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SHORT-PERIOD BALLISTIC OUT-OF-ECLIPTIC TRAJECTORIES VIA MULTIPLE VENUS &EARTH SWING-BYS AND VEGA-DRIVEN MULTIPLE EARTH SWING-BYS

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This paper presents a few alternative, still ballistic, realization of short-period and highly inclined orbits by utilizing Venus and Earth swing-bys. This paper presents therefore different new approaches. The use of VEGA (Venus-Earth Gravity Assist) strategy lowers the departure escape velocity from Earth. The initial escape v-infinity velocity is only 4.2 km/sec and the strategy enables 37 degrees inclination with respect to the ecliptic plane. At the same time, the paper presents also a derivative strategy, co-use of Delta-VEGA (Delta-V Earth Gravity Assist) strategy for shorter realization. The results are amazing and significantly relaxes the propulsion requirement enhancing the payload mass in comparison with what was shown last year.

INTRODUCTION

About out-of-ecliptic trajectories, in other words, high inclination trajectories with respect to the ecliptic plane, most of studies used to look at the use of Jupiter swing-bys represented by Ulysses mission. However, the period of Ulysses' trajectory was quite long and did not fit for frequent scientific observation of the polar region of the Sun. Short-period but highly inclined orbits have been sought for decades. JAXA currently intensively studies about the Hinode-follow-on, SOLAR-C missions which sees frequent solar polar observation from such orbits, i.e. short-period and highly inclined orbits. One idea is the use of propulsion to artificially make the inclination steep combined with the Earth swingbys. The method is what we call, Electric Delta-V Earth Gravity Assist (EDVEGA) strategy, which efficiently and quickly alters the inclination. The other idea is to ballistic building of short-period and highly inclined orbits via gravity assist. It does not consume any fuel, and can exclude heavy propulsion subsystem mass, and is well advantageous over the first method. The author last year presented, at the same conference, the idea of multiple synchronized Earth swing-bys following the Jupiter swing-by. This actually enables even 78 degrees inclination orbits whose orbital period is equivalent to that of Earth or shorter. Surprisingly no fuel is nominally necessary. While that Jupiter option has significant advantage, the SOLAR-C mission prefers the spacecraft design that preferably had better not fly for distant solar system as well as quick realization.

This paper presents a few alternative, still ballistic, realization of short-period and highly inclined orbits by utilizing Venus and Earth swing-bys. This paper presents therefore different new approaches. (1) The most straight forward approach is the multiple Venus swing-bys followed by high speed departure escape from Earth. However, this most straight forward approach of this requires the escape v-infinity of 10 km/sec and somewhat hardly practical. (2) The next method is the use of VEGA (Venus-Earth Gravity Assist) strategy to lower the departure escape velocity from Earth. The initial escape v-infinity velocity is only 4.2 km/sec. Despite such

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low escape energy, through purely ballistic flight, the strategy enables 37 degrees inclination with respect to the ecliptic plane. The result is amazing and significantly relaxes the propulsion requirement enhancing the payload mass. Besides the distance from Earth is enough short for communication, while the Jupiter option cannot provide such benefit. (3) The paper at the same time presents the derivative idea to them. It uses Earth swing-bys instead Venus for the purpose of alleviating the thermal design requirement and communication requirement at the cost of lowered inclination angle. (4) At the same time, the paper presents also derivative strategy, co-use of Delta-VEGA (Delta-V Earth Gravity Assist) strategy for shorter realization.

From inclination point of view, still Jupiter plus synchronized multiple Earth swing-bys provides the best result. However, what this paper presents shows the use of multiple Venus and Earth swing-bys do provide practical realization, and will fit for a wide variety of applications.

PREVIOUS RESULTS – JUPITER OPTION

The authors presented the idea of synchronized Earth swingbys at the same conference last year. There have been presented four options for Jupiter. They are summarized in the Table-1.

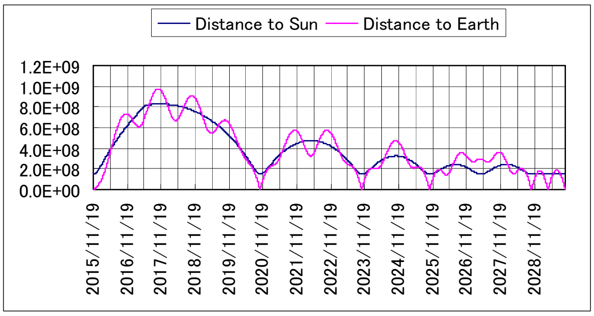

Fig.-1 Jupiter Scenario A_Ballsitic-1: Distance to Sun and Earth for 78deg, 1AU

Distinct from previous artificial options using electric propulsion, and also distinct from the ballistic trajectories with no synchronous strategies, this idea of using Jupiter multiple swingbys does efficiently make the inclination high as 78 degrees with short period of one year.

