for these trajectories than they would be with smaller approach velocities. The second effect is that the high approach velocities prohibit normal pre-Venus Orbit Determination (O.D.) accuracy as discussed in detail later in this section. Two of the trajectories, '77 and '85, involve a near zero equatorial declination during the pre-Venus tracking arc. Long-range tracking of a S/C in the Earth equatorial plane does not allow quality orbit determination. The other two, '80 and '88 are in the plane-of-the-sky during the pre-Venus tracking arc. The velocity of the S/C with respect to Earth is 63 km/s; however, the radial component is only 3 km/s. For these missions, long range and high approach velocity combined with poor velocity observability prohibit normal pre-Venus orbit determination accuracies. Although QVLBI or optical navigation might alleviate some of these problems, they were not included as assumptions for this analysis as discussed later.

A qualitative understanding of the navigation problem for these trajectories requires studying Figure VI-2. Time histories of O.D. uncertainties for inner planet approach phases typically follow the descending stair step pattern illustrated in Figure VI-2. A 30-day tracking arc beginning 34 days before encounter is a fairly standard planet approach strategy. This allows 30 days for tracking and one day for maneuver commands and execution which generally must occur 3 days before closest approach. If the pre-encounter maneuver is implemented later, that maneuver becomes larger and its expected execution errors become large. From an operational reliability point of view, it is considered that three days before encounter is the latest time a corrective maneuver should be planned. An effectively infinite uncertainty is assumed at the beginning of the tracking arc. Several days of doppler measurements decrease the expected knowledge error to some value representative of the ability to determine the heliocentric trajectory for a specified set of assumptions and the existing geometry. The knowledge error levels off at this plateau indicating all the useful information available has been assimilated and no improvement is expected until the geometry of the trajectory changes. Similar analyses for the MVM trajectory ($V_{HV} \sim 8$ km/s) and a 1978 Type II Pioneer Venus trajectory ($V_{HV} \sim 3$ km/s) indicate a heliocentric plateau of 20 to 30 km Z uncertainty. The heliocentric plateau for the 1985 trajectory is in the 100-150 km area for Z uncertainty. This occurs because the S/C trajectory is in the earth equatorial plane and the S/C-Earth range is larger. The heliocentric plateau for the 1980 trajectory is in the 60-90 km area for Z uncertainty. This occurs because the S/C trajectory remains in the plane-of-the-sky. Normally, as the S/C approaches Venus, new information becomes available for the orbit determination process.

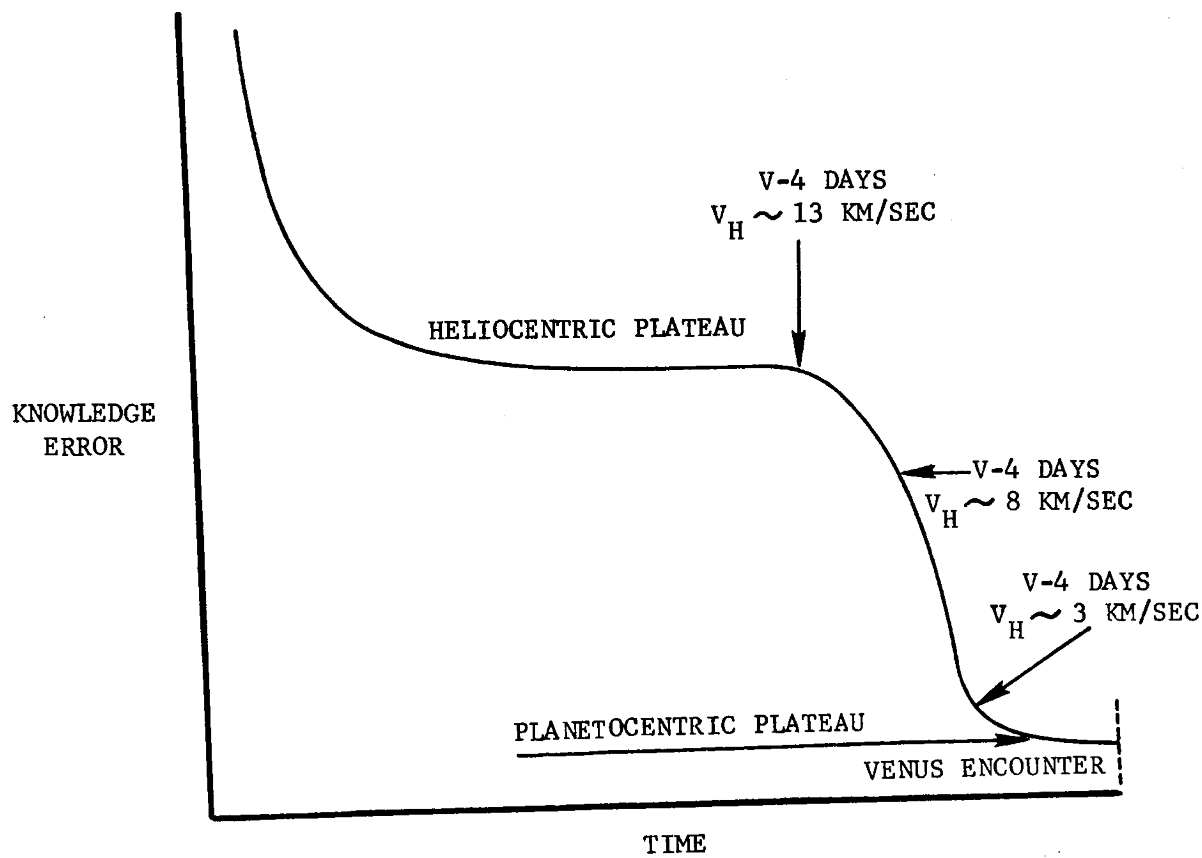


FIGURE VI-2 TYPICAL PRE-ENCOUNTER ORBIT DETERMINATION

When the S/C is approximately 2 times R_{SOI} (radius of the sphere of influence) from Venus, the trajectory begins bending toward the planet and some information of the planet relative hyperbola is contained in the doppler measurements. At this time, O.D. uncertainties decrease from the heliocentric plateau toward the planetocentric plateau. This second and lower plateau is a function of O.D. assumptions and specific geometry. For some Venus approach trajectories, such as the Pioneer Venus 1978 Type II, the planetocentric plateau, neglecting ephemeris contributions, is as low as 5 km. The importance of V_{HV} becomes quite clear if one realizes that the S/C-Venus range at V-4 is proportional to V_{HV}. With a V_{HV} of 3 km/s, the orbit determination process may reach the second plateau before V-4. With a V_{HV} of 8 km/s, the O.D. process may be between the two plateaus at V-4. With V_{HV} of 13 km/s, the O.D. process is still basically on the first plateau at V-4. Therefore, when the last useful pre-maneuver data is available, O.D. uncertainties for reasonable assumptions indicate an expected 100 to 142 km error in the Z position of the S/C for the 1985 trajectory. The same assumptions for the 1980 trajectory indicate an expected error of 58-80 kilometers.

B. Assumptions and Results

TABLE VI-1 SAMPLE TRAJECTORIES

YEAR	LAUNCH DATE	VENUS DATE	MERCURY DATE
1977	6-19-77	11-16-77	3-11-78
1985	6-15-85	11-11-85	8-15-86
1980	6-24-80	7-29-81	4-14-82
1988	6-26-88	7-30-89	9-17-90

The reference trajectories used to analyze the navigation problems for each opportunity are listed above. The maneuver times are listed below.

TABLE VI-2 MANEUVER SCHEDULE

	TRAJECTORY			
EVENT	1977	1985	1980	1988
Maneuver	E+10	E+10	E+10	E+10
Maneuver			E+260	E+260
Maneuver	V-3	V-3	V-3	V-3
Venus Encounter	E+150.2=V	E+149.=V	E+400.3=V	E+400.=V
Maneuver	V+2	V+2	V+2	V+2
Maneuver				M-250
Maneuver		M-100	M-100	M-100
Maneuver	M-30	M-3	M-3	M-8
Mercury Encounter	V+114.8=M	V+277.=M	V+258.7=M	V+314.=M

E = Earth V = Venus M = Mercury

It may be seen in the table that the last midcourse maneuver for the 1977 and 1988 trajectories is scheduled before M-3. In both cases, the Sun-Earth-S/C angle (Figures II-5 and V-4) is near zero at M-4. The tracking arcs and the last maneuver were backed up to times when the sun would not interfere with the doppler signal.

The equivalent station location errors (ESLE) assumed here do not reflect the possibility of using QVLBI or an optical navigation system in the tracking process. The error assumptions listed in Table VI-3 are one-sigma values and represent slightly pessimistic estimates of DSN improvements by the 80's with charged particle calibration. The primary data type assumed is S-band doppler with 1 mm/s per 1 minute count time noise level. The charged particle calibration may be accomplished in either of two manners: Dual frequency calibration or DRVID (differenced ranging vs integrated doppler). Dual frequency calibration requires an X-band transmitter while DRVID requires ranging transponder.

TABLE VI-3

STATION LOCATION ERROR ASSUMPTIONS

SIGMA R_S	=	.73 m
SIGMA λ	=	2.04 m
SIGMA Z_h	=	10 m
CORRELATION λ_i λ_j	=	.9

Ephemeris uncertainty assumptions are 20 km spherical for Venus and 60 km spherical for Mercury. Injection error assumptions are 3 km spherical in position and $\sqrt{3}$ m/s spherical in velocity.

With two exceptions, it is assumed that tracking begins 31 days before maneuvers. The assumed knowledge uncertainty is 1000 km and .5 m/s spherical at the beginning of every standard tracking arc. The tracking arcs preceeding the E+10 and V+2 maneuvers are the two exceptions. The first tracking arc begins at E+1 and ends at E+9. The initial knowledge error assumed for the injection point is equal to the assumed control error of 3 km and $\sqrt{3}$ m/s at E+0. Because this is mapped through the outgoing leg of a hyperbola between E+0 and E+1, it is reasonably large before the measurements begin. The tracking preceeding the V+2 maneuver begins at closest approach and ends at V+1. This one-day tracking arc is sufficient to plan the V+2 maneuver because it is sufficient to achieve a nominal estimate of the outgoing leg of the Venus relative hyperbola. Tracking before Venus (from V-2 to V) is not particularly useful because pre-Venus uncertainties are amplified by as much as two orders of magnitude by V+2. At no time are range measurements modeled in this analysis. A Kalman-Schmidt recursive filter was used for the O.D. algorithm. Trajectories were propagated using a Nystrom numerical integration of the equations of motion in an Encke formulation. State transition matrices were obtained by simultaneously integrating the variational equations of motions. Maneuver execution errors were assumed to be 1/3 of 1% and 1/3 of 1°. A statistical description of all the maneuvers using the Hoffman-Young approximation appears in Table VI-4.

A recently developed analytical technique, by Lee-Boain of Martin Marietta allows exact definitions of ΔV requirements versus cumulative probability level. Mean plus three sigma ΔV for the large V+2 1977 maneuver is 186.4 m/s from the Hoffman-Young approximation. The Lee-Boain technique for the same covariance indicates a .99 probability that 170 m/s is sufficient for that maneuver and a .999 probability that 212 m/s is sufficient. For the V+2 maneuver on the 1985 trajectory mean plus three sigma ΔV is 211.1 while the .99 cumulative probability is 193 m/s and .999 is 243 m/s. Thus, the Hoffman-Young method provides an acceptable approximation.

Sections III and V of this report discuss a planned maneuver (ΔV_v) occuring simultaneously with the large V+2 correction maneuver for the '80 and '88 trajectories. In order to evaluate the vector bargain achieved by implementing the maneuvers simulataneously, a Monte Carlo analysis was accomplished. For the 1980 trajectory, 2000 samples of the ΔV covariance (V+2) indicate a .9965 probability that the corrective maneuver would be 207 m/s (mean + 3 sigma from Table VI-4) or less. Vectorally adding the 100 m/s planned ΔV_v to each of the 2000 sample ΔV's indicated a .9965 probability of the combined maneuver being 233 m/s or less. This implies that the 100 m/s ΔV_v would cost only 26 m/s of extra requirements for the combined maneuvers. Histograms of the 2000 samples for 1980 with and without the 100 m/s ΔV_v appear in Figures VI-3 and VI-4.

For the 1988 trajectory, 2000 samples of the ΔV covariance (V+2) indicated a .9965 probability of the corrective maneuver being 226 m/s (mean + 3 sigma

TABLE VI-4 STATISTICAL DESCRIPTION OF MANEUVERS (m/s)

(Hoffman-Young Approximation)

YEAR	MANEUVER TIME	MEAN	SIGMA	MEAN PLUS THREE SIGMA
1977	E+10	6.90	4.57	20.6
	V-3	3.94	2.76	12.2
	V+2	62.15	41.40	186.4
	M-30	2.26	1.68	7.3
1985	E+10	6.95	4.61	20.8
	V-3	1.23	.71	3.4
	V+2	69.04	47.34	211.1
	M-100	1.20	.78	3.8
	M-3	1.00	.75	3.2
1980	E+10	7.53	5.12	22.9
	E+260	.06	.04	.2
	V-3	1.08	.72	3.2
	V+2	66.04	41.84	206.6
	M-100	.98	.58	2.7
	M-3	1.32	.99	4.3
1988	E+10	7.45	5.05	22.6
	E+260	.06	.04	.2
	V-3	1.23	.84	3.8
	V+2	71.70	51.43	226.0
	M-290	1.16	.67	3.2
	M-100	.43	.28	1.3
	M-8	2.40	1.82	7.8

