NEW TRAJECTORY OPTIONS FOR BALLISTIC MERCURY ORBITER MISSION

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This paper reports on recent advances made in obtaining low ΔV trajectories for Mercury Orbiter missions. Most ballistic Mercury mission designs to date have been based on the methodology and the data provided by the author in 1985 (Ref. 1). The trajectory design of MESSENGER (Ref. 2), a recent winner of the NASA Discovery Program, followed this similar path. To improve the performance margin of MESSENGER, a re-evaluation was made of the past trajectory optimization approach.

In the 1985 paper, only one double Venus gravity assists mode (V-V with 1:1 synchronicity) was considered. This study lead to twelve new ways of conducting Multiple Venus Gravity Assists which gave lower ΔV and/or ways to utilize more naturally the attendant Earth-Venus phasing. Two additional Multiple Mercury Gravity Assists types derived from the concept contained in the 1999 paper by Y. Langevin (Ref. 4) were investigated and shown to permit further reductions in the mission ΔV's with small additional mission times.

All useful $V^N M^K$ trajectory types, the detailed phasing requirements for each of these options as well as example launch opportunities are presented.

INTRODUCTION

A Mercury orbiter is a high-energy mission, impractical to implement using chemical propulsion without a number of gravity assists from Venus and Mercury. In a 1985 paper (Ref. 1), Yen introduced various minimum ΔV trajectories which would deliver a spacecraft into a 300 km circular orbit around Mercury. The paper investigated the total delta-V (ΔV_T) requirements for various trajectory options. It showed that ΔV_T can be reduced from 12.8 km/s in a direct Earth to Mercury trajectory type to as low as

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6.4 km/s when two Venus gravity assists followed by three Mercury gravity assists are incorporated in the trajectory. The main emphasis of the paper was to demonstrate the power of Mercury gravity assists (reverse gravity assists), and did not consider other potentially useful types of Venus gravity assists. In 1985, such an endeavor would have been difficult because the capability of the trajectory optimization code was rather limited. Thus, the only useful Venus gravity assists mode discussed in the paper was a 1:1 synchronous V-V transfer.

Because of the high orbit inclination (7°) of the Mercury orbit it is important that the last swingby of Venus takes place at the crossing of the Mercury and Venus orbit planes which correspond to the mean anomaly of Venus (M_V) of 74°. With this, the orbit plane of the spacecraft is placed into that of Mercury after the final Venus gravity assist (VGA) and results in a minimum V_∞ at the first Mercury encounter. If a V-V transfer is to be synchronous, the E-V transfer must also end at M_V of 74°. This is the phase-free optimal condition. For most of low-ΔV E-V transfer opportunities, the Venus position at arrival does not have M_V near 74°. As a result, extra ΔV is required and the performance is degraded compared to the phase-free expectations. The launch opportunities presented in Table 3 of Ref. 1 have this drawback but were considered for use by MESSENGER (Ref. 2&3), by ESA Cornerstone Mission to Mercury and by ISAS in planning Mercury missions of their interests. It is conceivable that consideration of different VGA modes can remove the disadvantages of inferior E-V phasing discussed above and can improve the mission performance.

Searching for alternate modes of VGA's culminated in twelve additional modes. They have lower ΔV trajectories (compared to that of Ref. 1) and/or offer more flexible use of each Earth-Venus opportunity. In section 2, all twelve VGA ideas and their performance potentials are discussed and compared. Similar to Ref. 1, all new ideas are evaluated on a phase-free basis (i.e. optimal Earth, Venus and Mercury phasing) and the required phasing among Earth, Venus and Mercury are given. The information can provide readers with a way to select the best mode of VGA to use based on one's needs and constraints imposed. Applicable launch opportunities corresponding to various modes are also presented as examples.