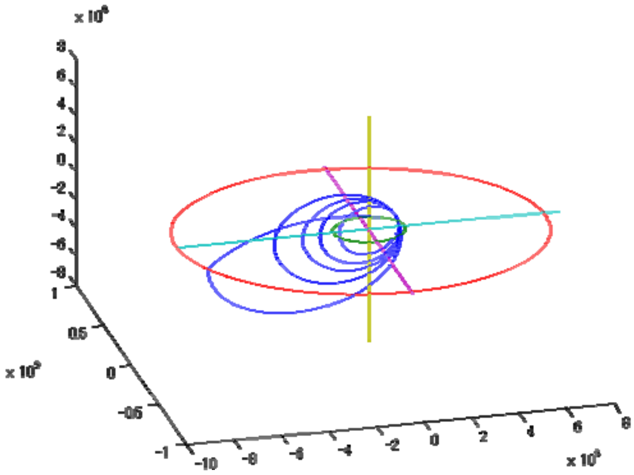

Fig. 2 Jupiter Strategy A-Ballistic-1

Table-1 Jupiter Strategies Summary of Ecliptic Inclination, Aphelion

	Strategy-1	Strategy -2+, -2+U	Strategy V2+	Strategy V2+U
Sequences Evolution	• 65deg, 5.5 (1.5) AU in 2 years, • 67 deg, 3.2 (1.4) AU in 5 years, E1 • 70deg, 1.6 (1.2) AU in 8 years, E2 • 73deg, 1.2 (1.1) AU in 10 years, E3 • 78deg, 1 (1.0) AU in 13 years. E4, E5, …	• 30 deg, 5.5 (1.5) AU in 2 years, • 35 deg, 2.2 (1.4) AU in 5 years, • 39 deg, 1.0 (1.0) AU in 7 years, • 41 deg, 0.52 (0.7) AU in 8 years, • 41 deg, 0.26 (0.4) AU in 10 years.	• 42 deg, 5.5 (1.2) AU in 2 years, • 44 deg, 2.3 (1.1) AU in 5 years, • 45 deg, 1.6 (1.0) AU in 8 years, • 47 deg, 1.2 (0.9) AU in 9 years, • 49 deg, 1.0 (0.85) AU in 11 years. • 50 deg, 0.9 (0.8) AU in 13 years	• 39 deg, 5.5 (1.2) AU in 2 years, • 41 deg, 2.3 (1.1) AU in 5 years, • 42 deg, 1.6 (1.0) AU in 8 years, • 44 deg, 1.2 (0.9) AU in 9 years, • 46 deg, 1.0 (0.85) AU in 11 years. • 47 deg, 0.9 (0.8) AU in 13 years.
Observation Times	With NO scheduled Delta-V, Science Observation possible all the time.	With NO scheduled Delta-V but 27m/s. Science Observation possible all the time.	With NO scheduled Delta-V, Science Observation possible all the time.	With NO scheduled Delta-V, Science Observation possible all the time.

With this advantage, this strategy still requires very high departure delta-V and also the spacecraft has to experience the cruise in a far distance from the Sun. This paper will look at the use of Venus-Earth swingbys to alleviate those difficulties.

VENUS MULTIPLE SWINGBYS (STRATEGY-V1)

The most straightforward approach is to make the spacecraft leave for Venus at high departure velocity so that the incoming excess velocity to Venus can be enough high. This is very much simple but requires high escape velocity from Earth. The orbital properties are summarized and show below.

Launch: 2017.9.2 **v-inf= 9.9 km/s**
Venus SW-1:2018.8.24 v-inf= 19.55 km/s, i=6.49 deg
Venus SW-2:2019.4.6 v-inf= 19.55 km/s, i=14.76 deg
Venus SW-3:2019.11.17 v-inf= 19.55 km/s, i=21.98 deg
Venus SW-4:2020.6.28 v-inf= 19.55 km/s, i=27.80 deg
Venus SW-5:2021.2.8 v-inf= 19.55 km/s, i=31.94 deg
Venus SW-6:2022. 5. 3 v-inf= 19.55 km/s, i=34.46 deg

This most straight forward approach in using the Venus is drawn in Fig. 3 below.

