BEPICOLOMBO TRAJECTORY OPTIONS TO MERCURY IN 2016 AND 2017

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Abstract: *Delivering a 4-ton spacecraft launched on an Ariane 5 to Mercury with a propulsion system that provides only 2 x 145 mN requires a series of flybys at Earth, Venus and Mercury. In 2017 the positions of Earth and Venus do not offer a reasonably cheap launch window and therefore an Earth flyby in July 2018 has to be selected. Six options are presented that are identical after the Earth flyby, but differ in the Earth-to-Earth arc. The current baseline foresees a midnight launch on 9 July 2016 and an arrival on 1 Jan 2024. The 5 alternative options have either a daytime launch (with an escape velocity directed radially outward from the Sun) or a 360° or 540° Earth-to-Earth transfer or both. Also a direct launch towards Venus in January 2017 is analysed.*

Keywords: *Interplanetary Trajectory Design, BepiColombo, Mercury, Low-Thrust Propulsion*

1. Introduction

BepiColombo is a cornerstone mission of the ESA Science Programme, to be launched towards Mercury in 2016 with back-up launch opportunities in 2017. After a journey of more than 7 years two probes, the Magnetospheric Orbiter (JAXA) and the Planetary Orbiter (ESA) will be separated and injected into their target orbits [1]. The baseline interplanetary trajectory includes flybys at the Earth, Venus (twice) and Mercury (five times), as well as several low-thrust arcs provided by the solar electric propulsion module. At the end of the transfer an orbit insertion burn will be performed. If it fails the spacecraft will still be gravitational captured in an orbit around Mercury [2].

Since a direct Hohmann transfer to Mercury requires excessive launch and arrival ΔVs of about 16 km/s in total, a more economic approach is the combination of low-thrust propulsion arcs with flybys. An Earth flyby is usually required to deflect the spacecraft into the right orbital plane to reach Venus and the two Venus flybys are required to reduce the perihelion distance by rotating the V_∞-vector at the Venus flybys from a radial direction to a retrograde direction.

In order to find transfer trajectories to Mercury, launch opportunities to Venus need to be investigated. Yen [3] and Langevin [4] have made extensive analyses of the basic transfer possibilities. Since Earth and Venus are roughly in a 8:13 resonance, almost the same launch windows repeat every 8 years. Already in 2008/09 there was an 18-month gap in launch opportunities and the same geometry is encountered in 2016/17. However, this can be mitigated by extending the Earth-to-Earth arc from 1 to 2 years: The launch will take place in July 2016 and the Earth flyby in July 2018. The advantage of this scenario is that back-up launches can be determined 6 and 12 months later, reducing the Earth-to-Earth arc to 540° or 360° (1.5 or 1 year), but following exactly the same trajectory after the Earth flyby. For each of three launch dates the options exist to launch radially inward or outward and thus be trailing or leading the Earth during the Earth-to-Earth arc. The current baseline is a radially inward launch which leads to an Earth-leading trajectory. These options will be discussed in this paper as well as a completely different trajectory.

2. Assumptions for the Transfer Trajectory Optimization

The specific impulse of the solar electric propulsion system is assumed here to be constant throughout the mission at 4022 s. The corresponding exhaust velocity of the Xenon is 39.5 km/s. In reality the specific impulse decreases over time, but this has only an influence on the fuel budget but a very small influence on the trajectory design. 5 % extra fuel is assumed to be consumed along the whole trajectory to take into account fuel consumption for navigation purposes. The effect is a slightly lighter spacecraft which leads to a smaller transfer delta-V. However it is assumed that no chemical fuel is consumed at all (worst case assumption from a mass point-of-view). Table 1 lists the assumptions made for the solar-electric propulsion.