The 1999 paper by Langevin (Ref. 4) contained an interesting strategy in the pursuit of yet lower ΔV Mercury orbiter missions. In Ref 1, the reduction of ΔV is realized by up to four reverse MGA's (mercury gravity assists). After each orbit pump down MGA, the orbit period ratio of the spacecraft to Mercury is progressively reduced from approximately 2:3 to 3:4 to 4:5 to 5:6 and so forth. To insert the fifth gravity assists to get a 6:7 period ratio is of no particular interest because it takes an additional seven Mercury years for a modest reduction in ΔV. In this scenario, all the mercury encounters are near its perihelion which gives low V_∞ at Mercury. This is due to the relative orbit geometry of Venus and Mercury. The observation of Langevin and his proposed idea in Ref. 4 can introduce a substantial (~ 300 m/s) reduction in ΔV at a mere 1.5 Mercury years in flight time penalty. He noted that, after the attainment of ~5:6 orbit, one can enter exact 1:1 orbit at the next MGA, then followed by a 180° M-M transfer to finally arrive at Mercury at its aphelion. In this case the V_∞ at arrival is only 1.5 km/s instead of

2.3 km/s at the end of the 4th MGA. In this paper, a more time efficient orbit reduction sequence, of from 2:3 to 3:4 to 5:6, is suggested. After these three MGA's we can add the 4th MGA to do a 180° M-M transfer and save 200 m/s with a 0.5 Mercury year flight time penalty or follow Langevin's method and do the 4th and 5th MGA's to get the 300 m/s ΔV saving. Scenarios of these new MGA methods are described in the last section.

VARIOUS VENUS GRAVITY ASSISTS OPTIONS

This section describes twelve newly introduced VGA modes. The various modes are designated as option-0 through option-12. Option-0 is the only mode contained in Ref. 1. This is not new, but included here for ease of comparison with the new options. The modes of VGA's are divided into three categories. The first category option-0 through option-2 is of V-V transfers with perfect synchronicity. The next category, option-3 through option-8, contains V-V transfer with approximate synchronicity and often contains a small ΔV between the two Venus swingbys. The last category, option-9 through option-12, involves three VGA's and is made from combinations of the first two categories.

Figure 1 depicts the orbital characteristics of each mode. Each option is characterized by the orbital revolution ratio of the spacecraft and Venus for each V-V leg. Some are in exact synchronicity but others are asynchronous. The minus sign attached to the orbit revolution designation indicates the short period Lambert solution of V-V transfer. Each plot represents a phase-free transfer and the performance resulted is the best one can expect flying that option. Designations E, V and M are used to denote the locations of the encounters with the three planets involved. When the encounters are repeated, designations such as V1, V2, and V3 are used to indicate the first, second and third encounter with Venus. The trajectories in the figures stop at the first Mercury encounter and the ΔV_T indicated assumes that Mercury orbit injection (300-km altitude circular orbit, as in Ref. 1) occurs at the first Mercury encounter. This is adequate for showing the relative merits of the various options. In actual mission design one would add a number of Mercury gravity assists (MGA's) to further reduce the ΔV_T requirement after the first Mercury encounter. It is not necessary here to include these complications because the effects of MGA's are nearly uniform irrespective of the VGA options used.

One is reminded to note that the transfers are phase-free. In a phase-constrained case the V-M legs often require more than one revolution unless the near optimal phasing exists. The aspect of interest to us is the locations of Earth and Venus in E-V transfers. Each E-V transfer pattern is different from the others. The presence of the variety in E-V transfer pictured here indicates that one has the freedom to choose a best option for a particular Venus launch opportunity. Some options are superior in ΔV_T but are inferior in flight time (FT) or vice versa. At first glance, options 2, 7, 10, 11 and 12 are less in ΔV_T by ~ 400 m/s than the option-0 at the expense of substantially longer FT's. However, the implications to the phase constrained transfers are not that straightforward.