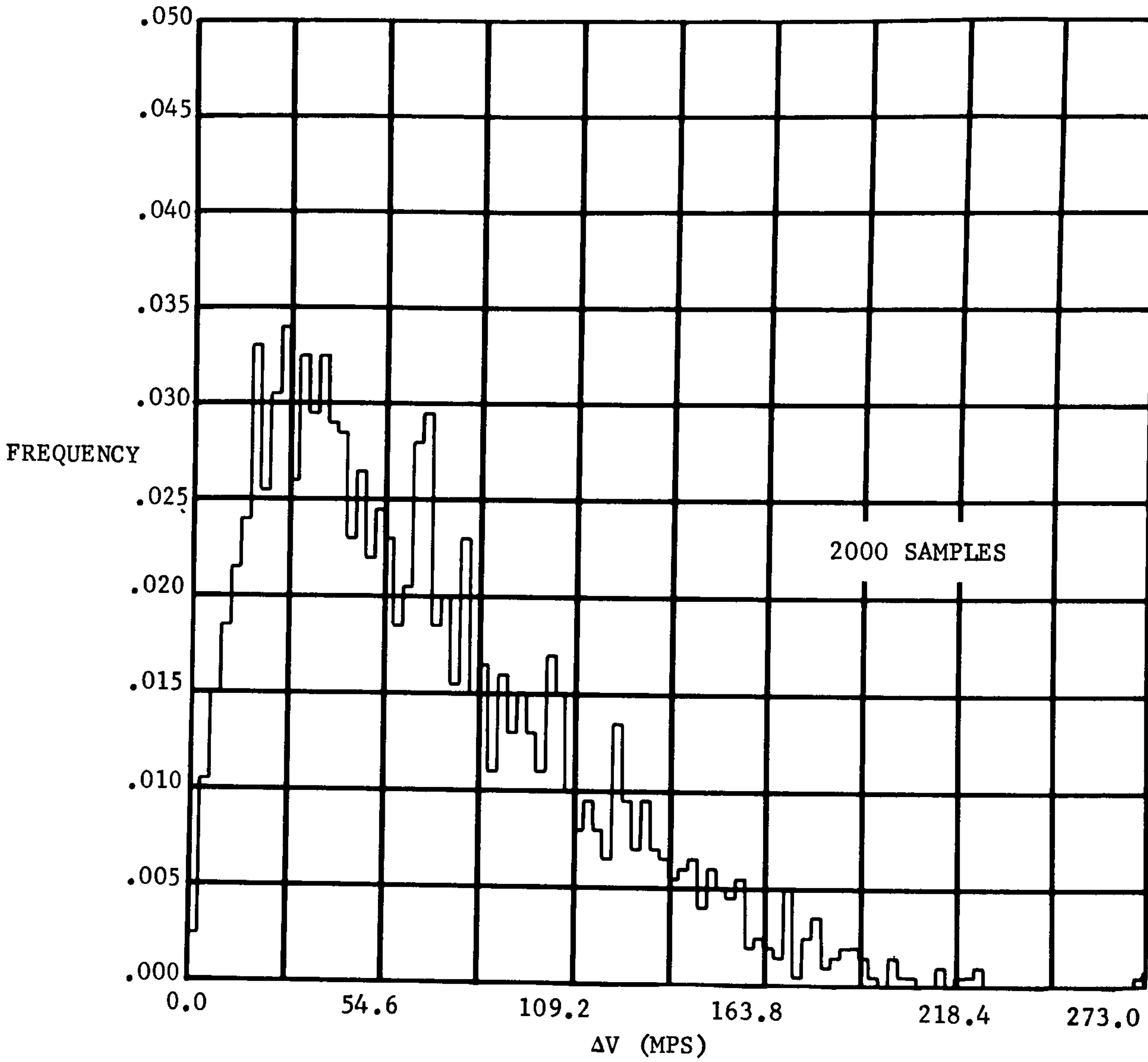


Figure VI-3. Post-Venus Correction Distribution, 1980 Without Venus Maneuver

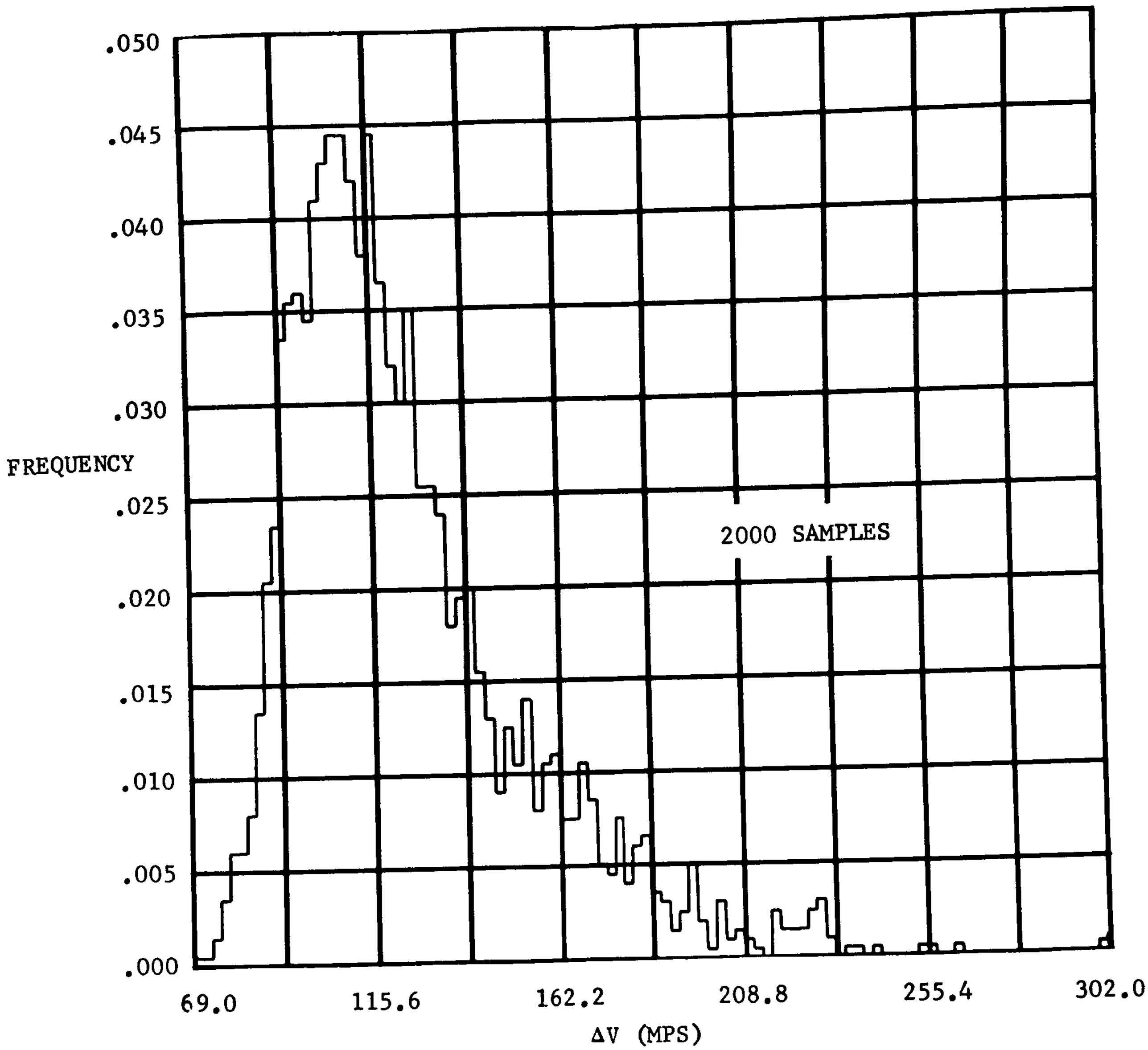


Figure VI-4. Post-Venus Correction Distribution, 1980 With 100 mps Venus Maneuver from Table VI-4) or less. (The .9965 accumulative probability from the Monte Carlo analysis equalled the mean plus three-sigma from the Hoffman-Young approximations for both '80 and '88. This was not forced but is not surprising since the two covariances have similar eigenvalue ratios resulting from similar trajectories and assumptions).

Vectorally adding the 75 m/s ΔV_v for the 1988 trajectory to the 2000 samples indicated a probability of .9965 that the combined maneuver would be 243 m/s or less. The 75 m/s planned maneuver required only 17 m/s for the same accumulative probability level. The two histograms for this ΔV covariance appear in Figures VI-5 and VI-6.

C. Parametric Analysis

The large post-Venus maneuver is very sensitive to pre-Venus orbit determination capability for all of these trajectories. The ephemeris error assumptions appear to have less impact than station location error assumptions. Three sets of equivalent station location error assumptions appear in Table VI-5. A parametric analysis of the pre-Venus tracking arc (V-34 to V-4) and the resulting post-Venus maneuver (V+2) was accomplished for the '80 and '85 trajectories.

TABLE VI-5

EQUIVALENT STATION LOCATION ERRORS

	A	B	C
SIGMA R_S	.43	.73	4.05
SIGMA λ	1.16	2.04	3.7
SIGMA Z_h	10.	10.	10.
CORRELATION λ_i λ_j	.9	.9	.9

Set A is intended to represent optimistic DSN improvements for the '80 time frame with charged particle calibration but without QVLBI. Set B is intended to represent pessimistic DSN improvements for the same conditions. Set B assumptions are used in the maneuver analysis in Section VI.B. Set C represents no charged particle calibration and is included to show that charged particle calibration is required for all of these trajectories.

Ephemeris errors are assumed to be 20 km spherical or are ignored. Execution errors are included throughout but their effect is negligible. The

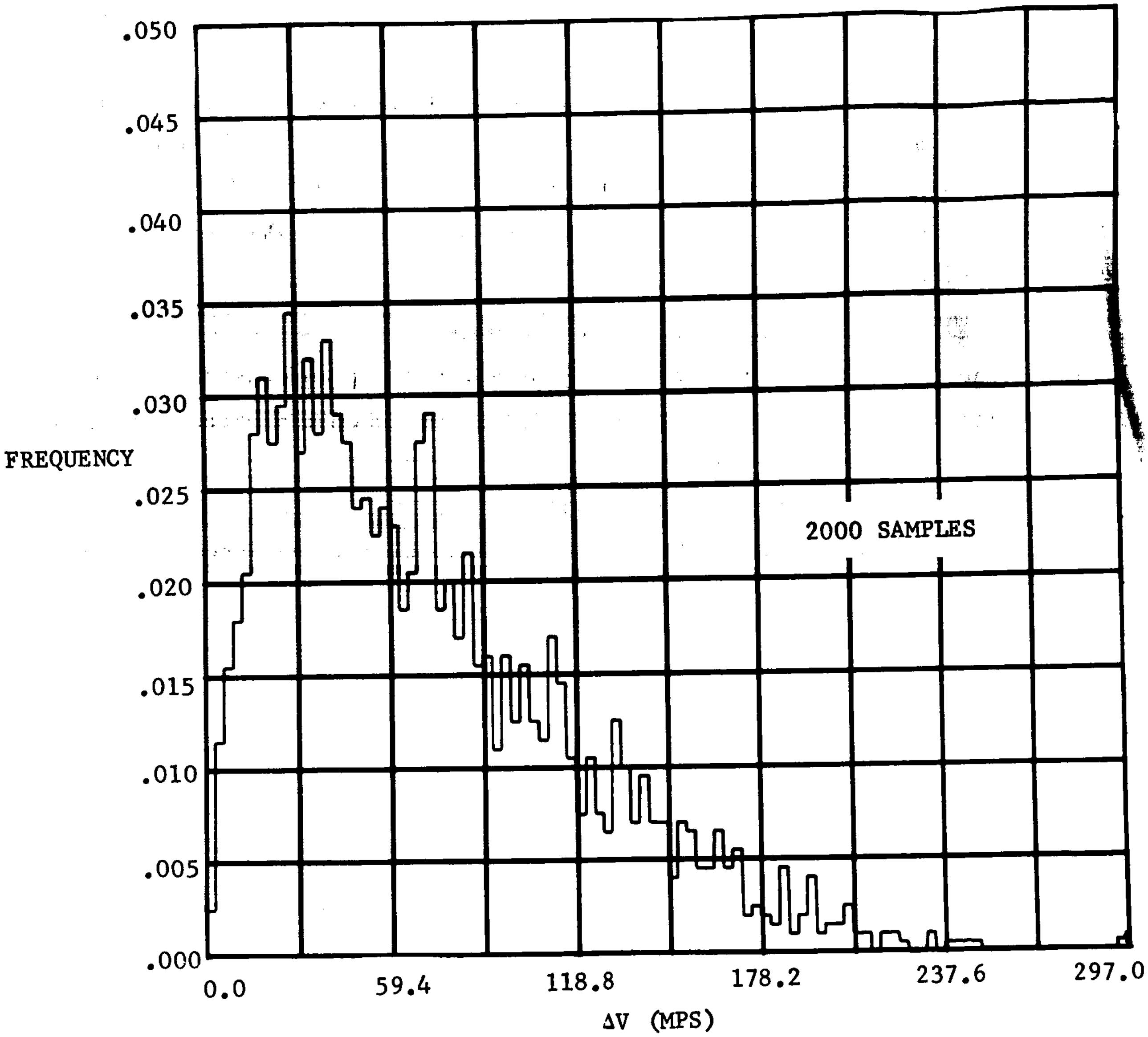


Figure VI-5. Post-Venus Correction Distribution, 1988 Without Venus Maneuver

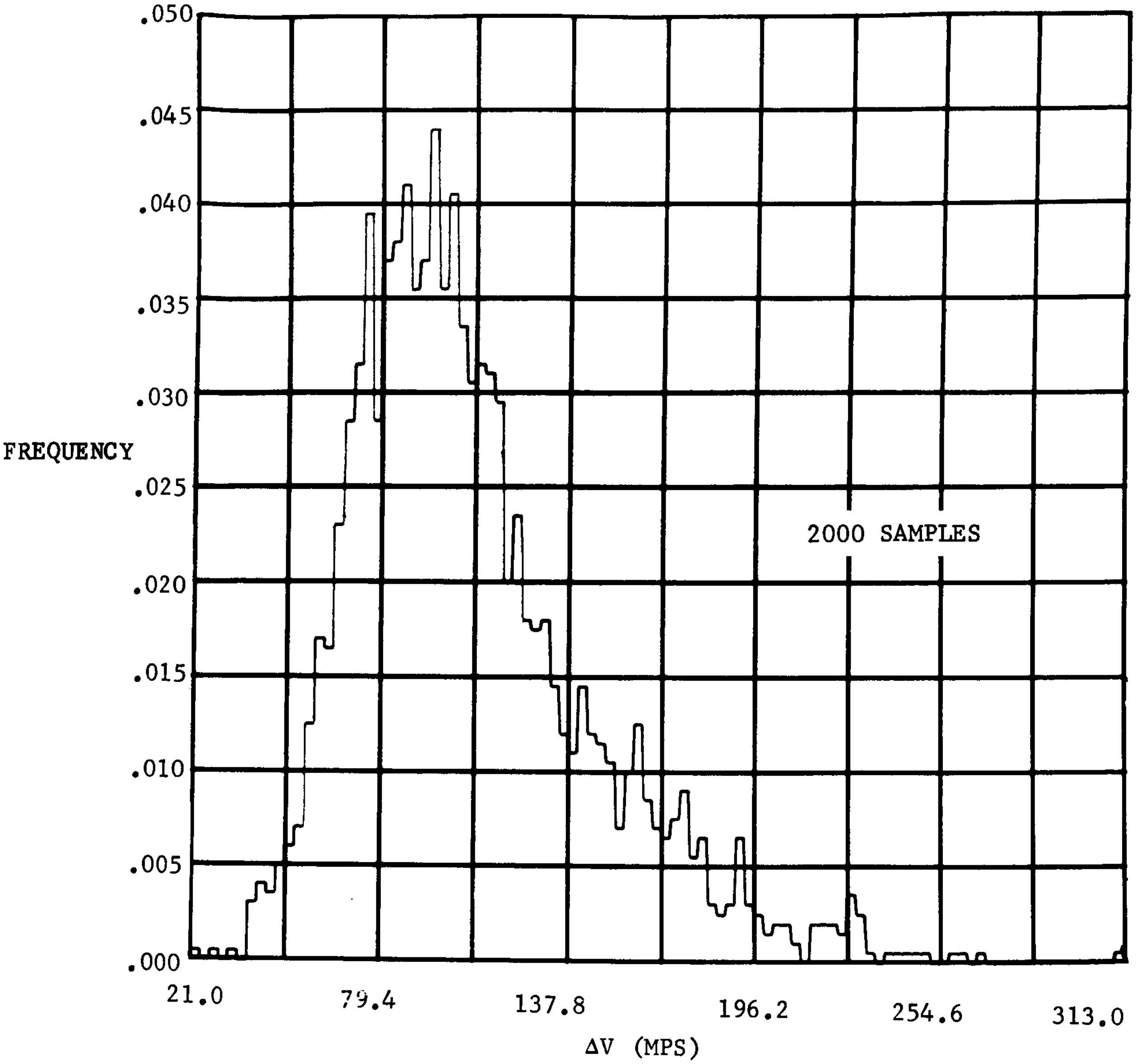


Figure VI-6. Post-Venus Correction Distribution, 1988 With 75 mps Venus Maneuver results are listed in Table VI-6. The cases at the bottom of each table represent the most practical assumptions, namely, reasonable levels of both ephemeris errors and equivalent station location errors (ESLE).

The qualitative discussions in Section VI.A explained why the pre-Venus expected knowledge error is high in Z and $\dot{Z}$ for both missions. For the '85 trajectory, the S/C declination with respect to Earth ranges from $+5^{\circ}$ to -10°, passing through zero, during the 30-day tracking arc. At zero declination, the primary data type, doppler, loses all sensitivity to equatorial Z-height. The large post-Venus maneuver for '85 and '77 might be reduced by optical navigation or QVLBI. At least the large variation in Venus closest approach (sigma h_p = 46 km) does not imply impact because the nominal altitude is about 1500 km.

For the '80 trajectory, declination is no problem (25° to 10°), but the S/C velocity vector is in and remains in the plane-of-the-sky. Since doppler only measures the velocity component along the line of sight, that component of velocity in the plane-of-the-sky is non-observable. The velocity angle to the plane-of-the-sky varies from $+4^{\circ}$ to -1° over the tracking arc. Under these conditions, there is little information about the inclination of S/C velocity to the Earth's equator. Hence, large $\dot{Z}$ and Z uncertainties appear in the knowledge covariances. Combining the large post-Venus statistical maneuver with a large post-Venus planned maneuver (which allows a reduction in the insertion maneuver at Mercury) offers a vector bargain in ΔV requirements and reduces the incentive to improve pre-Venus orbit determination capabilities for the '80 and '88 trajectories. Performance for the '80 and '88 opportunities is inversely proportional to the minimum swingby altitude allowed. The radius of Venus is 6050 km with a 200 km atmosphere. NASA document SP-8011 lists a pressure of 2.58×10^{-11} atmospheres at an altitude of 200 km. Before this analysis, it was assumed that a nominal swingby altitude of 250 km was adequate. The data in Table VI-6 indicates a three-sigma uncertainty in periapsis altitude of 87 kilometers. Hence, the allowable swingby altitude is treated parametrically in Sections III and V.

It may be seen from the table that the 20 km ephemeris error does not impact ΔV requirements significantly. Assumed ephemeris uncertainties do effect allowable Venus swingby altitudes and therefore performance for the 80

TABLE VI-6 PARAMETRIC ANALYSES OF VENUS SWINGBY CONDITIONS

ERROR SOURCES		1 SIGMA KNOWLEDGE		3 SIGMA h_p	MEAN +3 SIGMA ΔV
ESLE	VENUS EPHEM	RSS at V-4 POS. (km)	RSS at V-4 VEL (m/s)	AT VENUS (km)	AT V+2 (m/s)
0	0	64	.031	29	101
A	0	100	.050	77	150
B	0	142	.068	125	210
C	0	250	.118	200	373
0	20	64	.031	64	105
A	20	100	.050	97	152
B	20	142	.068	138	210

1985 Control and Knowledge Uncertainties

ERROR SOURCES		1 SIGMA KNOWLEDGE		3 SIGMA h_p	MEAN +3 SIGMA ΔV
ESLE	VENUS EPHEM	RSS at V-4 POS. (km)	RSS at V-4 VEL (m/s)	AT VENUS (km)	AT V+2 (m/s)
0	0	24	.016	24	66
A	0	58	.023	52	149
B	0	80	.030	66	201
C	0	210	.067	128	484
0	20	24	.016	63	84
A	20	58	.023	76	158
B	20	80	.030	87	208

1980 Control and Knowledge Uncertainties and 88 missions.

D. Conclusions

The sums of the mean plus three-sigma ΔVs of all the corrective maneuvers are 226.5, 265.9, 242.3, and 281.9 m/s for the four missions sequentially by launch year. The numbers for '80 and '88 include the 100 m/s and 75 m/s ΔV_vs vectorally added to the V+2 maneuver as discussed. Adding mean plus three-sigma Δ V for all maneuvers is generally considered a conservative method for estimating fuel requirements.