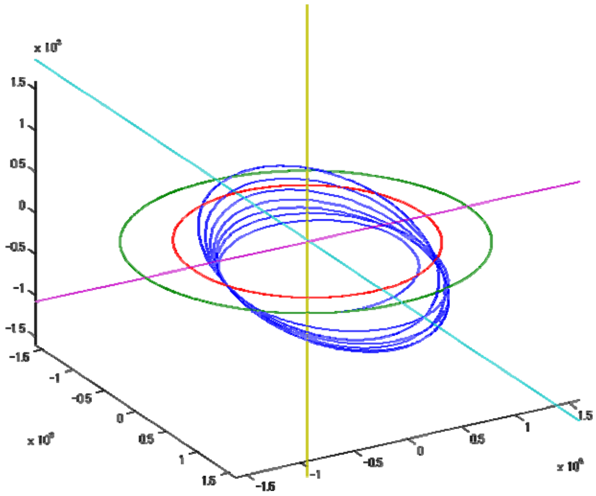

Fig. 3 Most Simplest Multiple Venus Swingby (Strategy-V1)

The biggest practical difficulty is in the launch energy represented by v-inf. at launch.

VENUS MULTIPLE SWINGBY (STRATEGY-V2A, B)

The next idea to the previous one is to make the high speed departure preceded by the so-called EVE flight so that the incoming v-inf. to Earth can be so high as 11 km/sec. The resulted v-inf. to Venus now is enhanced to 20 km/sec. Example of major orbital properties are listed below.

Launch: 2020.3.27 **v-inf= 4.2 km/s**
Venus SW-1:2020.8.24 v-inf= 6.1 km/s
Earth SW-1:2022.1.9 v-inf= 10.96 km/s
Earth SW-2:2024.1.9 v-inf= 11.19 km/s
Venus SW-2:2024.6.3 v-inf= 20.09 km/s, i=6.03deg
Venus SW-3:2025.1.14 v-inf= 20.09 km/s, i=13.23 deg
Venus SW-4:2025.8.27 v-inf= 20.09 km/s, i=19.27 deg
Venus SW-5:2026.4.8 v-inf= 20.09 km/s, i=23.96deg
Venus SW-6:2026.11.19v-inf= 20.09 km/s, i=27.29 deg
Venus SW-7:2027.7.2 v-inf= 20.09 km/s, i=29.23 deg
Venus SW-8:2028.2.11 v-inf= 20.09 km/s, **i=29.83 deg**

The difficulty found in the previous strategy was avoided by introducing Venus Earth gravity assist that makes the spacecraft reencounter with Venus at much higher v-inf. The idea is shown in Fig. 4.

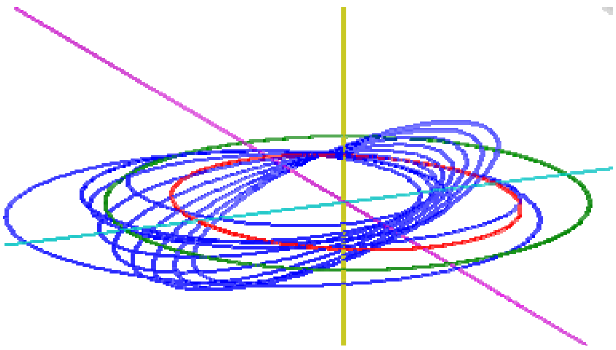

Fig. 4 Using Venus-Earth swingbys - (Strategy-V2A).

VENUS MULTIPLE SWINGBYS (STRATEGY-V2B)

Here is shown another attempt in using EVE strategy. The difference from the option-A is the inclination-alteration direction at each Venus swingby, while the swingby v-inf. Remains unchanged from that in Strategy-V2A. Major properties are also listed below.

Launch: 2020.3.27 **v-inf= 4.2 km/s**
Venus SW-1:2020.8.24 v-inf= 6.1 km/s
Earth SW-1:2022.1.9 v-inf= 10.96 km/s
Earth SW-2:2024.1.9 v-inf= 11.19 km/s
Venus SW-2:2024.6.3 v-inf= 20.09 km/s, i=0.41deg
Venus SW-3:2025.1.14 v-inf= 20.09 km/s, i=8.14 deg
Venus SW-4:2025.8.27 v-inf= 20.09 km/s, i=16.42 deg
Venus SW-5:2026.4.8 v-inf= 20.09 km/s, i=23.60deg

Venus SW-6:2026.11.19v-inf= 20.09 km/s, i=29.26 deg
Venus SW-7:2027.7.2 v-inf= 20.09 km/s, i=33.20 deg
Venus SW-8:2028.2.11 v-inf= 20.09 km/s, i=35.60 deg
Venus SW-9:2028.9.23 v-inf= 20.09 km/s, **i=36.59 deg**

The result is shown in Fig. 5 below.

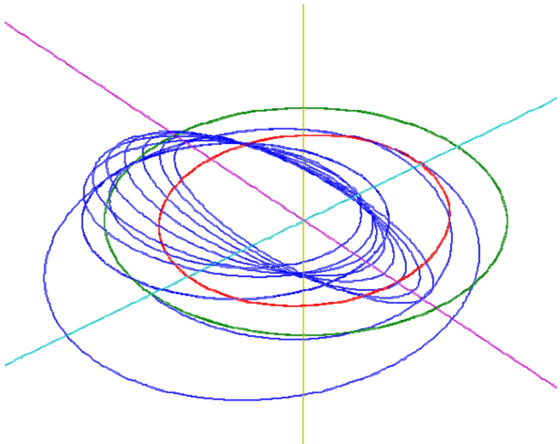

Fig. 5 An Alternative Venus-Earth Gravity Assist (Strategy-V2B).