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Option 1: (3SC : 2V)

²V=467 m/s

V1
V2

M

E

²V = 8.606 km/s, FT = 699 d

Option 2: (4SC : 3V)

M

V1
V2

E

²V = 7.928 km/s, FT = 912 d

Option3: (-1.3 SC : 1.3 V)

V1

M

E

V2

²V = 8.231 km/s, FT = 531 d

Option 4: (-2.9 SC : 1.9 V)

²V=227 m/s

E

M

V2

V1

²V = 8.328 km/s, FT = 582 d

Option5: (+2.9 SC : 1.9 V)

E

M

²V=287 m/s

V2
V1

²V = 8.407 km/s, FT = 606 d

Option6: (-2.3SC : 2.3 V)

V1

M

E

V2

²V = 8.345 km/s, FT = 762 d

Option7: (-3.8 SC : 2.8 V)

E

M

V2

V1

²V = 7.925 km/s, FT = 801 d

Option 8: (-3.4SC : 3.4 V)

V1

M

E

V2

²V = 8.409 km/s, FT = 989 d

Option9: (1.5 SC : 1.5 V) + (1SC : 1V)

V1

M

V2
V3

E

²V = 8.280 km/s, FT = 733 d

Option 10: (1SC:1V)+(2.8SC:1.8 V)

E

M

V3

V1
V2

²V = 7.923 km/s, FT = 817 d

Option 11: (-1.3 SC : 1.3 V) + (-2.9SC : 1.9V)

V2

M

V4

V3

E

²V = 7.923 km/s, FT = 969 d

Option 12: (-1.3 SC : 1.3 V) + (3SC : 2V)