The Mercury approach uncertainties for all four missions are depicted in Figure VI-7. The dispersions for the '85 and '88 encounters are dominated by the 60 km ephemeris error. The larger T-axis uncertainty for the '77 trajectory results from the longer mapping time from the last maneuver to encounter. The larger R-axis uncertainty for the '80 trajectory results from a pre-encounter zero declination problem (see Figure III-4). This analysis does not include solar pressure uncertainty effects or unmodeled acceleration effects which do not contribute significantly to the dispersions (assuming a Kalman-Schmidt Filter).

The parametric analysis discussed in the previous section clearly indicates that charged particle calibration would be a requirement for navigating these Mercury orbiter missions. Implementation of the calibration can be accomplished by using either of two standard techniques: DRVID (Differenced Range Versus Integrated Doppler) or Dual-Frequency (S- and X-band) doppler tracking.

The navigational characteristics of the missions could be improved further with the addition of either optical or QVLBI (Quasi Very Long Baseline Interferometry) data. A quantitative appraisal of the increased accuracies and reduced midcourse fuel requirements resulting from either of these two data types has not been made, but a qualitative assessment of their impact is possible. Based upon analyses of optical data from Mariner '71 and the planned navigation system for the Viking '75 mission, it appears that optical navigation would not significantly reduce either the Venus approach orbit determination uncertainties or the mid-course maneuver requirements for the large post-Venus maneuver. The best optical data type involves imaging the natural satellites of a target body against a star background. The trajectory is then estimated

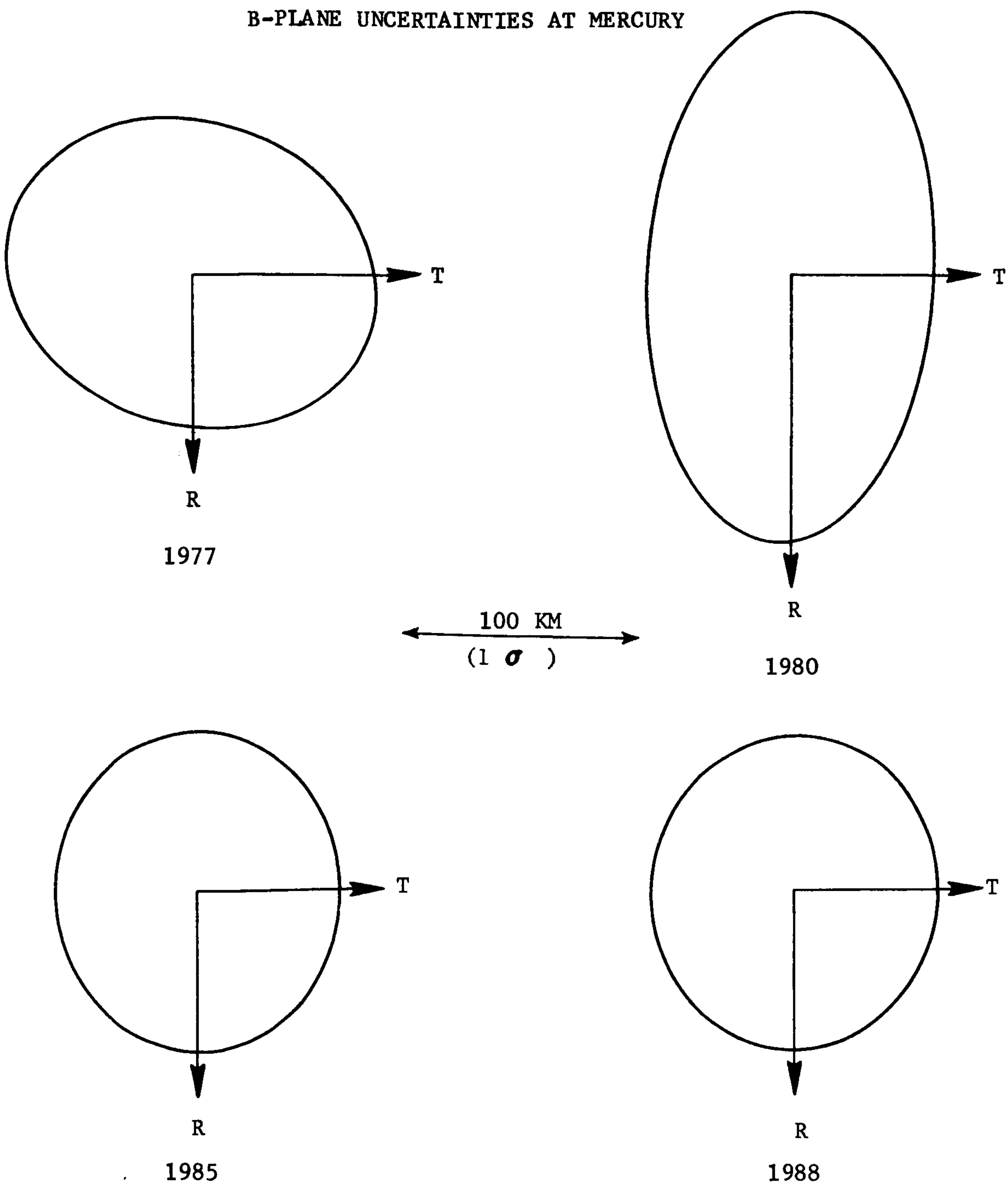


Figure VI-7. Mercury Encounter Dispersions based upon this optical information. Since Venus has no natural satellites, optical navigation near Venus would be restricted to using photographs of the planet limb against a star background. For Viking-type approach trajectories to Mars, which have an approach velocity magnitude of about 3 km/s, planet limb/star angle measurements permit determination of the trajectory to about 50 km (1σ) four days from encounter. Twelve days away from encounter on a Viking mission, planet limb imaging results in trajectory uncertainties of roughly 125 km (1σ).

As has been pointed out earlier, the Mercury orbiter missions approach Venus at a very high velocity of 13 km/s. Thus the distance from Venus encounter at the time of the pre-Venus maneuver is roughly the same as the Viking distance from Mars at E-12 days. Even if it is assumed that the larger radius of Venus permits a somewhat reduced optical orbit determination uncertainty of 100 km (1σ), the post-Venus midcourse maneuver would still require 150 m/s resulting in only 60 m/s savings due to the optical navigation system.

Past analyses have shown that QVLBI data can be very efficient in reducing orbit determination uncertainties caused by either unmodeled accelerations or the zero declination problem. QVLBI data involves simultaneous tracking of the spacecraft from two separate Earth stations. Differencing the simultaneous range or doppler data can provide an excellent estimate of the trajectory when the geocentric equatorial declination is low. For both the 1977 and 1985 trajectories, whose approach orbit determination uncertainties are large due to the low geocentric equatorial declination during Venus approach, it is safe to assume that the midcourse maneuver requirements could be reduced by implementing QVLBI. The magnitude of the reduction would depend on the ground and spacecraft system designs that implement the QVLBI date type. QVLBI has not yet, however, been used as an operational data type for an interplanetary mission and several possibly significant ground and spacecraft system design requirements must be met before the orbit determination accuracies are significantly improved over conventional methods.

For the 1980 and 1988 Mercury orbiter trajectories, the size of the post-Venus midcourse maneuver is even more sensitive to the Venus approach orbit determination errors. An approach orbit determination uncertainty of 80 km (1σ) at V-4 requires a midcourse fuel allocation of 210 m/s for the post-

Venus correction. No published analyses are available that show whether or not QVLBI can significantly reduce orbit determination errors resulting from the plane-of-the-sky geometry. However, it is clear that the QVLBI data would have to be very strong and result in an orbit determination error of about 30 km (1σ) four days before Venus encounter to reduce the post-Venus midcourse allocation by as much as 50%.

VII. ALTERNATE FLIGHT TECHNIQUES

VII. ALTERNATE FLIGHT TECHNIQUES

The four mission opportunities described in the preceding sections were based on simple ballistic transfer between planets and a single gravity-assist swingby of Venus. Velocity maneuvers were limited to small values in the vicinity of Venus to provide continuity of launch period (for the 1988 opportunity) and to improve performance within Venus altitude constraints (1980 and 1988 opportunties). This flight technique is adequate to support an orderly program of Mercury exploration through the 1980's.

Additional investigations were conducted to explore the performance improvement potential of alternate flight techniques. In particular, the following approaches were assessed.

1. Midcourse velocity maneuvers to compensate for imperfect planet alignments.
2. Multiple Venus swingby to increase utilization of gravity-assist benefits.

Results of these analyses are presented in this section. Performance parameters have not been fully optimized and should, therefore, be construed as indicative of potential.

A. Midcourse Maneuvers

Alignments of Earth, Venus, and Mercury are near ideal for the 1980 and 1988 mission opportunities. The resulting high performance is due to high utilization of Venus gravity-assist effects and is reflected in the low Venus swingby altitudes involved. In contrast, the 1977 and 1985 mission opportunites are characterized by higher Venus swingby altitudes and corresponding lower performance. This can be attributed to relatively poor planetary alignments which limit the benefits of Venus gravity-assist for simple ballistic transfer between planets.

The nature of the planet misalignment problem is illustrated in Figure VII-1 for the 1985 opportunity which is most adversely affected. As shown, low values of Mercury approach velocity are possible if the Venus departure date can be properly timed. However, ballistic Earth-Venus transfers produce incompatible Venus arrival dates.

For unpowered Venus swingby, the relative velocity at Venus arrival and Venus departure must be equal in magnitude. As shown by the figure, this condition limits Venus date to no later than 12 November and corresponds to a minimum velocity at Mercury arrival of about 8 km/sec. The results presented in Section IV for the 1985 opportunity reflect this situation.

A technique which could be employed to permit delayed Venus encounter (and consequent reduced relative velocity at Mercury) would involve a velocity maneuver in the vicinity of Venus to change magnitude of the Venus hyperbolic velocity at arrival and/or departure. As shown by Figure VII-1, such powered swingby maneuvers produce decreases in Mercury arrival velocity approximately double the magnitude of the velocity increments provided at Venus. Exploitation of this option could significantly improve net performance for the 1985 mission opportunity but would require a major propulsion phase which could seriously complicate spacecraft design.

An alternative method of circumventing the ballistic mismatch of Venus conditions involves application of midcourse velocity maneuvers during the Earth-Venus and/or the Venus-Mercury transfer orbits. The purpose would be to displace the Earth-Venus lower envelope on Figure VII-1 down and/or to the right or to produce the reverse effects on the Venus-Mercury transfer characteristics.

The midcourse maneuver technique is presented schematically in Figure VII-2. As shown, a typical ballistic Earth-Venus transfer orbit can be modified with a

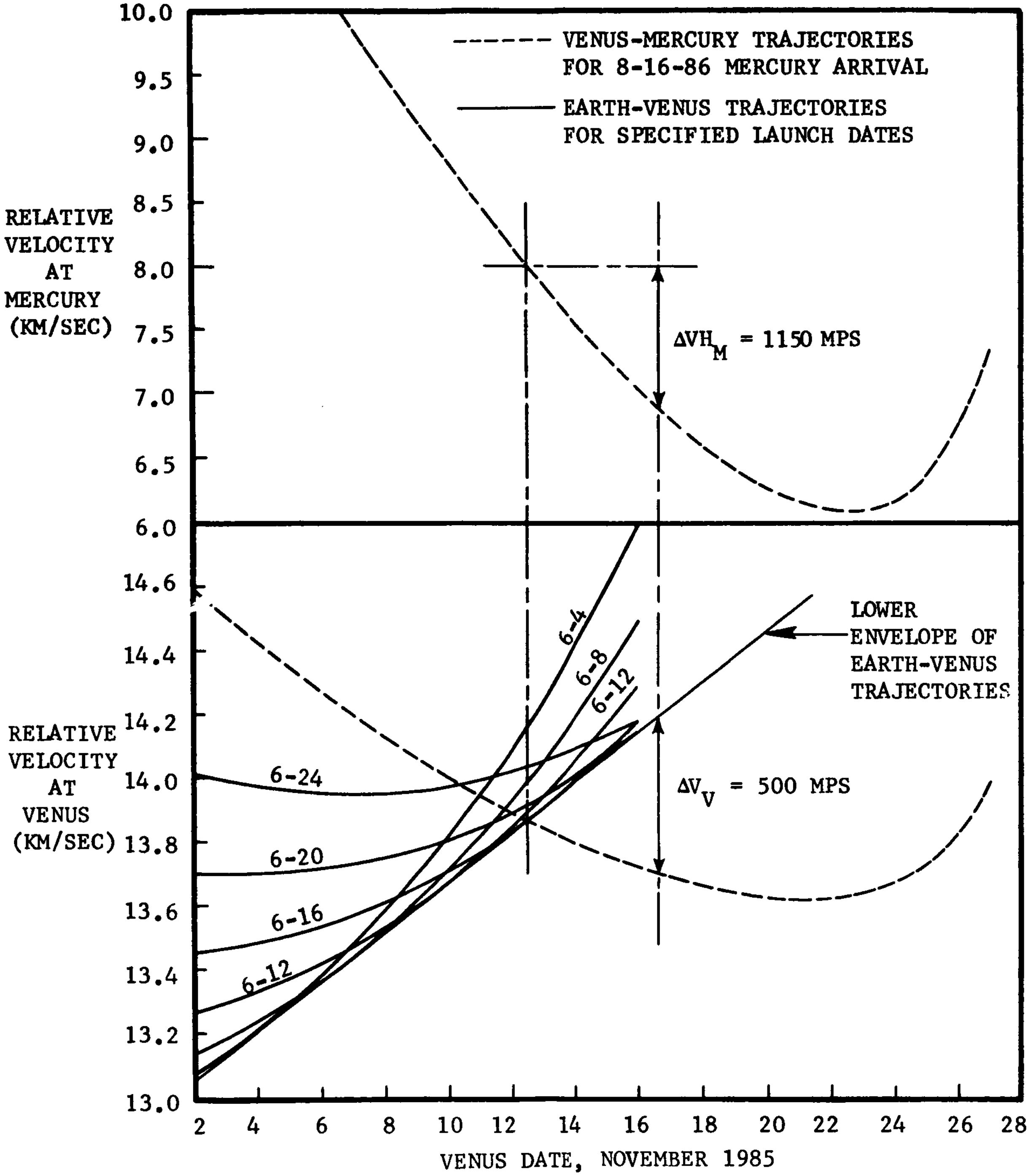


Figure VII-1. Venus Arrival/Departure Characteristics, 1985 Opportunity retarding velocity maneuver to produce delayed Venus arrival. The resulting Venus encounter is more nearly tangential to the Venus orbit with a corresponding reduction in relative velocity. Both of these effects are beneficial in the context of the Venus swingby requirements indicated by Figure VII-1.

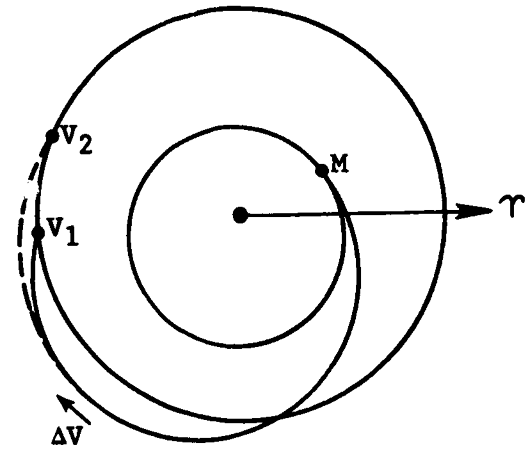
The counterpart maneuver for non-ballistic Venus-Mercury transfer is also depicted on Figure VII-2. In this case, early departure from Venus with low departure velocity can be accomplished while maintaining low approach velocity at Mercury.

To assess the quantitative requirements and net benefits of the midcourse maneuver technique, the Earth-Venus transfer orbit was selected for analysis. Preliminary results are presented in Figure VII-3 to illustrate the effect on Venus arrival conditions. As shown, midcourse maneuvers applied near perihelion of Earth-Venus transfer orbits are quite effective in reducing Mercury arrival velocity. The advantage factor of about 4 is considerably greater than corresponding maneuvers executed near Venus.

To follow up the indicated potential of midcourse maneuvers, three-planet trajectories were generated to confirm the performance effects and check such parameters as Venus swingby altitude not treated in the foregoing analysis. Results for three specific Venus encounter dates are presented in Figure VII-4. Equivalent ballistic conditions are shown to facilitate interpretation of the partially optimized performance advantages of modest midcourse velocity maneuvers.

Direct application of the midcourse maneuver technique to the 1977 mission opportunity is also presented on Figure VII-4. While significant improvement is indicated, the net effects are less pronounced. This is apparently due to relatively high ballistic performance corresponding to better planet alignments and consequent reduced room for improvement with the non-ballistic flight technique.