This option-B seems to reach higher inclination, but the orbital plane with respect to Sun is not erected more efficiently than that in Option-A. The inclination and solar distance as well as solar latitude information are all drawn in Fig. 6. And the trajectory plots in Option-A are presented below in figure 7 and 8.

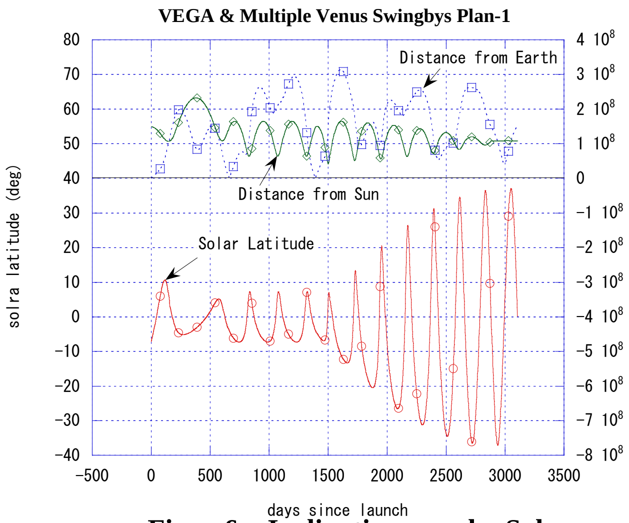

Fig. 6 Inclination and Solar Distance History in Venus-Earth (Strategy-V2A).

As this plot shows, the solar latitude is very much efficiently altered and erected to reach close to 40 degrees in nine years. This never uses the Jovian gravity assist.

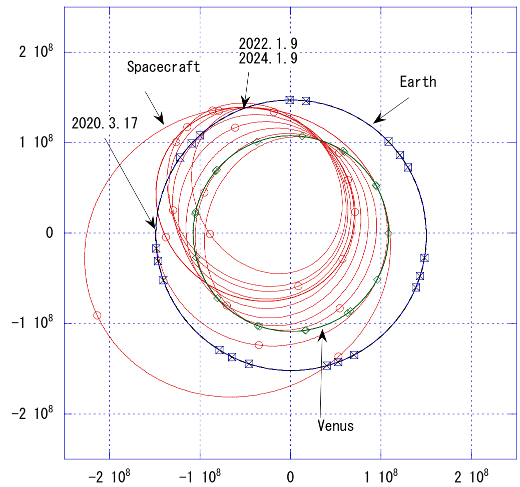

Fig. 7 Venus-Earth Gravity Assist (Strategy-V2A) (Inertial Plot)

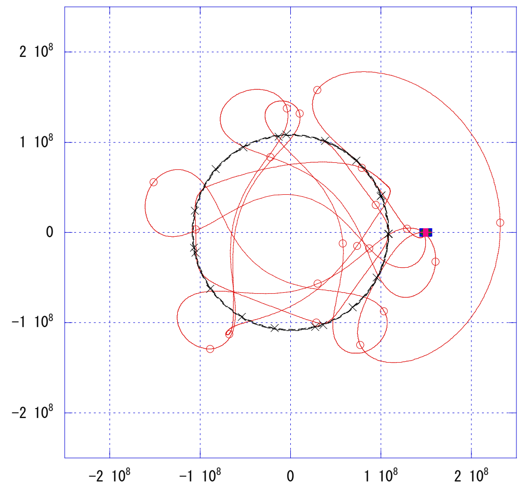

Fig. 8 Venus-Earth Gravity Assist (Strategy-V2A) (Rotation Plot)

VEGA & MULTIPLE EARTH SWINGBYS – (STRATEGY-E1)

The strategies shown so far simply assume the use of Venus for the celestial body by which the trajectories can be inclined gradually. However, when seen from communications and thermal point of views, the expected strategy shall make a flight near Earth, and may not be preferred from those points. Here is given another alternative strategy of using Earth instead of Venus enabling the spacecraft fly near Earth during the inclination alteration process. As in previous sections, the major orbital properties are written below. The trajectory is drawn in Fig. 9.