V1

M

E

V2
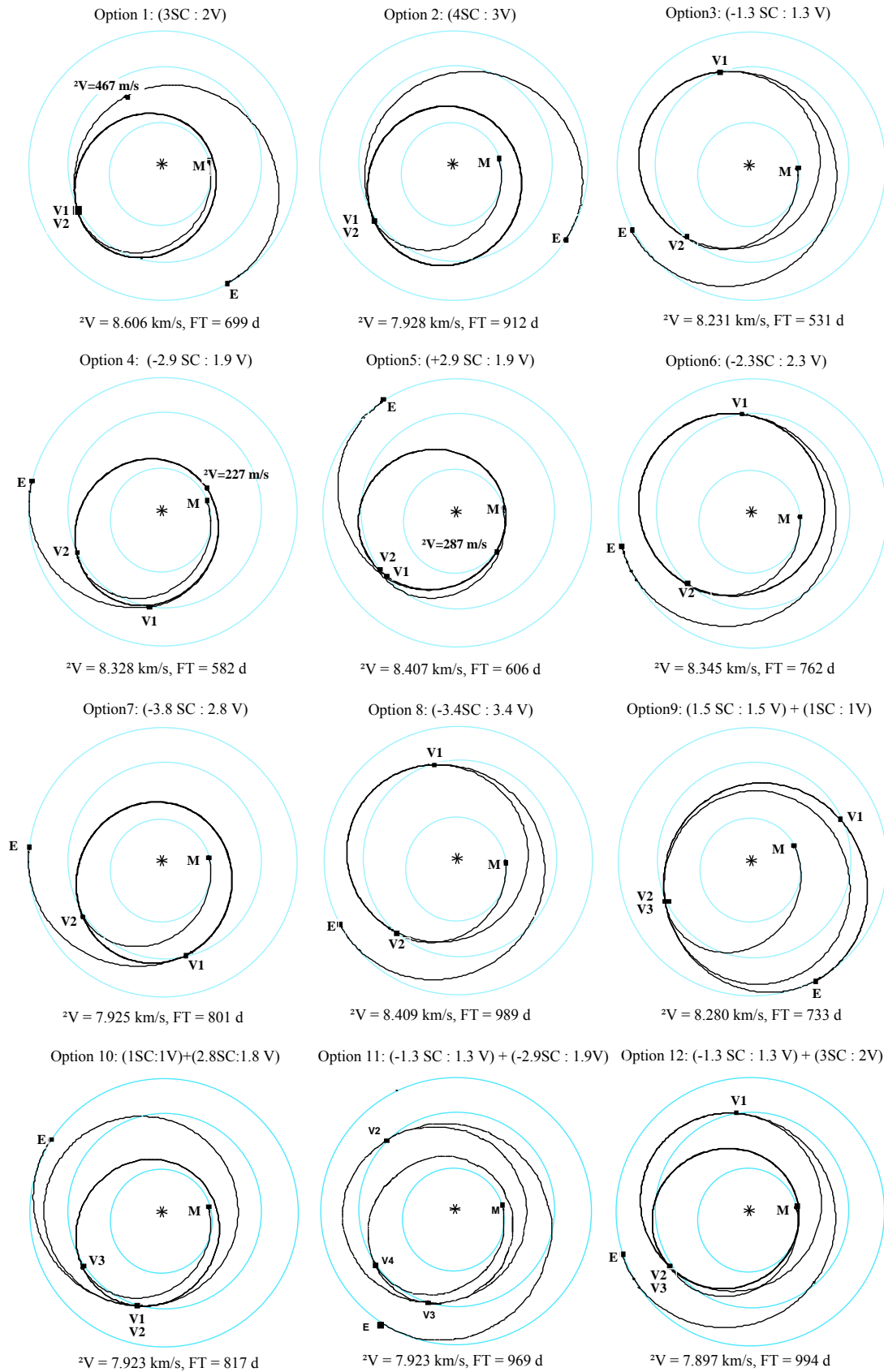**V3**

²V = 7.897 km/s, FT = 994 d

Figure 1: Trajectories Associated with Various VGA Options

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Even for the short FT options such as options 0, 3, 4 the phase-restricted FT cannot be short due to the relative phasing of E, V and M. Often, multiple revolution transfers are needed for E-V and/or V-M legs.

Final selection of which option to use will depend on the needs and constraints each user is faced with. The details of mission parameters associated with each of these and phase-free example cases are given next.

Performance Parameters of Various VGA Options

Mission parameters corresponding to each of the VGA options shown above are summarized in Table 1. This includes the performance parameters and the required relative phasing of three planets. The times of the planet encounters are also shown.

Table 1
Mission Parameters vs. VGA Options – Phase Free

Option	Revs (SC : Venus)	M_{VF} (deg)	M_E (deg)	M_M (deg)	TE (d)	TV1 (d)	TV2 (d)	TV3 (d)	TM (d)	C3 (km/s)^2	ΔV_{PL} (km/s)	ΔV_T (km/s)	FT (d)
0	1 : 1	74	150	307	-394	-225	0		79	16.8	4.35	8.31	473
1	3 : 2	78	87	353	-620	-449	0		87	19.5	4.53	8.61	699
2	4 : 3	84	336	26	-843	-674	0		26	13.7	4.09	7.93	912
3	-1.3 : 1.3	94	213	69	-475	-300	0		57	13.4	4.41	8.23	531
4	2.9 : 1.9	79	202	1	-506	-418	0		84	18.6	4.28	8.33	582
5	3.1 : 2.1	83	187	23	-542	-446	0		63	18.4	4.09	8.41	605
6	-2.3 : 2.3	95	68	76	-707	-533	0		55	13.7	4.51	8.33	762
7	3.8 : 2.8	83	70	23	-731	-631	0		70	13.8	4.09	7.93	801
8	-3.3 : 3.3	96	286	78	-935	-761	0		54	14.0	4.56	8.41	989
9	(1.5 : 1.5) + (1 : 1)	76	113	329	-648	-562	-225	0	86	20.6	4.16	8.28	733
10	(1 : 1) + (-2.9 : 1.9)	82	59	22	-746	-648	-423	0	70	13.7	4.09	7.92	817
11	(-1.3:1.3) + (-2.9 : 1.9)	83	300	23	-900	-724	-424	0	70	14.8	4.09	7.97	969
12	(-1.3 : 1.3) + (3 : 2)	76	286	27	-924	-750	-449	0	69	12.9	4.10	7.90	994