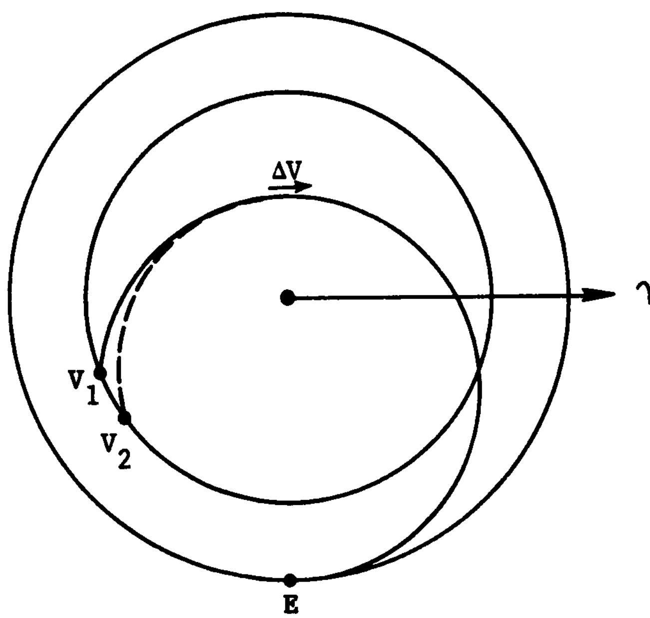
Figure VII-5 summarizes the performance improvement potential of midcourse maneuvers in the context of the baseline ballistic mission opportunities. As noted, midcourse maneuvers were implemented with a low performance auxiliary propulsion system compatible with navigation requirements.



VENUS-MERCURY TRANSFER

V_1: VENUS DEPARTURE FOR BALLISTIC TRAJECTORY TO MERCURY

V_2: EARLY VENUS DEPARTURE CORRESPONDING TO VELOCITY MANEUVER NEAR APHELION



EARTH-VENUS TRANSFER

V_1: VENUS ARRIVAL FOR BALLISTIC TRAJECTORY FROM EARTH

V_2: DELAYED VENUS ARRIVAL PRODUCED BY VELOCITY MANEUVER NEAR PERIHELION

Figure VII-2 Midcourse Maneuver Options

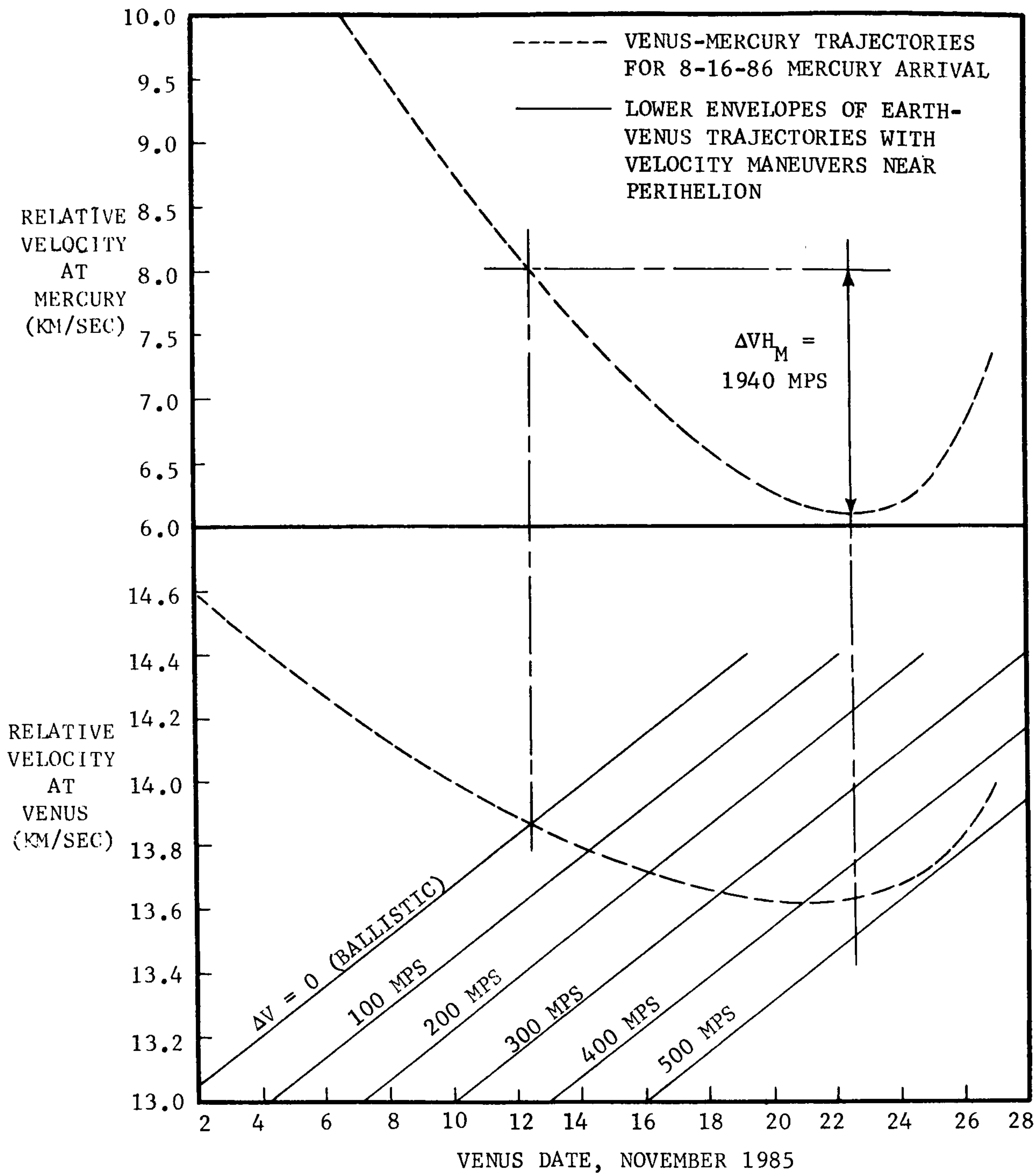
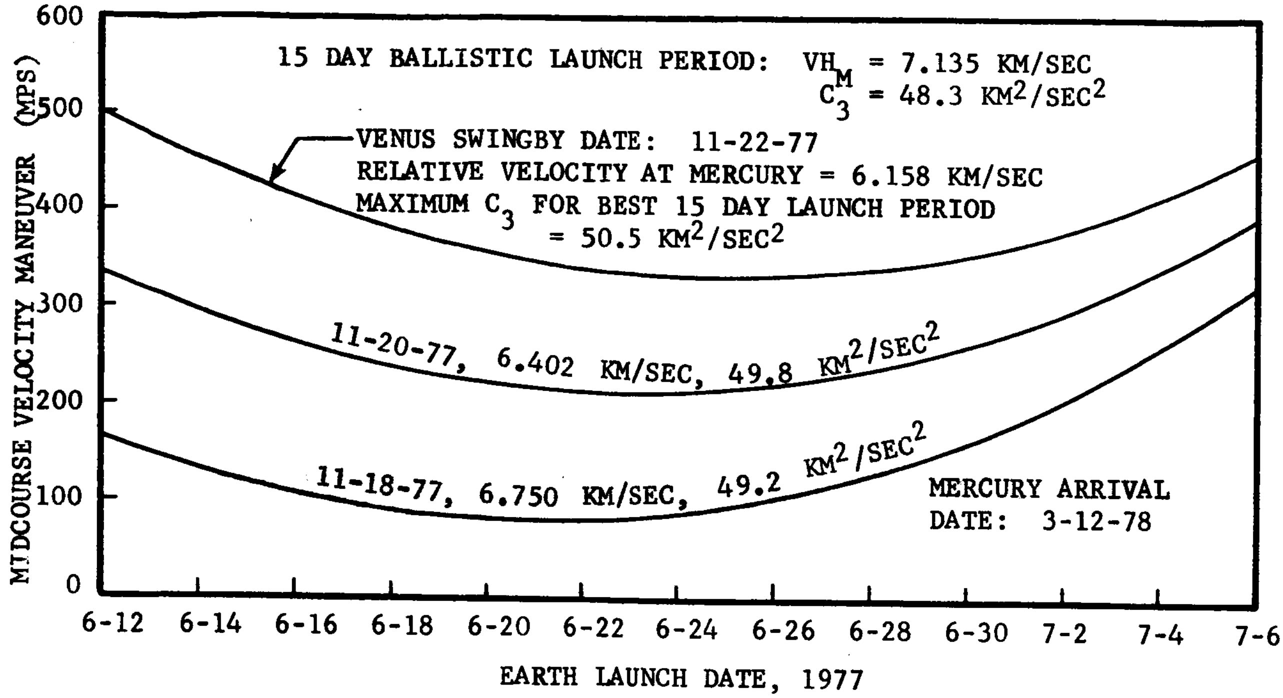


Figure VII-3. Predicted Potential of Midcourse Maneuvers, 1985 Opportunity



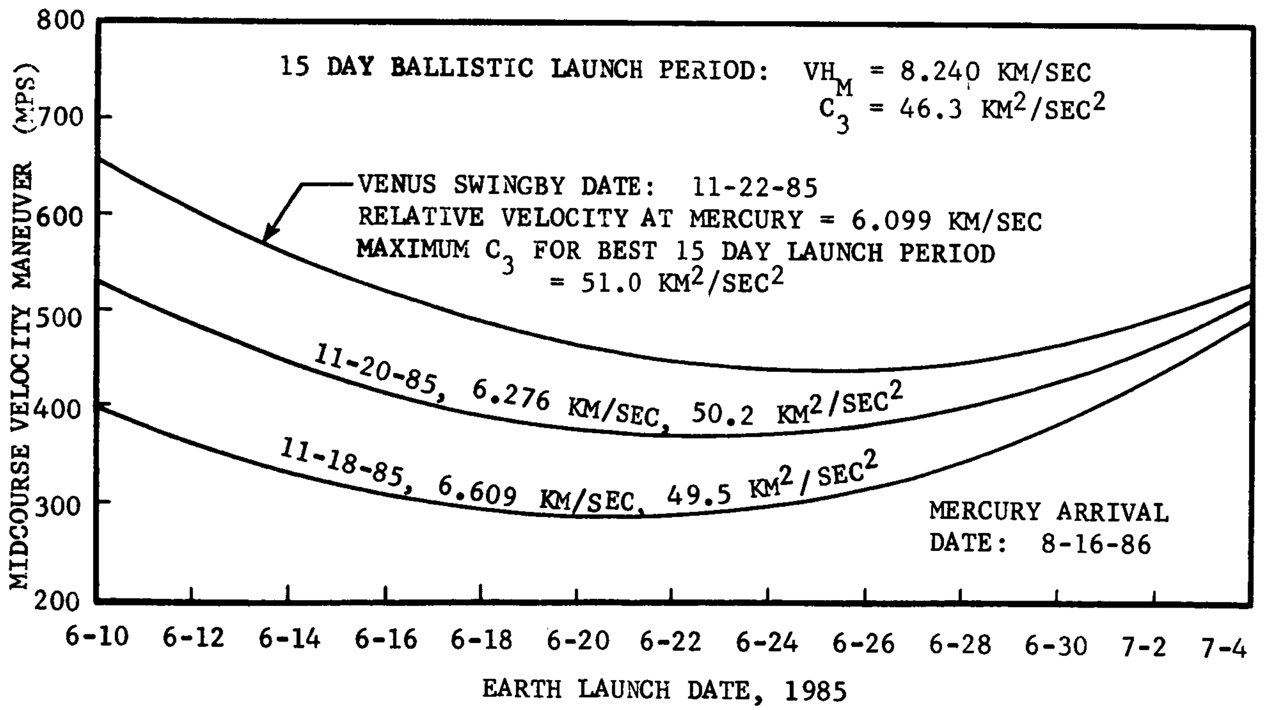


Figure VII-4. Typical Midcourse Maneuver Effects, 1977 and 1985 Opportunities

The primary beneficiary of the midcourse maneuver technique is the 1985 mission opportunity. Even though a larger capability launch vehicle such as Shuttle/Centaur may be available in this time period, the poor performance of the pure ballistic mode may be inadequate to support a useful orbiter mission. For this reason, and since the mid-1980 period will continue to be of interest, follow-up of the midcourse maneuver potential should be pursued for the 1985 opportunity. Feasibility of the mission will probably depend on spacecraft design requirements imposed by integration of an appropriate propulsion system.

CONDITIONS:

TITAN IIIE/CENTAUR LAUNCH VEHICLE

15 DAY LAUNCH PERIOD

MIDCOURSE CORRECTIONS = 250 MPS TOTAL
(AUXILIARY PROPULSION SPECIFIC IMPULSE = 235 SEC)

MINIMUM VENUS SWINGBY ALTITUDE = 250 KM

MERCURY ORBIT PERIAPSIS ALTITUDE = 500 KM

MERCURY ORBIT ECCENTRICITY = 0.8 MAXIMUM

MERCURY ORBIT INSERTION PROPULSION: SINGLE STAGE SOLID
SPECIFIC IMPULSE = 290 SEC
MASS FRACTION = 0.93

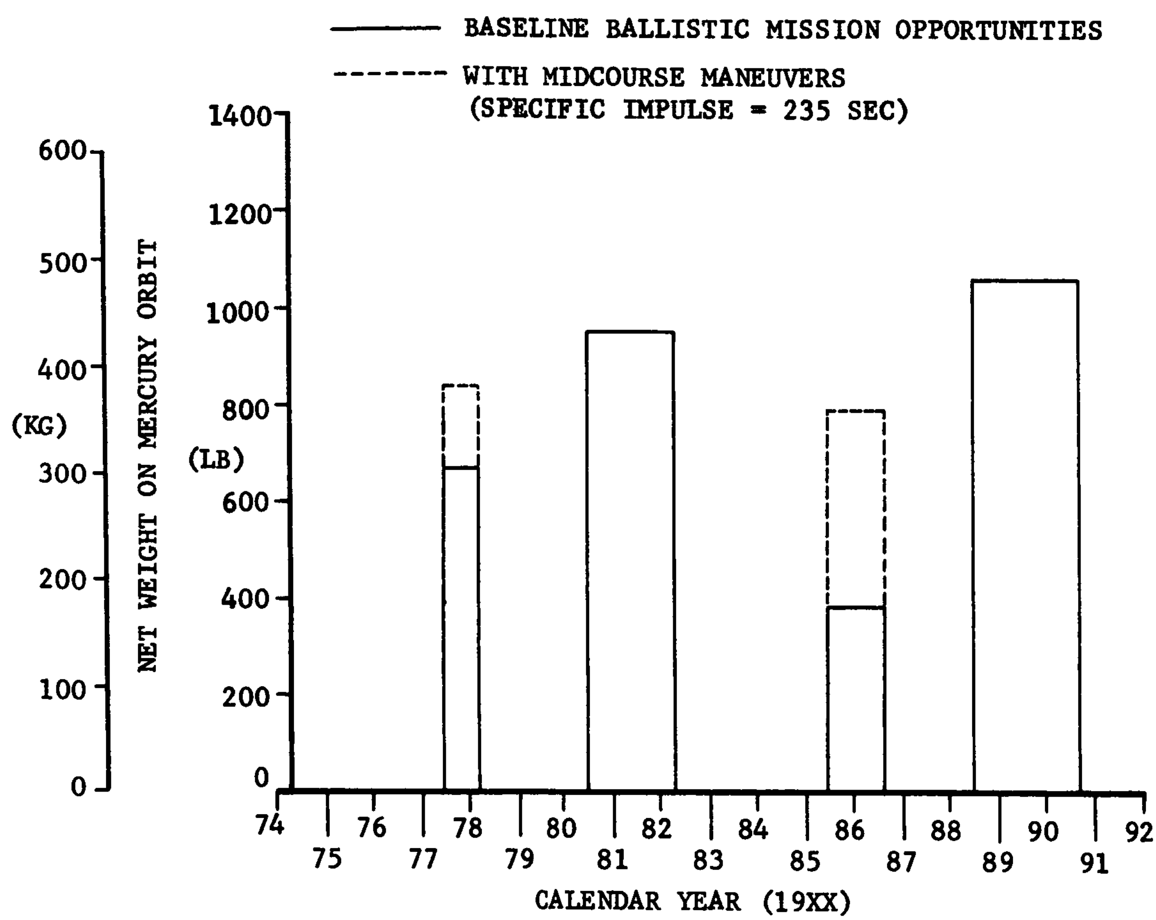


Figure VII-5. Improvement Potential of Midcourse Maneuvers

B. Multiple Venus Swingby

The performance benefits of utilizing Venus gravity-assist for ballistic Mercury missions begin with reduction of launch energy requirements. Earth launched trajectories which would pass outside the Mercury orbit can be deflected to result in Mercury encounter by employing the Venus gravity field to decelerate heliocentric velocity. This effect is applicable to all Mercury missions including the flyby mode.

A second effect of equal importance to orbiter missions is the associated reduction in Mercury approach velocity produced by Venus swingby. The combined performance improvements of Venus gravity-assist are basic to the Mercury orbiter opportunities presented in this document.

The two baseline mission opportunities with highest performance (1980 and 1988 launch) are limited by Venus swingby altitude. This implies that more gravity-turn could further improve performance. Due to the constraints on Venus altitude, the only means of achieving greater effect from Venus is to combine the contributions of multiple successive swingby's.

Initial investigations of the potential of multiple Venus swingby were predicated on the data presented in Figure VII-6. For the simplified case of circular, co-planar Earth and Venus orbits, maximum capabilities of a single Venus swingby to reduce launch requirements for attaining low perihelia are shown. Comparison with direct ballistic requirements for reaching the region of Mercury perihelion demonstrates the significance of Venus gravity-assist for Mercury orbiter missions.

The maximum effect on perihelion radius which can be produced by a planet in the Venus orbit is to deflect the hyperbolic approach velocity in the direction to directly subtract from the Venus orbit heliocentric velocity. This condition is shown on Figure VII-6 for the perihelion range of interest and corresponds to two successive swingbys of Venus. The indicated launch performance improvement potential and the related effects on Mercury approach velocity motivated investigation of the multiple Venus swingby flight technique.