Launch: 2020.3.17 **v-inf= 4.9 km/s**
Venus SW: 2020.8.21 v-inf= 6.90 km/s
Earth SW-1: 2021.12.20 v-inf= 11.28 km/s, i=3.07 deg
Earth SW-2: 2022.12.21 v-inf= 11.28 km/s, i=10.04 deg
Earth SW-3: 2023.12.21 v-inf= 11.28 km/s, i=19.27deg
Earth SW-4: 2024.12.20 v-inf= 11.28 km/s, **i=21.41 deg**

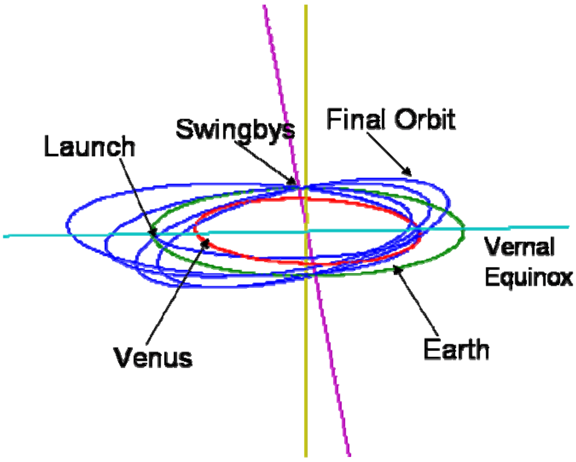

Fig. 9 VEGA followed by Repetition of Earth Swingbys (Strategy-E1)

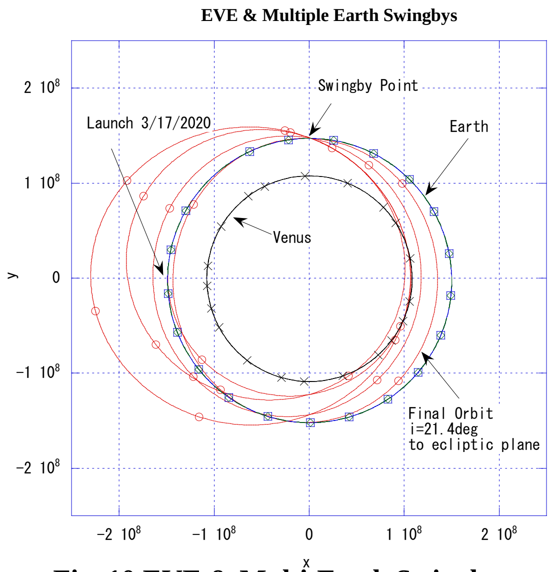

Fig. 10 EVE & Multi-Earth Swingbys (Strategy-E1) (Inertial Plot)

The repetition of Venus swingbys suffer from the lowered perihelion distance. In case the Earth is used instead, this problem is avoided. In this strategy, the swingby velocity with respect to Earth is tried enhanced to 11.28 km/sec via an EVE flight. Since the relative velocity to Earth is less than that for Venus in previous strategies, the resulted inclination is reduced to 21.4 degrees. However, while the inclination does not reach so high as those via Venus, the strategy maintains the perihelion distance and provides feasible solutions. Both inertial and rotation motions are shown in Fig. 10 and also in Fig. 11 below.

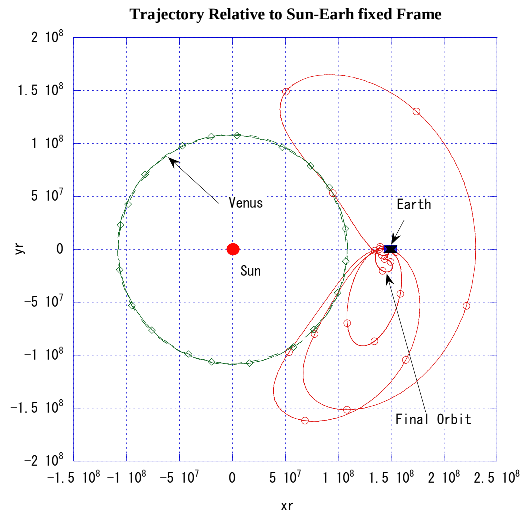

Fig. 11 EVE & Multi-Earth Swingbys (Strategy-E1) (Rotation Plot)

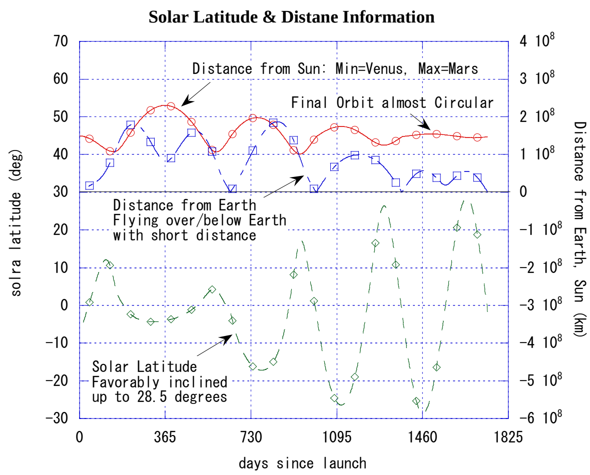

Fig. 12 Inclination and Solar Distance History in EVE & Multi Earth Swingby (Strategy-E1)

VEGA & MULTIPLE EARTH SWINGBYS (STRATEGY-E2)

Via the EVE (VEGA) strategy, there is the relative velocity upper limit while maintaining the perihelion distance. Here is another practical strategy, which is to use the Delta-V-VEGA sequence to maintain the perihelion distance on the way as in Fig. 13. The associated properties are summarized below.