Notations:
Revs : Orbit revolution count between V-V for (spacecraft : Venus)
M_{VF} : Mean anomaly in degrees of Venus at the last VGA before Mercury transfer
M_E, M_M : Mean anomaly of Earth and Mercury at the last VGA epoch
TE TM : Encounter time of Earth and Mercury in days from the last VGA epoch
TV1 : Encounter time of first, second and third (TV2, TV3) VGA in days from last VGA epoch
ΔV_{PL} : Total post launch ΔV, only the deterministic ΔV's
FT : Flight time from Earth to Mercury

As explained before, since the last VGA location is nearly fixed, it is convenient to use the last VGA time as the reference. So the epoch of reference is the day the mean anomaly of Venus is equal to the value M_{VF}.

Example Mission Opportunities

Example mission opportunities may be found using the information contained in Table 1. Find the date the mean anomaly of Venus is equal to the value of M_{VF} and examine where Earth and Mercury are on that date. If these mean anomalies are close to

M_M, and M_E then one has a good match to the given option. Generally, it is unlikely that both Earth and Mercury phasing are well matched. Since the V-M leg orbit period is short, without too much flight time penalty we can modify the V-M leg into multiple revolutions to obtain a performance closer to the phase-free cases indicated in Table 1. One can find how to do this in Table 2 of Ref. 1.

Table 2 gives the results of the exercise described, i.e. the actual (phase-constrained) useable trajectories.

Table 2
Example Mission Opportunities using Various VGA Options

Option	Rev VF to M	L.D. (M/D/Y)	V1.D (M/D/Y)	V2.D (M/D/Y)	V3.D (M/D/Y)	M.D (M/D/Y)	C3 (km/s)^2	ΔV_{PL} (km/s)	ΔV_T (km/s)	FT (days)
9	-4.5	8/07/02	11/07/02	10/10/03	5/21/04	2/23/06	20.9	4.70	8.84	1296
6	3.5	3/08/04	10/10/04	3/25/06		7/21/07	15.8	4.76	8.68	1208
10	3.5	3/08/04	6/15/04	1/25/05	3/15/06	7/26/07	23.0	4.30	8.52	1235
*7	-3.5	3/16/04	6/25/04	3/17/06		7/23/07	14.7	4.07	7.95	1225
4	-2.5	3/20/04	6/16/04	8/03/05		8/09/06	22.7	4.30	8.52	873
8	2.5	3/28/04	10/06/04	11/07/06		10/18/07	14.3	5.02	8.88	1299
12	-2.5	4/03/04	10/08/04	8/04/05	10/28/06	10/20/07	13.1	4.61	8.42	1294
3	-4.4	4/10/04	10/17/04	8/13/05		4/25/07	16.1	4.41	8.35	1110
**11	-2.5	5/18/04	11/04/04	8/30/05	10/24/06	10/19/07	17.1	4.07	8.05	1249
0	-1.5	7/29/07	1/14/08	08/25/08		3/29/09	16.8	4.44	8.40	609
1	0.5	7/29/07	6/17/08	4/10/09		6/26/09	16.9	4.71	8.68	698
2	-1.5	8/02/07	1/16/08	11/20/09		6/13/10	17.1	4.32	8.30	1047
5	0.5	1/12/09	4/12/09	7/02/10		9/04/10	17.1	4.83	8.81	600
10	4.5	1/15/09	4/25/09	12/06/09	2/13/11	11/05/12	11.2	4.75	8.48	1391
9	-5.5	7/03/10	10/30/10	10/01/11	5/13/12	7/20/14	27.0	4.51	8.90	1478
2	-3.5	8/17/10	2/25/11	12/30/12		4/22/14	18.7	4.59	8.64	1344
10	-1.5	2/27/12	6/15/12	1/26/13	3/21/14	10/14/14	20.3	4.51	8.62	960
7	-1.5	3/14/12	6/24/12	3/16/14		10/13/14	14.3	4.08	7.94	943
4	-2.5	3/20/12	6/17/12	8/11/13		7/18/14	18.3	4.60	8.63	860
6	1.5	4/01/12	10/09/12	3/28/14		10/12/14	15.2	4.81	8.71	924
12	0.5	4/08/12	10/13/12	8/08/13	11/01/14	1/11/15	14.5	4.48	8.35	1008
3	-2.5	4/11/12	10/16/12	8/12/13		7/16/14	15.4	4.42	8.32	826
11	0.5	5/18/12	11/06/12	8/31/13	10/24/14	1/10/15	18.0	4.06	8.07	967