Attempts to incorporate multiple Venus swingby in the Venus-altitude-limited 1980 and 1988 baseline mission opportunities were unsuccessful. Analysis showed that the planet alignments producing high performance for these opportunities were uniquely suited to utilization of a single Venus swingby and completely out of phase with geometry options permitting successive Venus encounters within a reasonable time interval. Accordingly, a search was initiated for new mission opportunities consistant with multiple Venus swingby requirements and potential.

Figure VII-7 illustrates the basic options by which successive Venus encounters can be produced. For example, if the first Venus swingby is employed to achieve a spacecraft orbit period of precisely one Venus year (or an integral fraction thereof), the second encounter is assured. In these cases, the plane of the intermediate spacecraft orbit is not uniquely determined and can be tailored to accommodate other considerations.

Alternatively, the first Venus swingby can be used to produce a spacecraft period permitting second encounter at the other radius intersection with the Venus orbit. For this case, it is necessary that the spacecraft complete at least one solar revolution between Venus encounters. Also, the plane of the intermediate spacecraft orbit must precisely match the Venus orbit plane.

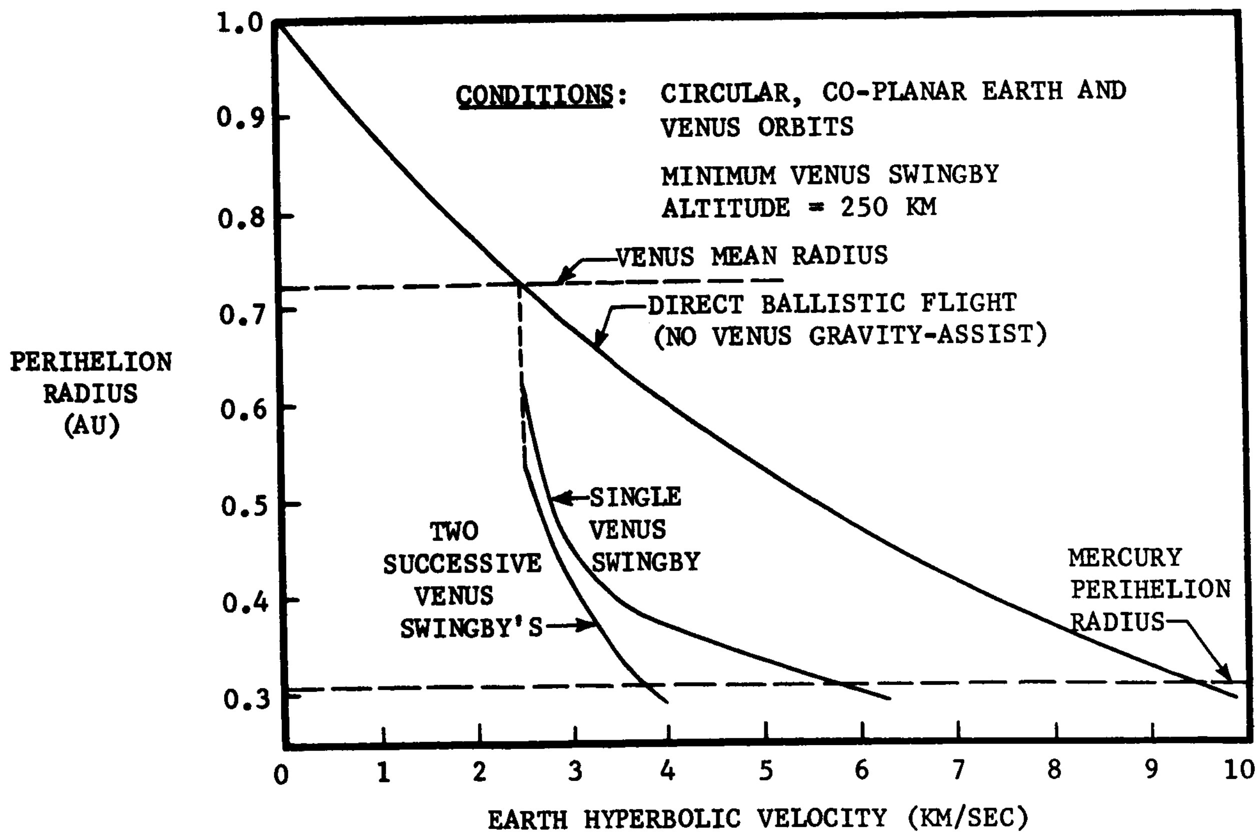


Figure VII-6. Venus Gravity-Assist Potential

Geometries corresponding to Type I and Type II transfers from Earth to the first Venus swingby are depicted on Figure VII-7. Both types of initial transfer are compatible with second Venus encounters after integral or non-integral solar revolutions of the spacecraft. However, a significant difference can be seen in the relation of non-integral encounters. For Type I initial trajectories, the second Venus orbit intersection is rotated counterclockwise while the opposite rotation is associated with Type II transfer. A primary result is that different spacecraft orbit periods are required for the two encounter sequences with corresponding differences in the conditions which must be produced by the first Venus swingby.

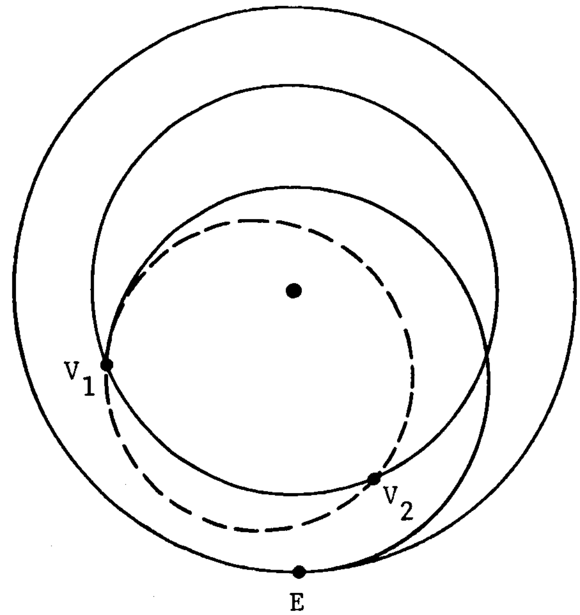
A large number of three-planet geometries satisfying the conditions for successive Venus encounters can be derived. In addition to the options of integral and non-integral spacecraft revolutions between Venus swingby's, the simple introduction of extra revolutions during the initial Earth-Venus transfer and/or the final Venus-Mercury transfer (as employed for some of the baseline single Venus swingby mission opportunities) remains applicable.

A search for multiple Venus swingby mission opportunities corresponding to the manifold idealized three-planet geometry options was undertaken. For practical reasons, this investigation was limited to total mission flight times no greater than 36 months. To permit valid assessment of the flight technique, launch opportunities through the remainder of the century were considered.

Alignment of four bodies in unique relative geometries is a rare occurence. However, due to the many applicable geometry options, several opportunities to utilize multiple Venus swingby for Mercury orbiter missions have been identified. Two of the most promising and timely opportunities were selected for further investigation.

Figure VII-8 presents the heliocentric geometry of a typical multiple Venus swingby mission employing an intermediate spacecraft orbit period precisely equal to the period of Venus. This opportunity involves several solar revolutions for phasing with a resultant total flight time of about 31 months. The 1983 launch timing compensates for this disadvantage by providing an alternative for the low-performance 1985 baseline mission opportunity.

As shown by the figure, the first Venus swingby produces a modest change in the spacecraft orbit to set up conditions for a second encounter 2 Venus years



V_1: FIRST VENUS SWINGBY. ALSO SECOND VENUS SWINGBY FOR SPACECRAFT ORBIT PERIOD INTEGRAL FRACTION OF VENUS ORBIT PERIOD.

V_2: ALTERNATE SECOND VENUS SWINGBY FOR NON-INTEGRAL SPACECRAFT SOLAR REVOLUTIONS (GREATER THAN ONE).

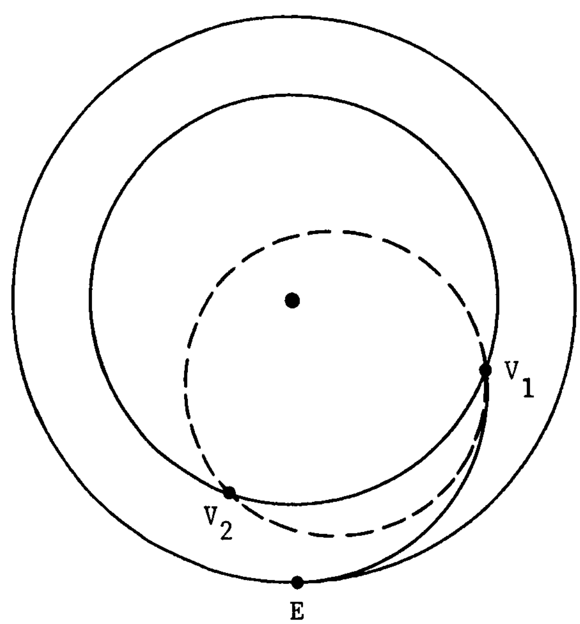


Figure VII-7. Multiple Venus Swingby Geometry Options later following two complete solar revolutions of the spacecraft. At the final Venus swingby, Mercury encounter conditions are established

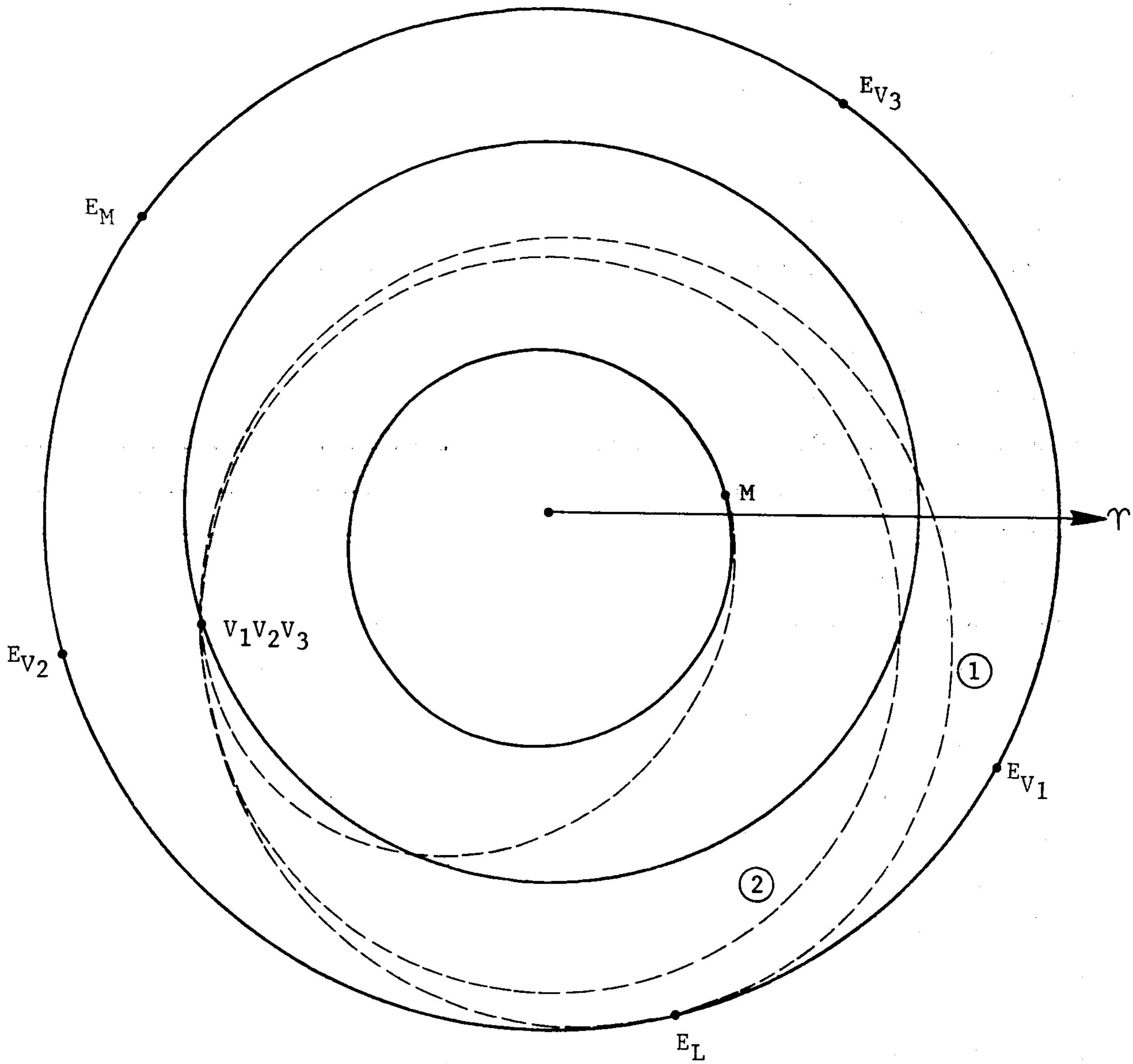
All of the Venus gravity-assist performance benefits are within the capabilities of two Venus swingbys. However, due to the 1983 mission phasing requirements, the opportunity is necessarily a triple swingby operation. An additional Venus encounter one Venus year after the first swingby and one Venus year prior to the final swingby is unavoidable. Fortunately, due to the orbit inclination flexibility associated with successive encounters separated by integral solar revolutions, the middle Venus swingby can be finessed. The first swingby can avoid changing the spacecraft orbit plane and thereby leave a function to be performed by the second Venus encounter. With the final required spacecraft orbit plane established by the second swingby, the third gravity-assist can be devoted to in-plane effects with consequent relief of Venus swingby altitude.

Performance parameters for the 1983 multiple Venus swingby mission opportunity have not been completely optimized. However, performance potential is illustrated in Figure VII-9 for a single near-optimum Mercury arrival date. As shown, the effects on Mercury arrival velocity are comparable to the best single Venus swingby cases. The significant performance improvement involves corresponding launch energy requirements which are substantially lower than the best single Venus swingby values.

The other multiple Venus swingby mission opportunity evaluated is defined in Figure VII-10. Although involving the more complex non-integral revolution phasing option, the net result is a simpler, shorter flight profile.

The mission is initiated with Type I transfer to Venus without extra solar revolutions for phasing. The first Venus swingby sets up conditions for a second encounter at the other Venus orbit intersection after about 2 5/6 solar revolutions of the spacecraft and 1 5/6 revolutions of Venus. For this mission, the first swingby must simultaneously reduce perihelion to near Mercury encounter conditions and deflect the spacecraft orbit into the Venus orbit plane. The second swingby produces Mercury encounter conditions with final approach delayed by one extra spacecraft revolution for phasing.

Although launch timing for this mission opportunity nearly duplicates the high performance 1988 baseline case, quantitative evaluation was pursued to



E_L: EARTH AT LAUNCH, 7-8-83

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

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

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

E_M: EARTH AT MERCURY ENCOUNTER, 2-14-86

(1) ONE COMPLETE SOLAR REVOLUTION BEFORE FIRST VENUS SWINGBY

(2) ONE COMPLETE SOLAR REVOLUTION BETWEEN FIRST AND SECOND VENUS SWINGBY'S
ONE COMPLETE SOLAR REVOLUTION BETWEEN SECOND AND THIRD VENUS SWINGBY'S