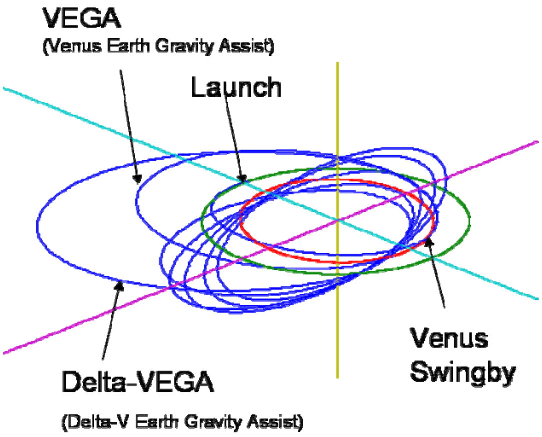

Fig. 13 Delta-VEGA & Multi-Earth Swingbys (Strategy-E2) (Inertial Plot)

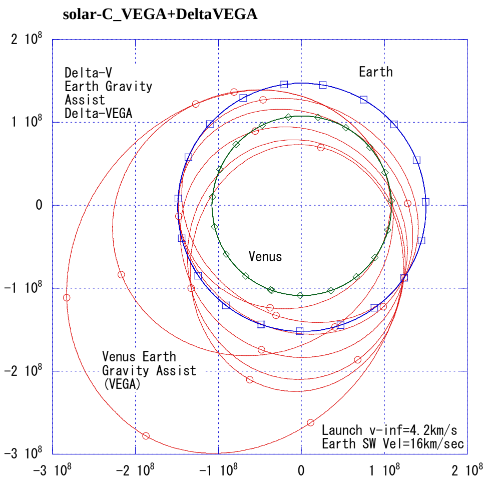

Fig. 14 Delta-VEGA & Multi-Earth Swingbys (Strategy-E2) (Inertial Plot)

Launch: 2020.3.17 **v-inf= 4.2 km/s**
Venus SW: 2020.8.24 v-inf= 6.07 km/s
Earth SW-1: 2022.1.9 v-inf= 10.96 km/s, i=2.77 deg
Deep Space Maneuver : 2022.11.1, **delta-V=1354 m/s.**
Earth SW-2: 2023.8.17 v-inf= 16.08 km/s, i= 0.0 deg
Earth SW-3: 2024.8.17 v-inf= 16.08 km/s, i=6.98deg
Earth SW-4: 2025.8.17 v-inf= 16.07 km/s, **i=18.05 deg**
Earth SW-5: 2026.8.17 v-inf= 16.07 km/s, **i=26.08 deg**
Earth SW-6: 2027.8.17 v-inf= 16.07 km/s, **i=30.64 deg**
Earth SW-7: 2028.8.17 v-inf= 16.07 km/s, **i=31.64 deg**

With this strategy, the Earth swingby speed is upgraded to 16.1 km/sec significantly enhanced enabling the inclination to reach 32 degrees even via the Earth swingby.

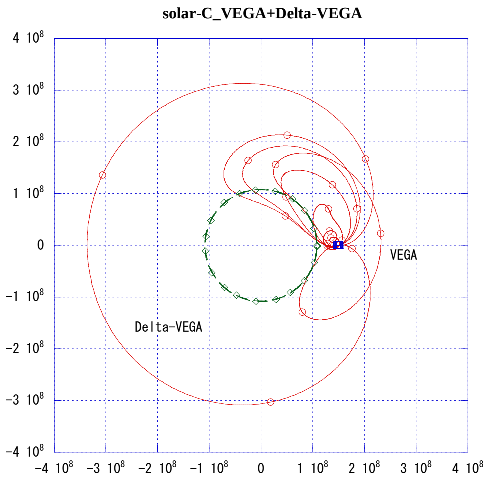

Fig. 15 Delta-VEGA & Multi-Earth Swingbys (Strategy-E2) (Rotation Plot)