* MESSENGER primary opportunity   ** MESSENGER backup opportunity

The author has not intentionally screened the results of these examples to remove inferior ones within a given Venus launch opportunity. The main purpose here is to fly the specific option because the phasing condition is approximately right (within ~ 20 degrees). The table clearly indicates that there is a best option for each Venus opportunity. For example, options 7, 11, 3, 12, 4, 10, 6, and 8 in the order of ascending ΔV_T could be considered for the 2004 Venus opportunity. The final choice would depend on the user's needs. If a short flight time were desired one would choose option-4 for the 2004 opportunity. MESSENGER is currently planning to fly options 7 and 11 as indicated. Strangely, there is no attractive case, which utilizes type-I or type-II Venus opportunity in 2005. More mission opportunities can be added if we considered type-III or type-IV E-V transfers in addition to the type-I and type-II considered here.

MORE MERCURY GRAVITY ASSISTS OPTIONS

This section provides numerical illustrations of the idea contained in Ref. 4. Before presenting the case of Ref. 4, some alternate approaches are considered and suggested. Using the phase-free case of option-7 in Table 1, the mission is extended with additions of MGA's. The profile of performance improvement is shown in Table 3.

Table 3
Profile of Delta-V Reduction using Mercury Gravity Assists
(Starting from Trajectory Option 7 with C3= 13.8 $(km/s)^2$)

No of MGA	TM1 (days)	TM2 (days)	TM3 (days)	TM4 (days)	TM5 (days)	TM6 (days)	ΔV_{PL} (km/s)	ΔV_T (km/s)	$\delta\text{-}\Delta V_T$ (km/s)	FT (days)	δ-FT (days)
Synch	~ 2 : 3	~ 3 : 4	~ 5 : 6	a:(180°) Flip b: 1 : 1	~ 1:1 + Flip						
0	70						4.09	7.93	0	801	
1	68	337					3.50	7.34	-0.59	1066	265
2	68	333	692				2.76	6.60	-0.74	1421	355
3	68	334	691	1226			2.23	6.07	-0.53	1956	475
4	68	334	691	1226	1270		2.04	5.87	-0.20	2000	44
5	68	334	691	1224	1312	1355	1.93	5.77	-0.10	2085	85

The table contains up to five MGAs. The times of first, second and up to sixth encounter are denoted as TM1, TM2--- TM6 etc. The reference time of TM1 etc. here gain is the time of the last VGA. The M-M synchronicity attained after each swingby is shown in the row noted as "Synch". One will see that the orbit reduction sequence contained in Ref. 1 is changed in this table, notably 4:5 orbit sequence is skipped. This is more time efficient. On the 4th MGA at TM4, one can take two differing actions; a) do a 180 transfer to arrive near mercury aphelion, or b) to get into 1:1 resonant orbit then do a 5th gravity assist and arrive near aphelion on the 6th encounter. The ΔV savings and the flight time penalties with each additional MGA are given in columns noted as $\delta\text{-}\Delta V_T$ and δ-FT.

Adding a 4th MGA will cost only 44 days in flight time but will save 200 m/s in ΔV. Adding the 5th MGA will add another 88 days in flight time but can reduce ΔV by additional 100 m/s. The conclusion is that 4th and 5th MGA additions are very effective.