Figure VII-8. Heliocentric Geometry, 1983 Multiple Venus Swingby Opportunity

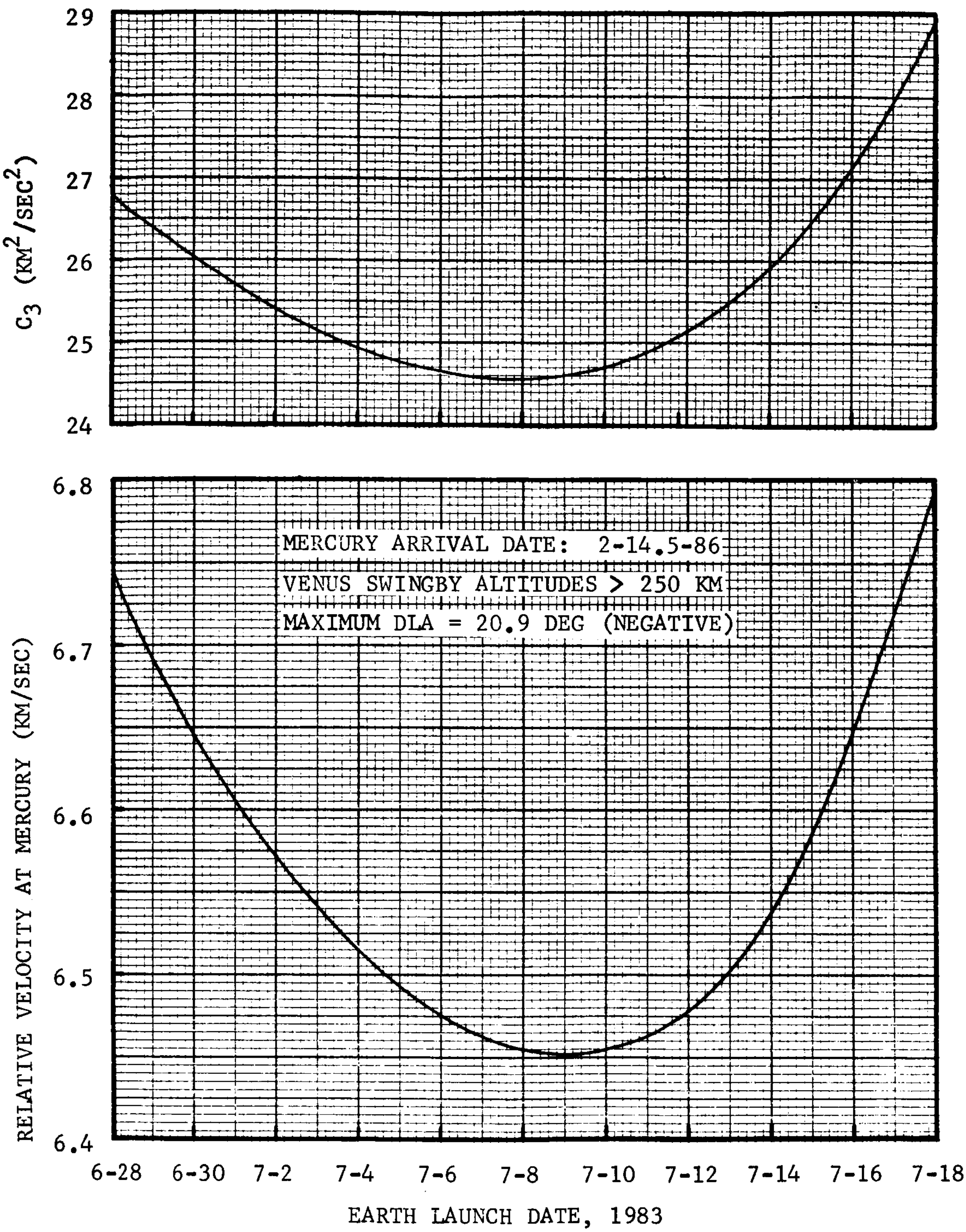
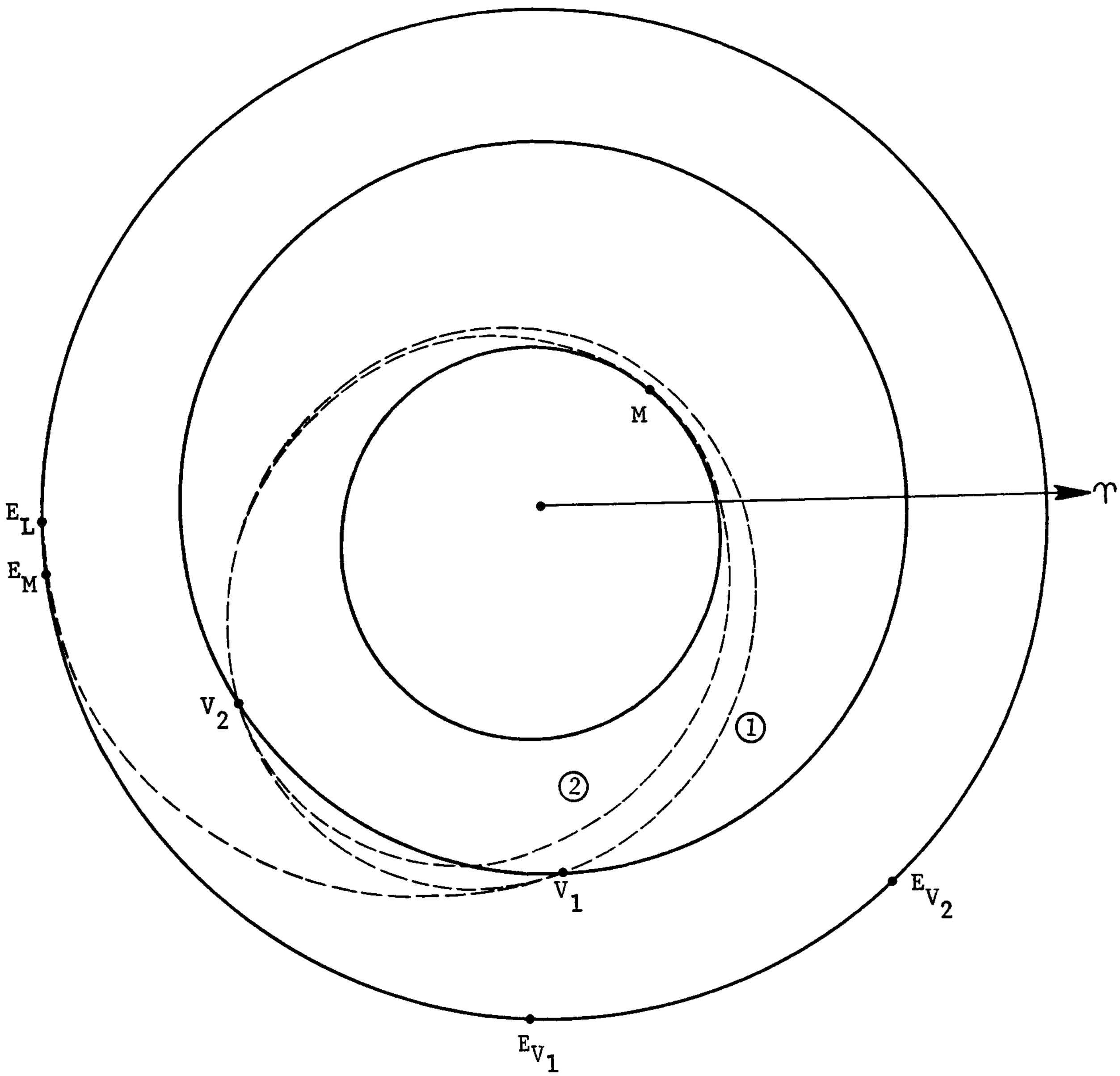


Figure VII-9. Typical Performance Requirements, 1983 Multiple Venus Swingby Opportunity



E_L: EARTH AT LAUNCH, 3-22-88

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

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

E_M: EARTH AT MERCURY ENCOUNTER, 3-27-90

① TWO COMPLETE SOLAR REVOLUTIONS BETWEEN FIRST AND SECOND VENUS SWINGBY'S

② ONE COMPLETE SOLAR REVOLUTION BEFORE MERCURY ENCOUNTER

Figure VII-10. Heliocentric Geometry, 1988 Multiple Venus Swingby Opportunity further assess the relative merits of the multiple Venus swingby flight technique.

Figure VII-11 presents performance parameters for a set of Mercury arrival dates demonstrating mission potential and requirements. As shown, conditions at Earth launch and at Mercury arrival are both superior to the best single Venus swingby opportunities. However, due to the requirements imposed on the first Venus swingby, a velocity maneuver in the vicinity of Venus is necessary to limit swingby altitude. Selection of an Earth launch period of best performance involves substantial interactions between the parameters presented.

Minimum verified performance potentials for the two multiple Venus swingby opportunities evaluated are depicted on Figure VII-12 in context with the baseline single Venus swingby missions. Both new cases exhibit superior performance and serve to demonstrate the significant potential of the multiple Venus swingby flight technique. Moreover, preliminary analysis of the conditions at critical Venus swingby events has indicated that the midcourse maneuver technique may be applicable to the multiple Venus swingby mission opportunities and further improve performance capabilities beyond those established.

Since both alternate flight techniques explored have shown substantial promise, and may be even more effective in combination, additional analysis could further improve the prospects of advanced Mercury exploration with ballistic mode missions.

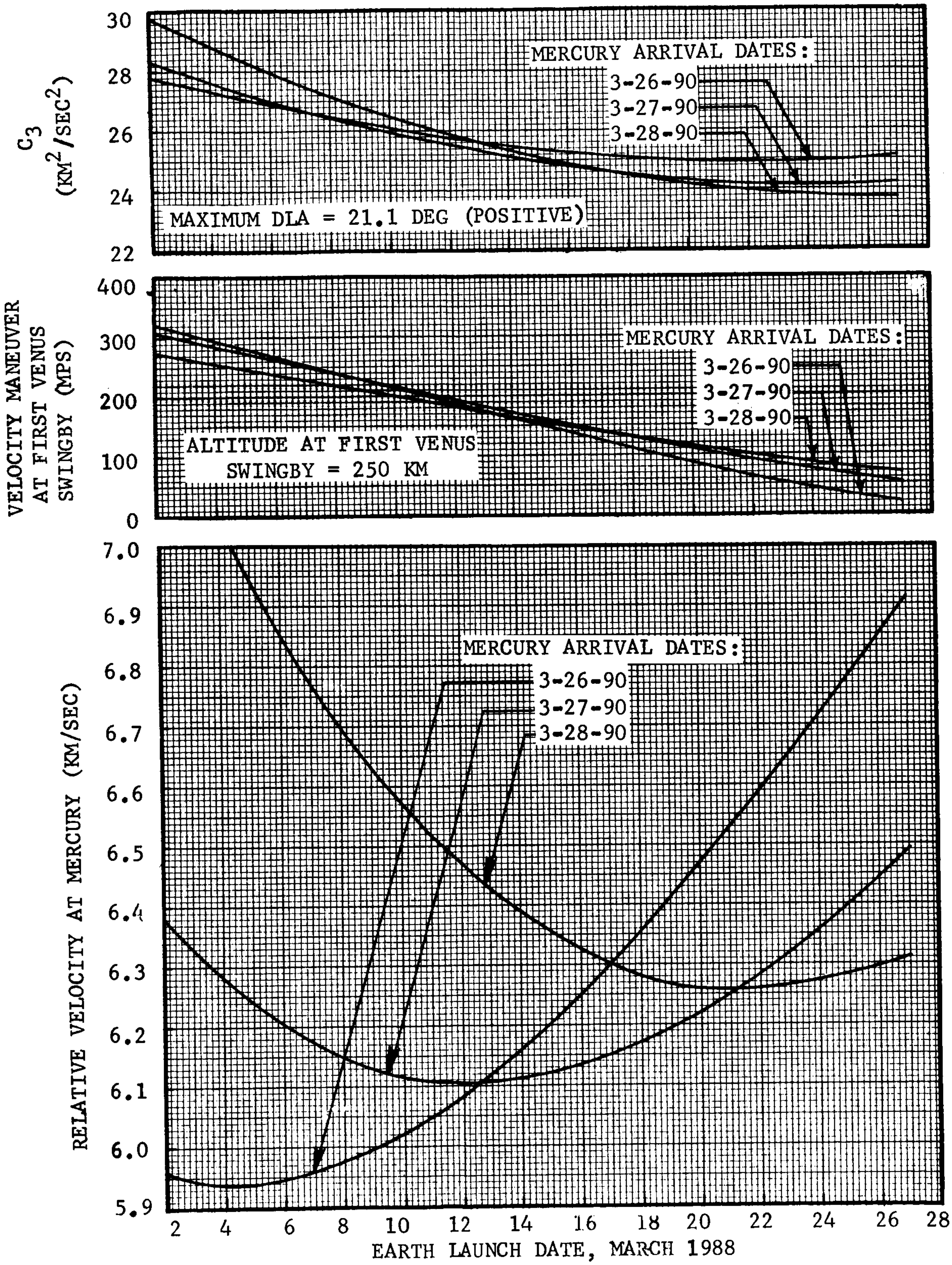


Figure VII-11. Typical Performance Requirements, 1988 Multiple Venus Swingby Opportunity

CONDITIONS:

TITAN IIIE/CENTAUR LAUNCH VEHICLE

15 DAY LAUNCH PERIOD

MIDCOURSE CORRECTIONS = 250 MPS TOTAL
(AUXILIARY PROPULSION SPECIFIC IMPULSE = 235 SEC)

MINIMUM VENUS SWINGBY ALTITUDE = 250 KM

MERCURY ORBIT PERIAPSIS ALTITUDE = 500 KM

MERCURY ORBIT ECCENTRICITY = 0.8 MAXIMUM

MERCURY ORBIT INSERTION PROPULSION: SINGLE STAGE SOLID
SPECIFIC IMPULSE = 290 SEC
MASS FRACTION = 0.93

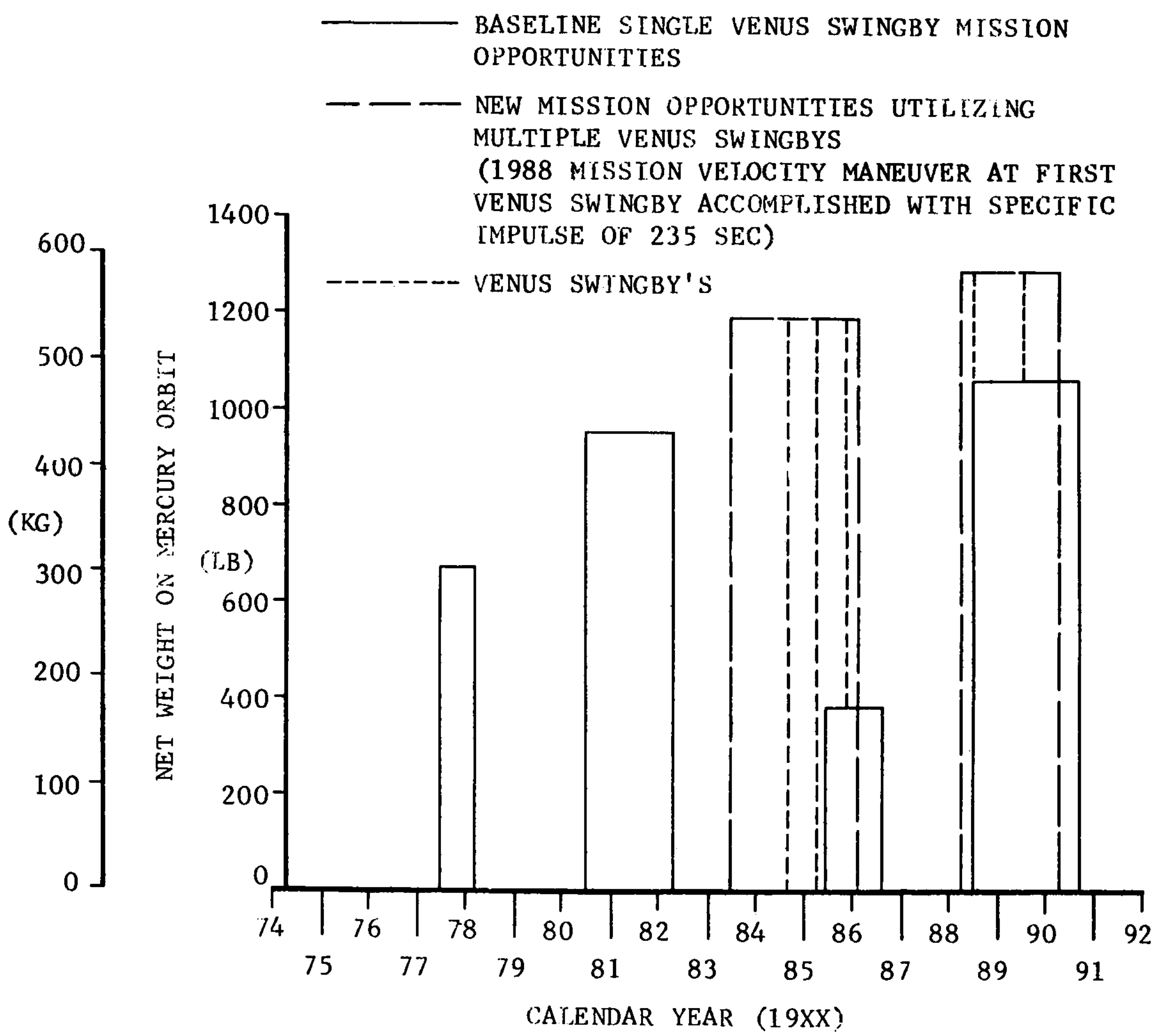


Figure VII-12. Improvement Potential of Multiple Venus Swingby

APPENDIX

1. Trajectory Simulation Program

All trajectory data in this document were generated with the MMA computer program AIMS (Advanced Interplanetary Mission Search). Planetary positions, masses, etc. are based on JPL document TR32-1508. Lambert's Theorem is solved by the Lancaster-Blanchard formulation in NASA document TN D-5368. Typical patched conic assumptions are used to simulate Venus swingby conditions. The navigation analysis (Sec. VI) required integrated trajectories which also served as a check for the conic trajectories defined by AIMS.

Ballistic trajectories are identified by defining three dates (Earth launch date, Venus swingby date, and Mercury encounter date) for which the approach relative velocity at Venus equals the departure relative velocity. Swingby altitude, required aiming conditions, and Venus relative geometry are defined by assuming pure hyperbolic motion relative to Venus from sphere-of-influence entry to sphere-of-influence exit. In some cases, as many as three different Venus swingby dates (VSD) yield solutions for fixed Earth launch date (ELD) and fixed Mercury encounter date (MED). When this occurs, the different solutions are investigated and distinguished by a category label.