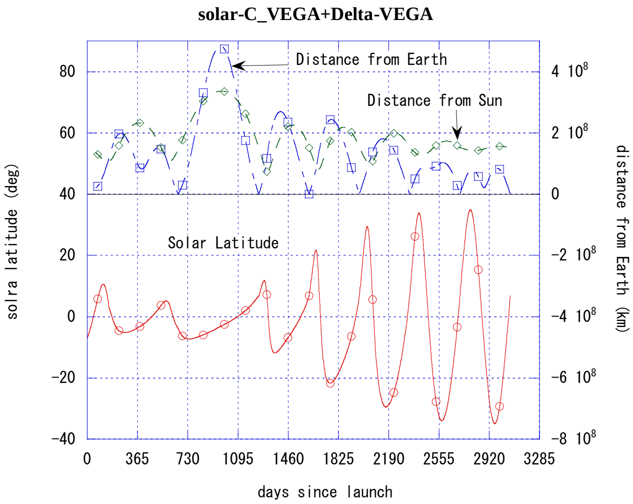

Fig. 16 Inclination and Solar Distance History in Delta-VEGA & Multi Earth Swingbys (Strategy-E2)

VEGA + DELTA-VEGA MAINTAINING PERIHELION DISTANCE (STRATEGY-E2B)

Launch: 2020.3.17 **v-inf= 4.2 km/s**
Venus SW: 2020.8.24 v-inf= 6.08 km/s
Earth SW-1: 2022. 1. 9 v-inf= 10.96 km/s, i=2.77 deg
Mid-Course DV: 2022.11.1 delta-V=1.354 km/s
Earth SW-2: 2023. 8.17 v-inf= 15.60 km/s, i= 0 deg
Earth SW-3: 2025. 8.16 v-inf= 15.60 km/s, i=10.52deg
Earth SW-4: 2027. 8.17 v-inf= 15.60 km/s, **i=19.15 deg**
Earth SW-5: 2028. 8.16 v-inf= 15.60 km/s, i=24.98deg
Earth SW-6: 2029. 8.16 v-inf= 15.60 km/s, i=29.86deg
Earth SW-7: 2030. 8.17 v-inf= 15.60 km/s, **i=30.72deg**

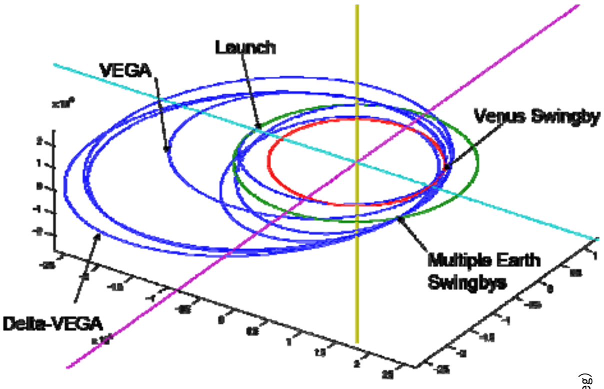

Fig. 17 Delta-VEGA & Multi-Earth Swingbys – (Strategy-E2b)

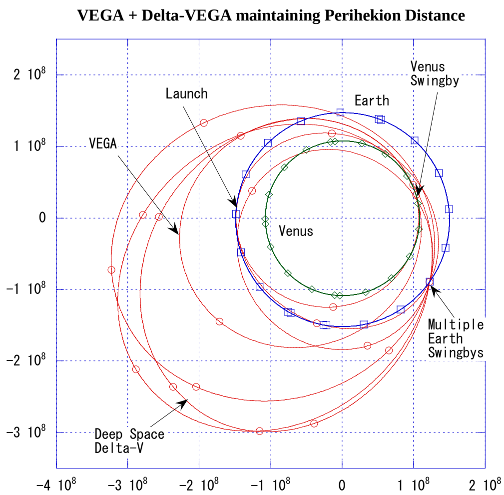

Fig. 18 Delta-VEGA & Multi-Earth Swingbys (Strategy-E2b) (Inertial Plot)

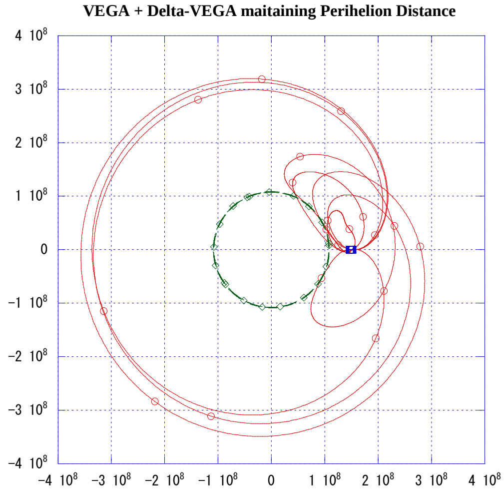

Fig. 19 Delta-VEGA & Multi-Earth Swingbys (Strategy-E2b) (Rotation Plot)