Trajectory plots of four MGA and five MGA cases are shown in Figure 2. Note that powered swingby is incurred in the four MGA case. The inclinations of the 1:1 synchronous transfer and 180° flip transfers are also shown in the figure.
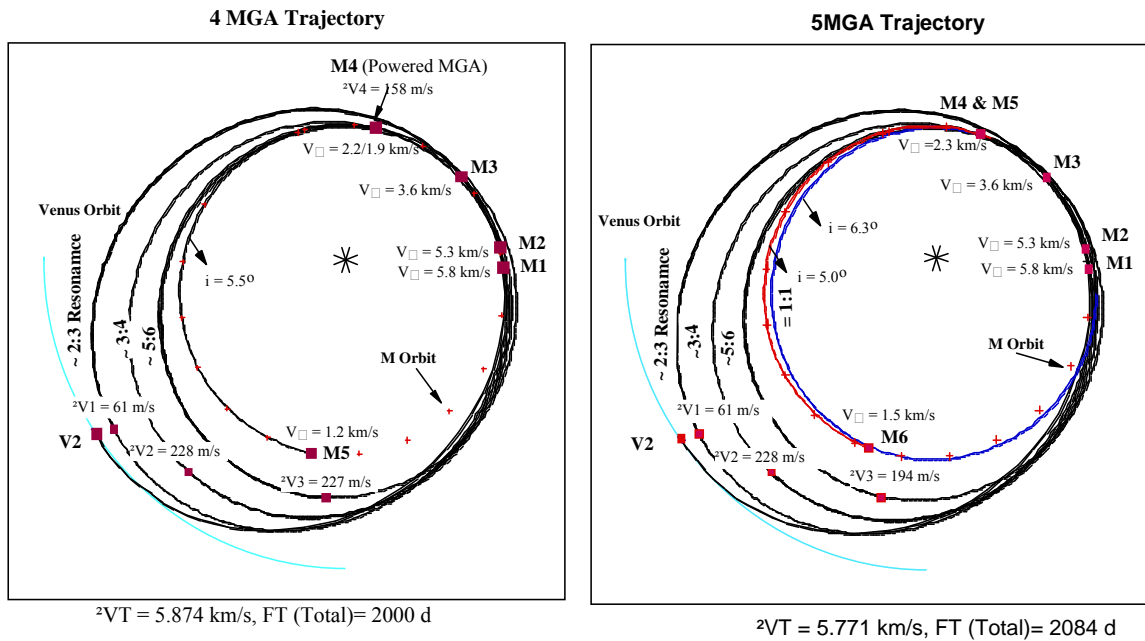
4 MGA Trajectory

M4 (Powered MGA)
²V4 = 158 m/s

V = 2.2/1.9 km/s

M3

V = 3.6 km/s

Venus Orbit

M2

V = 5.3 km/s

M1

V = 5.8 km/s

i = 5.5°

M Orbit

²V1 = 61 m/s

V2

²V2 = 228 m/s

V = 1.2 km/s

M5

²V3 = 227 m/s

~ 2:3 Resonance   ~ 3:4   ~5:6

²VT = 5.874 km/s, FT (Total)= 2000 d

5MGA Trajectory

M4 & M5

V = 2.3 km/s

M3

V = 3.6 km/s

Venus Orbit

i = 6.3°

M2

V = 5.3 km/s

i = 5.0°

M1

V = 5.8 km/s

= 1:1

M Orbit

²V1 = 61 m/s

V2

²V2 = 228 m/s

V = 1.5 km/s

M6

²V3 = 194 m/s

~ 2:3 Resonance   ~ 3:4   ~5:6

²VT = 5.771 km/s, FT (Total)= 2084 d

Figure 2. Trajectories for Four and Five MGA Cases

SUMMARY

This paper adds twelve new VGA options for the design of Mercury orbiter missions. This is expected to provide ways to make every Venus launch opportunity into an attractive (low ΔV) Mercury orbiter mission opportunity. Type-III and type-IV transfers between Earth and Venus were not included in this paper, but it is a straightforward extension of the analysis method described here or in Ref 1. If this is included, more attractive and frequent mercury mission opportunities will emerge. The idea included in Ref. 4 has been considered. The 4th and 5th MGA's are very effective ΔV reducers with very short flight time penalties.

ACKNOWLEDGMENTS

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