Powered swingbys are accomplished by the use of ΔV_V, a Venus sphere exit velocity maneuver equal to the vectoral difference between the required velocity leaving Venus and the achievable velocity leaving Venus. This velocity maneuver is defined in Figure A-1. A given ELD-VSD-MED combination defines Earth-Venus and Venus-Mercury trajectories. This defines spacecraft velocity at arrival and departure. Subtracting the velocity of Venus defines arrival and departure relative velocities. The gravity-assist capability of Venus is a function of its mass, spacecraft relative approach velocity, and the minimum allowable altitude of closest approach. The approach velocity vector is turned toward the required departure velocity through the angle ϕ (the maximum turn possible for a given set of conditions) to define Venus departure velocity after swingby. The propulsive maneuver required to complete the velocity match is labeled ΔV_V. The magnitude of the velocity maneuver is exaggerated for illustration in Figure A-1. ΔV_V may function as a powered swingby maneuver or radius-adjust maneuver or both. When relative velocities are unequal in magnitude, ΔV_V acts as a powered swingby maneuver; when gravity turn is insufficient, it acts as a radius-adjust maneuver. In some instances, a maneuver just before Venus encounter or at Venus closest approach will achieve the same effect as ΔV_V (after Venus) for less ΔV. However, a planned maneuver before or at Venus would increase statistical ΔV requirements considerably. Executing ΔV_V simultaneously with the large V+2 statistical midcourse maneuver offers a vector bargain explained in Section VI.B. When considering nominal trajectories plus navigation effects, a sphere exit maneuver is the most efficient method for handling necessary radius-adjust maneuvers and beneficial powered swingby maneuvers.

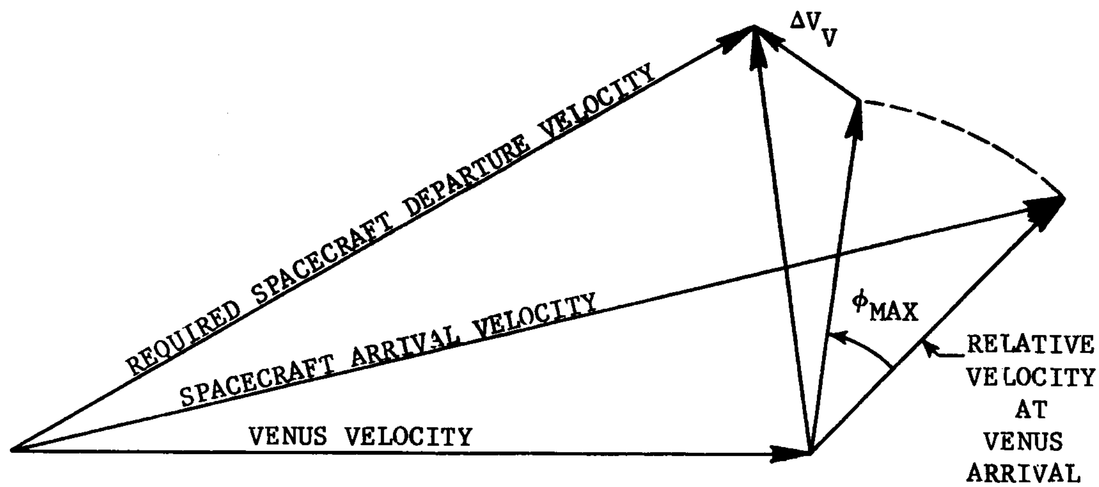


Figure A-1. Definition of Velocity Maneuver at Venus

Many of these opportunities involve extra revolution trajectories. Lambert's Theorem states: given R_1, R_2, θ, and ΔT there exists one, and only one, posigrade conic solution for $0^o < \theta < 360^o$ ($\theta \neq 180$).

R_1 = Radius to initial planet

R_2 = Radius to final planet

θ = Posigrade angle from R_1 to R_2

$\Delta T = T_2 - T_1$ where T is the time at either planet

For $\theta < 360^o$ the solution is easily found. For $\theta > 360^o$ there exists zero or two solutions. In all cases, both sets of solutions were examined. The Lancaster-Blanchard formulation allows easy and accurate selection of the preferred solution. In general, for these Mercury orbiter cases, the left-hand solution is the only usable solution.

Selected trajectories from each baseline opportunity are tabulated in detail in Sections II through V. The following table defines each parameter in that tabular data. Data are divided into three or four blocks. The first block defines geometry at launch and orbital elements of the Earth-Venus leg. The second block defines Venus relative swingby geometry and orbital elements of the Venus-Mercury leg. The final block defines Mercury encounter conditions. If there are four blocks, the third block defines the Venus sphere exit maneuver (ΔV_V). All units are in km, kg, degrees, and seconds unless otherwise noted.

TABLE A-1

PRINT KEY FOR TABULAR DATA

- - - LAUNCH BLOCK - - -

JD	= Julian Date at launch
C_3	= 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 S/C in Heliocentric coordinates
V_{HE}	= 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
A	= Semi-major axis E-V leg
E	= Eccentricity of E-V leg

TABLE A-1 (Continued)

(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
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 V-M leg
TURN	= Turn Angle relative to Venus ($\emptyset$ in ΔV_v sketch)
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)
PERIHELION	Of V-M leg
APHELION	Of V-M leg

- - - MANEUVER BLOCK - - -

DV = ΔV_v

Includes minimum allowable and actual RCA at Venus.

TABLE A-1 (Continued)

- - - 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
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. Venus Swingby Analysis

Defining a ballistic Earth-Venus-Mercury trajectory for a given Earth date (ELD) - Mercury date (MED) combination requires selecting a Venus swingby date (VSD) which yields equal Venus relative approach (V_{HA}) and departure (V_{HD}) velocities. A secondary requirement for ballistic trajectories is that the angle between the V_{HA} and V_{HD} be less than the maximum allowable turn angle which is defined by the minimum allowable radius of closest approach. Because many of these trajectories involve double and triple solutions for VSD, it is necessary to understand the data in Figures A-2 through A-7 to understand the Mercury orbiter opportunities. The '77 and '85 Venus arrival/departure characteristics are well behaved and easy to understand, but they yield the first clue that the performance can be improved with midcourse maneuvers as described in Section VII.

The '80 and '88 Venus arrival/departure characteristics are complex and understanding them was necessary for utilization of ΔV_v, which improved the performance of these opportunities considerably. The following discussions are important for anyone who desires to reproduce or thoroughly understand the data in this document.

a. 1977 Mission Opportunity

The relatively poor performance of the '77 ballistic opportunity (compared to the '80 and '88 opportunities) results from a mismatch in VSD. The solid lines in Figure A-2 represent V_{HA} for several fixed ELDs as a function of VSD. The dotted line in the lower portion of the figure represents V_{HD} for a 3-12-78 MED as a function of Venus departure date. The dotted line in the upper portion of the figure indicates approach velocity at Mercury (V_{HM}) corresponding to a trajectory leaving Venus at the dates shown across the bottom. Thus, if a trajectory could be designed that departs Venus on 11-22-77 with a V_{HD} of 13.6 km/s, then the approach velocity at Mercury could be minimized around 6.1 km/s.

Unfortunately, there are no E-V trajectories that arrive at Venus near the 24th with V_{HA} of 13.6 km/s. Since the angle between the V_{HA} and V_{HD} vectors is well within Venus gravity assist capabilities, any intersection between the dotted line and a solid line represents a potential ballistic trajectory. Intersections occur around the 16th and V_{HM} is constrained to a minimum of about

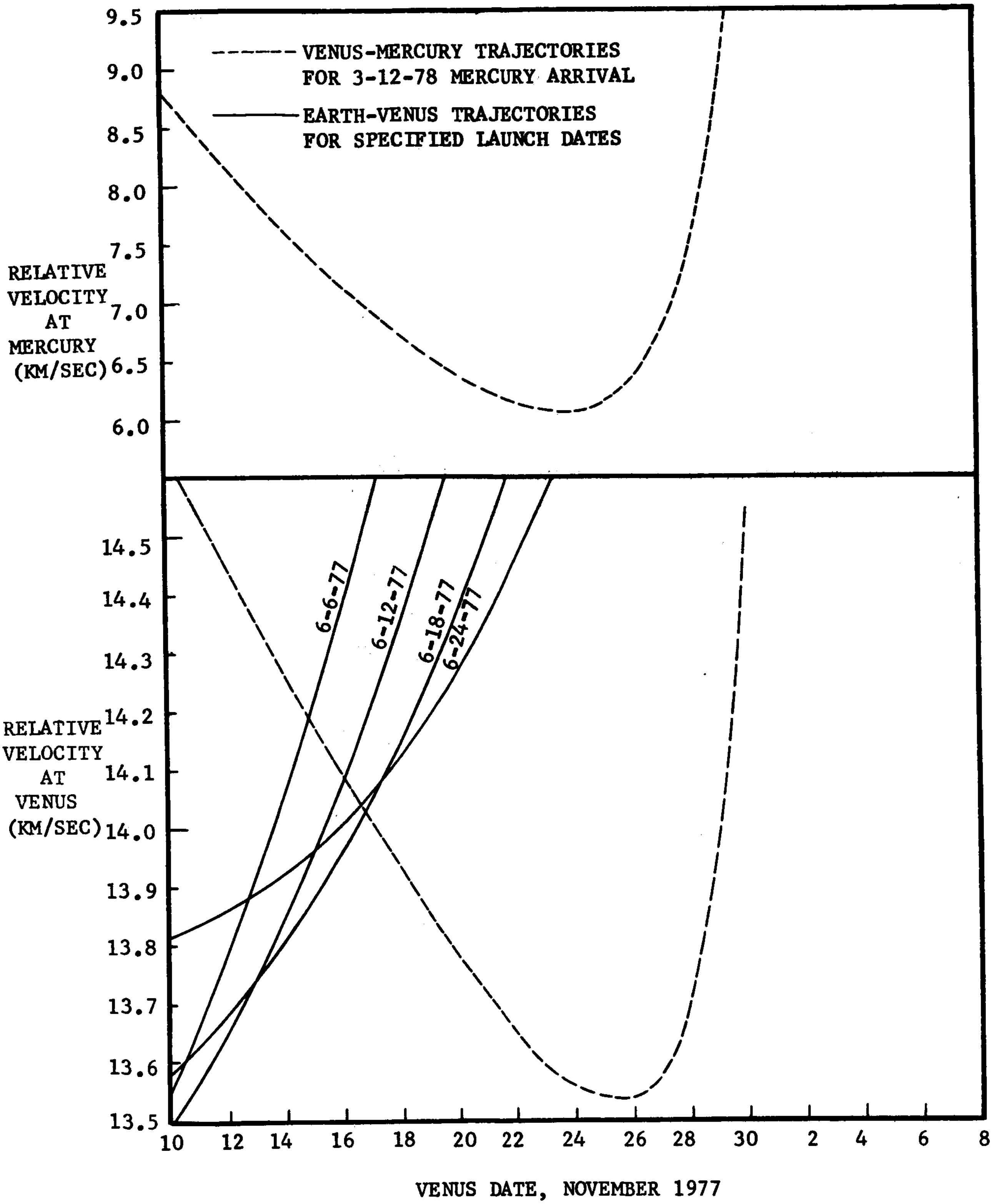


Figure A-2. Venus Arrival/Departure Characteristics, 1977 Opportunity

7 km/s. In effect, there are high performance E-V legs and high performance V-M legs but they differ in Venus date by two weeks.

A ΔV_V can be employed to produce an effective match of V_H magnitude at later Venus dates than the natural intersections. The exchange ratio is approximately 115 mps less approach velocity at Mercury for 100 mps ΔV_V applied at Venus. While this technique is not worthwhile for this opportunity, understanding the advantages of arriving at Venus on the 24th with a low V_{HA} led to the midcourse maneuver analysis discussed in Section VII.

b. 1980 Mission Opportunity

Figure A-3 presents the basic Venus swingby data for the 1980 opportunity. For illustration, a Mercury date was selected for convenient display of the Type I options for the V-M leg. As shown, the Type I Venus-Mercury trajectories can be matched but the Mercury approach velocities make it academic.

Three regions of the Venus swingby date represent three different phenomena for these trajectories. Intersections occur in the July 27 (VSD) region which produce V_{HM} of about 7 km/s. For lack of any known standard terminology, the left-hand intersections are called Category I. The Category I intersections do provide V_{HM} around 6.8 km/s for slightly different MEDs. Venus swingby altitudes for the Category I solutions are positive but Earth launch dates are restricted to before June 30. It may be seen in the figure that the Category I intersections do not exist for June 30 launches, but there are a pair of Category I intersections for slightly earlier Earth launch dates.

Low relative velocity at Mercury can be achieved by the right-hand Type II intersections (defined as Category II) occuring for VSD of 8-2-81. Although Category II intersections correspond to low V_{HM}'s of about 6.2 km/s, the turn angles at Venus (not apparent from the figure) require negative altitudes of about 1000 km. These intersections are not useful for ballistic trajectories.

A third region of interest for VSD is the 7-28 to 8-1 region where no intersections occur. Velocity mismatches up to 200 m/s at Venus eliminate a set of trajectories which would have resulted in V_{HM} between 6.2 and 7.0 km/s for the 4-13-82 encounter. Three regions of VSD from left to right involve:

1. Early launch dates and high V_{HM} (Category I).
2. No ballistic solutions but reduced V_{HM} for 200 m/s ΔV_V.
3. Late launch dates, low V_{HM} but large negative altitudes (Category II).

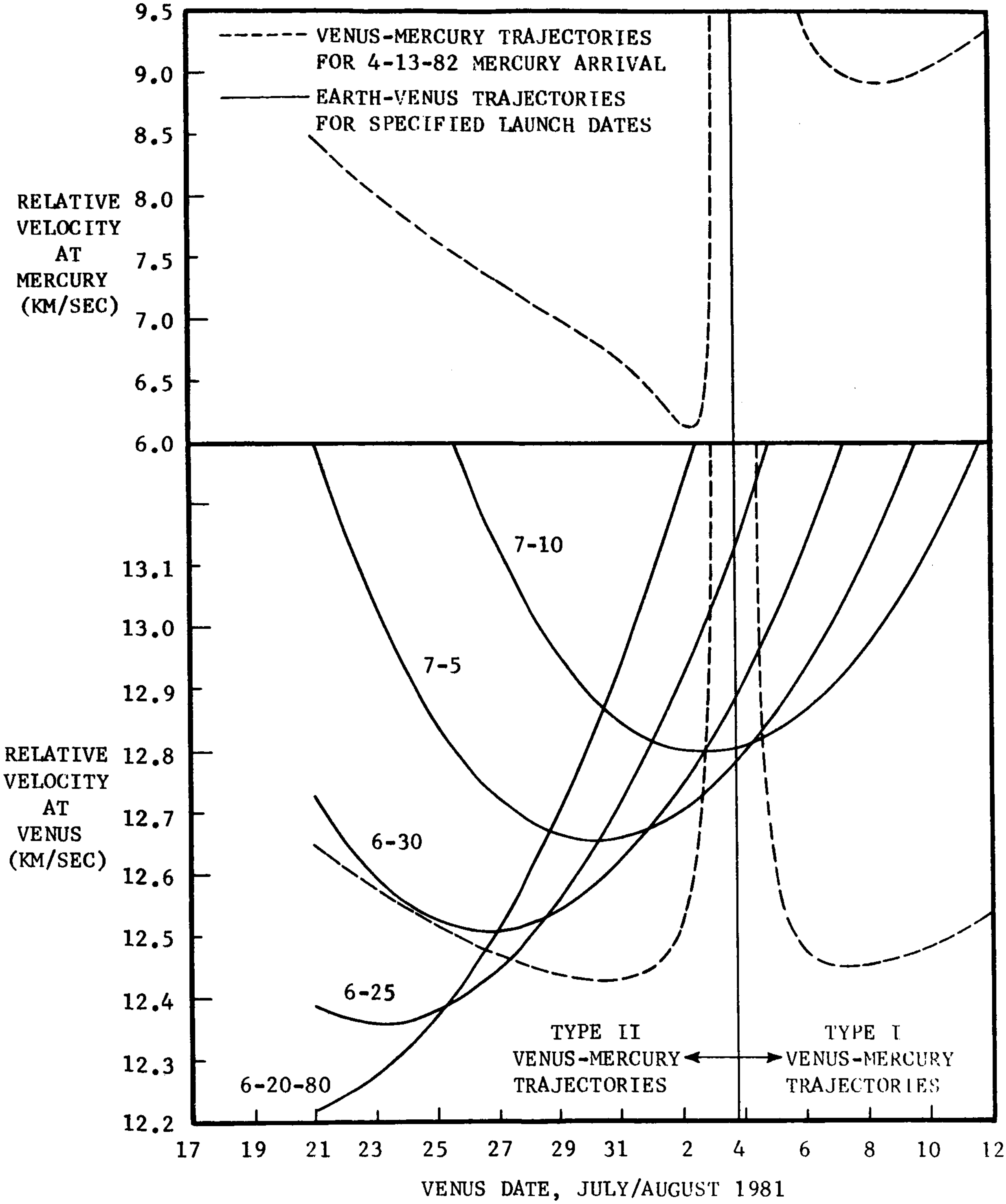


Figure A-3. Venus Arrival/Departure Characteristics, 1980 Opportunity

Figure A-4 depicts three planet data for the usable and prospective launch period. As predicted by Figure A-3, the Category I solutions double back restricting them to June launches. Category II intersections provide later launches with low V_{HM} but they imply flying below the surface of Venus without a large radius adjust maneuver. A composite view of the best performance possibilities for this opportunity as a function of ΔV_v, minimum allowable Venus swingby altitude and launch period is presented in Section III. Generating the good data for variable Mercury encounter date and multiple solution Venus swingby dates was not possible until the data in Figure A-3 were understood.

c. 1985 Opportunity

Just as in the similar figure for 1977, low V_{HM} at Mercury is possible for the 1985 opportunity if the later Venus swingby dates are attainable with low Venus relative velocities (Figure A-5). However, no E-V legs can be designed to arrive at Venus after 11-12-85 with the proper V_{HA}. The resulting V_{HM} at Mercury for attainable ballistic missions is thus constrained above 8.0 km/s (Section IV). The situation of a good E-V leg and a good V-M leg with different swingby dates is even more pronounced for '85 than for '77, and is responsible for the poor performance of the '85 opportunity.