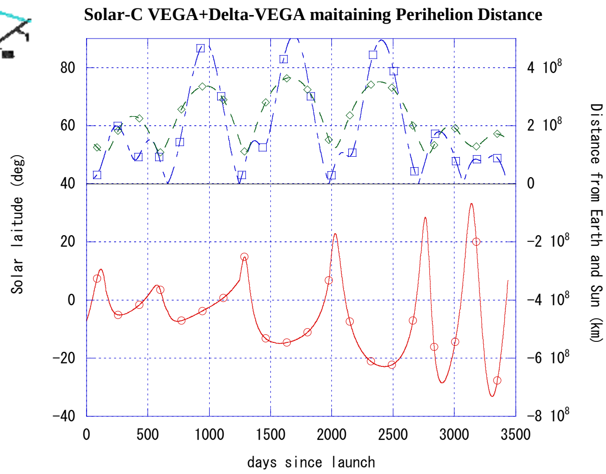

Fig. 20 Inclination and Solar Distance History in Delta-VEGA & Multi-Earth Swingbys (Strategy-E2b)

CONCLUSION

This paper presented different new approaches than those presented last year. They are

(1) The multiple Venus swing-bys followed by high speed departure escape from Earth. (Strategy-V1)
(2) The use of VEGA (Venus-Earth Gravity Assist) strategy to lower the departure escape velocity from Earth. (Strategy-V2A, B)
(3) Similar approach but with the Earth swing-bys instead Venus (Strategy-E1)
(4) The use of Delta-VEGA strategy. (Strategy-E2)
(5) The use of Delta-VEGA strategy (Strategy-E2b)

First two correspond to the Venus multiple swingbys strategies, and the last three correspond to the Earth multiple strategies.

The initial escape v-infinity velocity was lowered down to only 4.2 km/sec with still higher inclination of 30 degrees or higher with respect to ecliptic plane without flying to the outer solar system bodies.

There are many Pros and Cons as for the strategies presented. Among the strategies, the author prefers

Strategy-E1 : with V-inf. of 4.9 km/s, 28.4 deg solar latitude is attainable in 4.5 years with the perihelion distance maintained around Venus distance.

Strategy-E2 : with V-inf. of 4.2 km/s plus mid-course delta-V, 20 deg and 35 deg solar latitude is attainable in 4.5 and 8.5 years respectively with shorter but manageable perihelion distance of about 0.5AU.

Venus multiple Strategies are still attractive but have some difficulties in terms of perihelion distance and communication conditions.

From inclination point of view, still Jupiter plus synchronized multiple Earth swing-bys provides the best result as reported last year. But the use of multiple Venus and Earth swing-bys do provide practical realization, and will fit for a wide variety of applications.

REFERENCES

[1] The Ulysses mission - a voyage to the poles of the sun, Nuclear Physics B - Proceedings Supplements, Volume 39, Issue 1, February 1995, Pages 59-68, K.-P. Wenzel

[2] Ulysses at high latitudes: An overview of recent results, Advances in Space Research, Volume 17, Issues 4-5, 1996, Pages 293-302, R. G. Marsden, E. J. Smith

[3] Solar Orbiter - mission profile, main goals and present status, Advances in Space Research, Volume 36, Issue 8, 2005, Pages 1360-1366, Eckart Marsch, Richard Marsden, Richard Harrison, Robert Wimmer-Schweingruber, Bernhard Fleck

[4] The solar orbiter mission, Advances in Space Research, Volume 32, Issue 12, 2003, Pages 2699-2704, R.G. Marsden, B. Fleck, P. Sivac, Solar Orbiter TTC Way Forward, 30 Oct. 1 Nov 06; Page, http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=33281

[5] NASA Solar Probe mission and system concepts, Advances in Space Research, Volume 17, Issue 3, 1996, Pages 3-12, J. E. Randolph

[6] Solar Probe+ Mission Engineering Study Report, Prepared for NASA's Heliophysics Division, By The Johns Hopkins University Applied Physics Laboratory (Under Contract NNN06AA01C), March 10, 2008

[7] Electric propulsion in Europe, Acta Astronautica, Volume 14, 1986, Pages 393-412, C. Bartoli, H.W. Loeb, H. Bassner, D. Valentian, G. Baiocchi, A. Atzei, H. von Rohden, A. Trippi, H.O. Schrade, M. Andrenucci, E. Igenbergs

[8] Orbital mechanics of propellantless propulsion systems, Elsevier Astrodynamics Series, Volume 1, 2007, Pages 189-235, Colin R. McInnes, Matthew P. Cartmell

[9] Controlled solar sail transfers into the near-sun orbits, Advances in Space Research, Volume 29, Issue 12, June 2002, Pages 2083-2088, V. Koblik, E. Polyakhova, L. Sokolov, A. Shmyrov