For this mission, the benefits of powered swingby are enhanced. As derived from the figure, the initial exchange ratio is 280 m/s reduction in Mercury approach velocity for 100 m/s ΔV_v. Even more effective improvement of the '85 opportunity can be accomplished with midcourse maneuvers. The data in Section VII demonstrates how a V_{HM} of 6.1 km/s can be achieved for a 480 m/s maneuver during the E-V leg resulting in about 100% performance increase.

d. 1988 Opportunity

This opportunity is very similar to the '80 opportunity. However, as shown in Figure A-6, subtle differences in geometry have replaced the 1980 region of excluded Venus date with a region of excluded Earth dates. Also, the paired set of solutions (Category I) straddles the Mercury approach velocity minimum for early ELDs. Category II single solutions do not appear until later ELD's by which time Category I cases cease to exist. Notice, in Figure A-6, that with an ELD of 6-28-88, in the middle of the parametric family displayed, the solid line does not intersect the dashed line. It is clear from

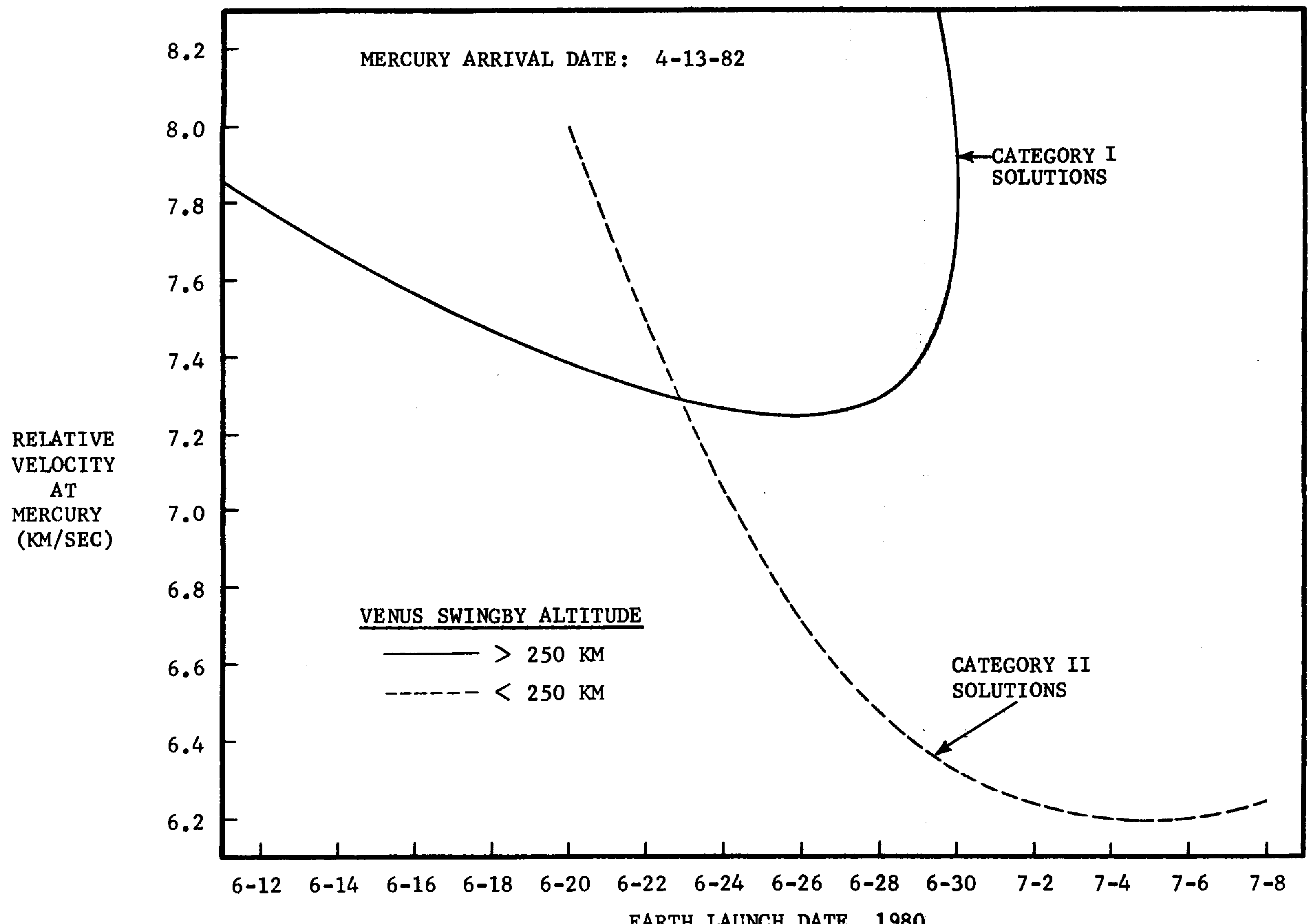


Figure A-4. Typical Multiple Solutions, 1980 Opportunity

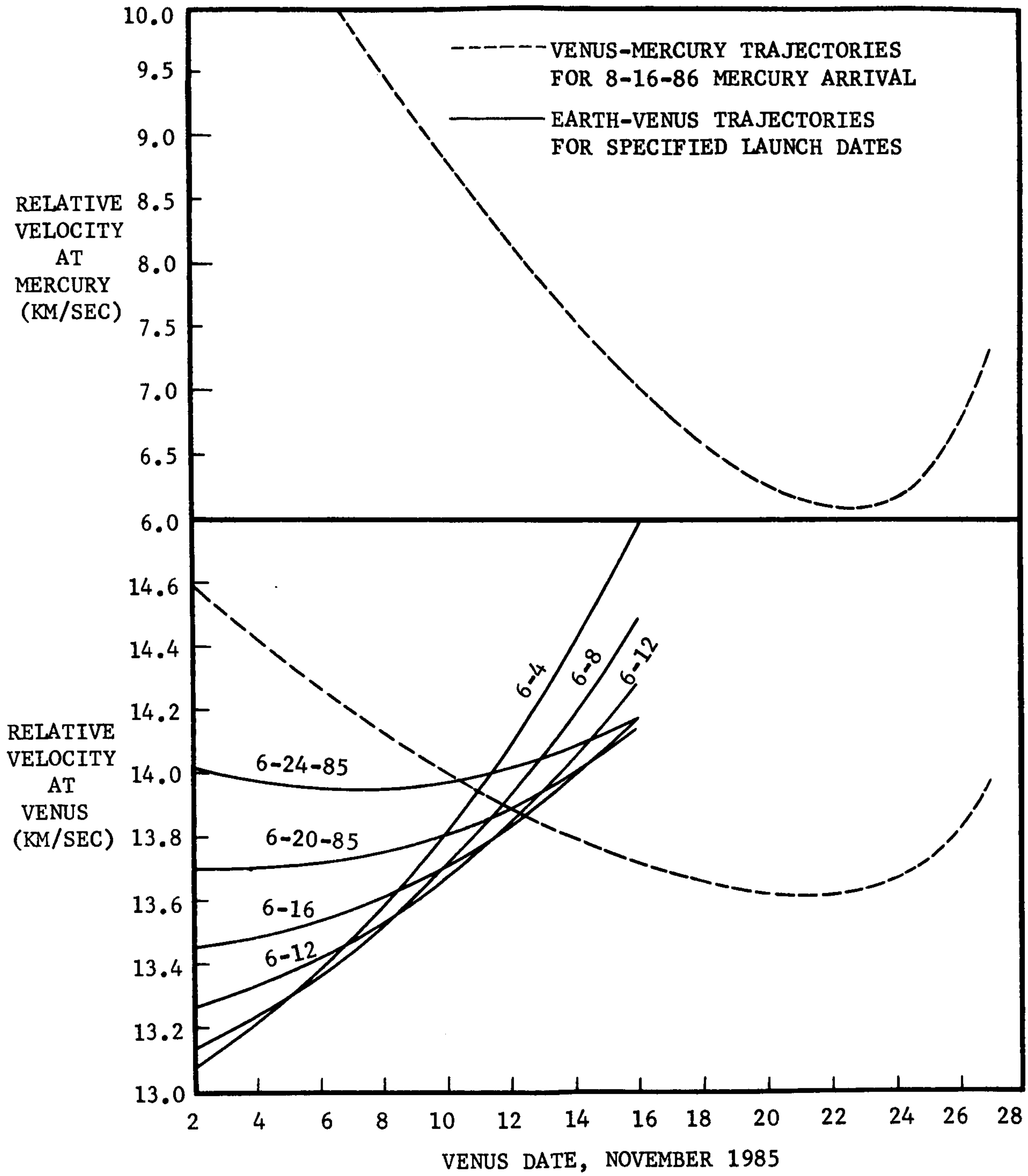


Figure A-5. Venus Arrival/Departure Characteristics, 1985 Opportunity

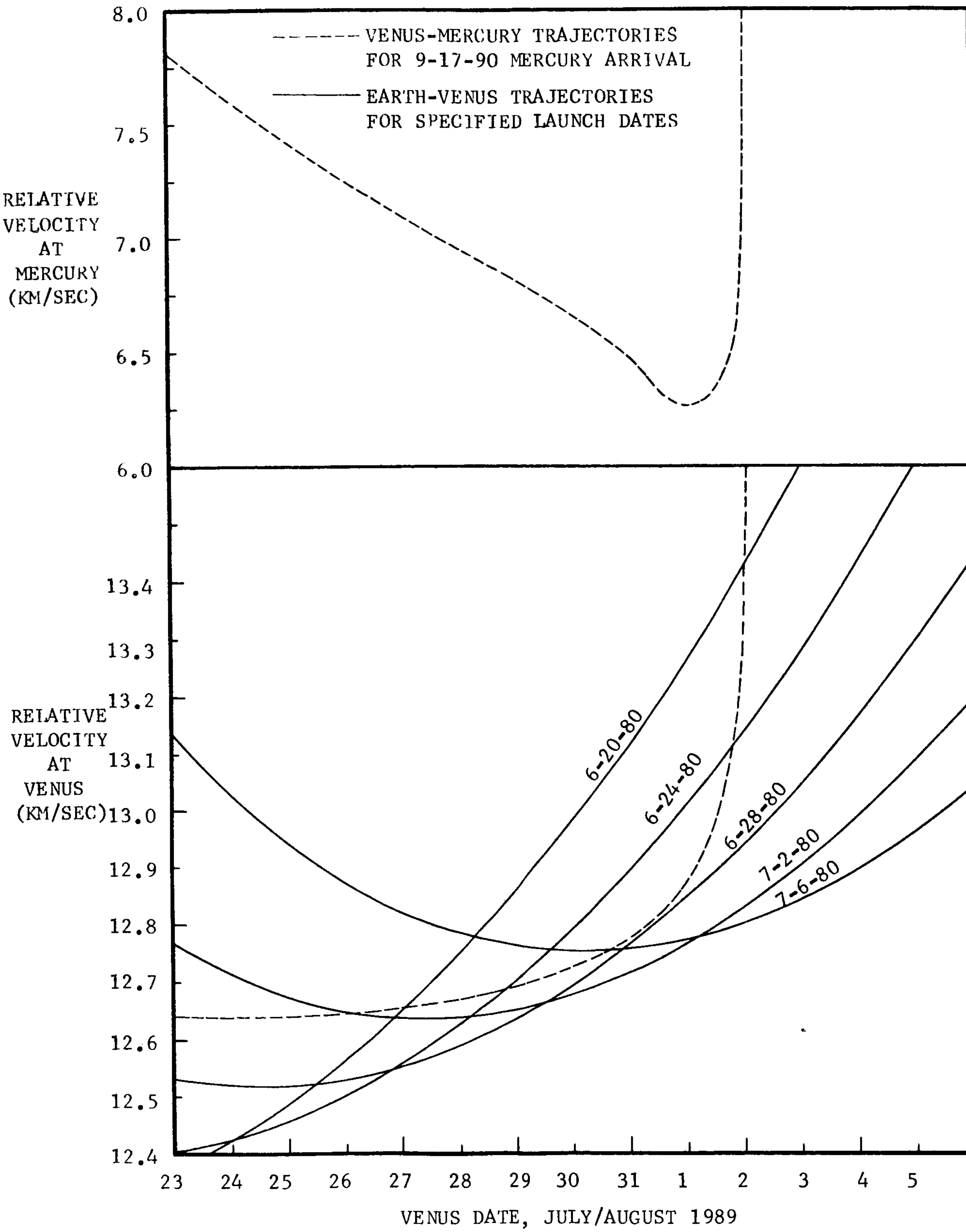


Figure A-6. Venus Arrival/Departure Characteristics, 1988 Opportunity

these curves, however, that a small ΔV_v will solve the problem and close the gap in the launch period. All summary data in Section V include a 75 m/s ΔV_v which allows a significant performance improvement even if the whole 75 m/s is translated into extra fuel requirements. It is shown in Section VI however, that 75 m/s ΔV_v increases total ΔV requirements only 17 m/s if it is executed simultaneously with the large post-Venus statistical midcourse maneuver.

Figure A-7 illustrates the behavior of a single Mercury arrival date with variation in Earth launch date. Both categories of solution are shown and both exhibit regions of satisfactory Venus swingby altitude. The peculiar hookback of the Category I solutions is produced by trajectories corresponding to both sides of the V_{HM} minimum.

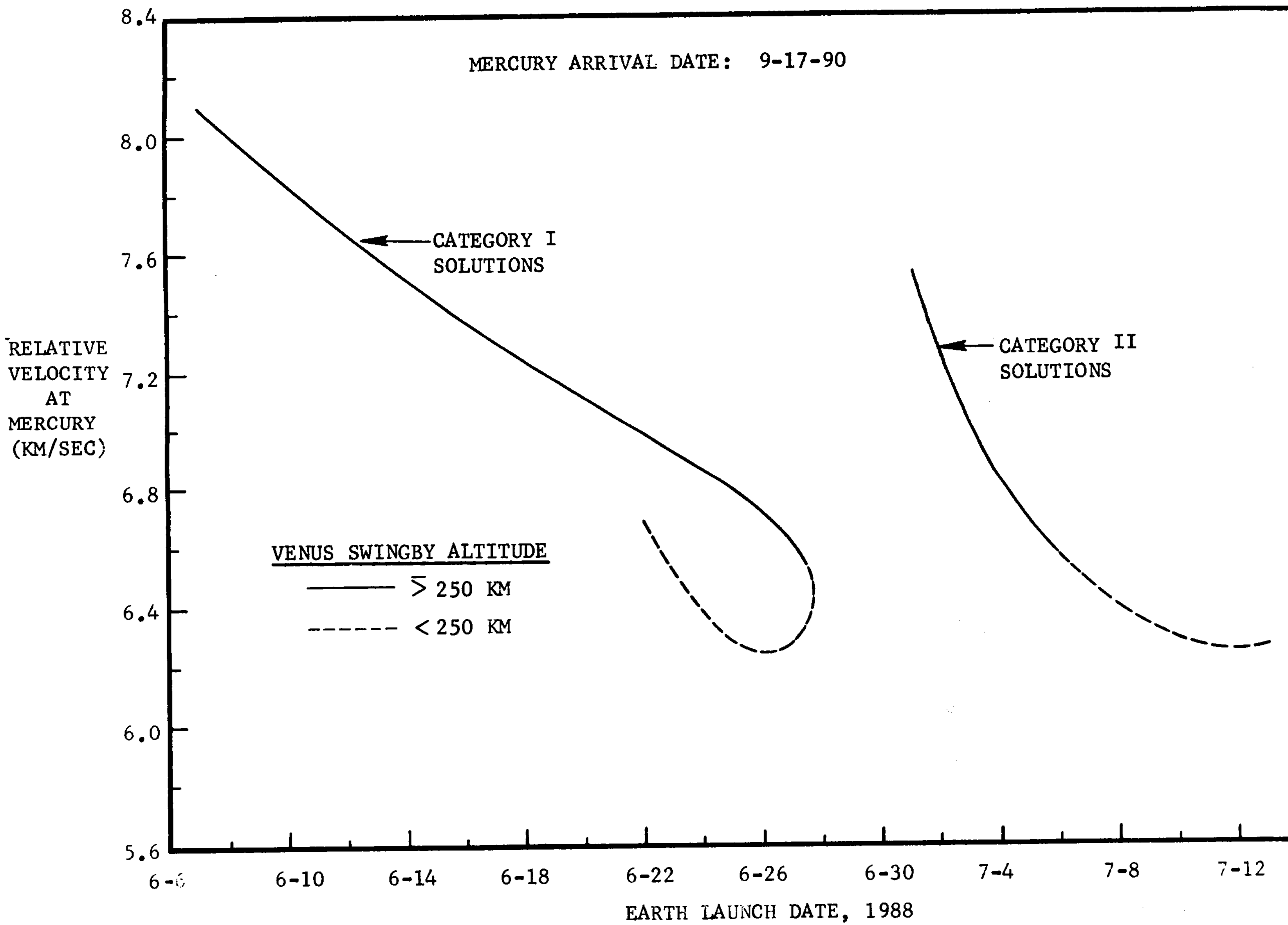


Figure A-7. Typical Multiple Solutions, 1988 Opportunity

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