Table 1: Parameters defining thrust

Specific Impulse (sec)	4022
Maximum thrust (N)	0.290
SEP availability	90%
Fuel consumption for navigation	5%

Minimum flyby altitudes of 200 km for Mercury (except for the last Mercury flyby) and 300 km for Earth and Venus are imposed. At the first Venus flyby the altitude is limited to 1500 km in order to keep the eclipse duration below 50 minutes. For the January 2016 transfer there are no eclipses during the Venus flybys. The spacecraft is propagated in a heliocentric coordinate system taking into account the third-body perturbations of Earth, Venus and Mercury whenever they are relevant. Flybys are calculated by numerical integration. Coast arcs of 30 days before and 7 days after each flyby are introduced to allow for accurate orbit determination. There is a 90-day commissioning phase after launch without any nominal thrust. There must be no nominal thrust arc during the last 60 days.

There are two sets of solar aspect angle constraints which depend on the assumption which thruster will fail in orbit [5]. If a +Y thruster fails, then the solar aspect angle has to stay inside the interval of [67.2°, 94.5°] (when the spacecraft is inside 0.8 AU) at Beginning-of-Life (BoL) and inside the interval of [69.7°, 96.5°] at End-of-Life (EoL), otherwise if a -Y thruster fails, the solar aspect angle has to stay inside the interval of [75.5°, 102.8°] at BoL and inside the interval of [77°, 103.9°] at EoL. For the sake of a robust transfer trajectory optimisation the combination of all constraints are combined which leads to a penalty of less than 100 m/s. Table 2 summarizes all constraints.

Table 2: Constraints after launch, during flybys and at arrival.

Constraint	Value
Earth flyby altitude	> 300 km
Venus 1 flyby altitude	< 1500 km
Venus 2 flyby altitude	> 300 km
Mercury flyby altitudes	> 200 km
Last Mercury flyby altitude	> 300 km
Duration of coast arc before flybys	> 30 days
Duration of coast arc after flybys (	> 7 days
Duration of coast arc after launch	> 90 days
Duration of coast arc before MOI	> 60 days
Solar aspect angle (outside 0.8 AU)	77° < SAA < 112.5°
Solar aspect angle (inside 0.8 AU)	77° < SAA < 94.5°

3. Baseline Transfer Trajectory with Night Launch in July 2016

The software DITAN [6] was used to find the detailed structure of the optimum solution and MANTRA [7] was used to determine a high-fidelity, numerically propagated trajectory. The 30-day launch window of BepiColombo opens on 9 July 2016 and closes on 9 August 2016.

Table 3 provides the details of the trajectory. Figure 1 shows this trajectory projected onto the ecliptic plane. The spacecraft leaves the Earth with an escape velocity of 3.475~km/s with Ariane 5. After two years the spacecraft comes back to the Earth and is deflected towards Venus. In the selected trajectory the spacecraft travels first inwards and then outwards with respect to Earth in the Earth-to-Earth phase. All the required thrust to increase the Earth flyby velocity is placed in the first year. This is not delta-V optimal but it provides a higher robustness in case of thruster problems.

Two consecutive Venus flybys (in a 1:1 resonance, i.e. 225 days apart) reduce the perihelion to nearly Mercury distance. A sequence of 5 Mercury flybys (passing through a 3:2 resonance, a 5:4 resonance, a 2:2 resonance and a 180 degrees singular transfer) lower the relative velocity down to 1.82 km/s. Five final thrust arcs further reduce the relative velocity such that the spacecraft will be weakly captured by Mercury on 01 January 2024 even if no orbit insertion manoeuvre takes place.

Table 3: Main characteristics of the 9 July 2016 trajectory.

Departure	Launch Date	9 July 2016
	Escape velocity	3.475 km/s
	Escape declination	-3.8°
	Initial mass	4100 kg
Cruise	ΔV SEP	4.254 km/s
	Total impulse (only nominal thrust)	16.6 MNs
	Cruise time	7.5 years

Arrival	Date Mercury true anomaly Velocity at periherm Ωarr ωarr	01 Jan 2024 67.8° 3.793 km/s 67.7° -2° (South pole)

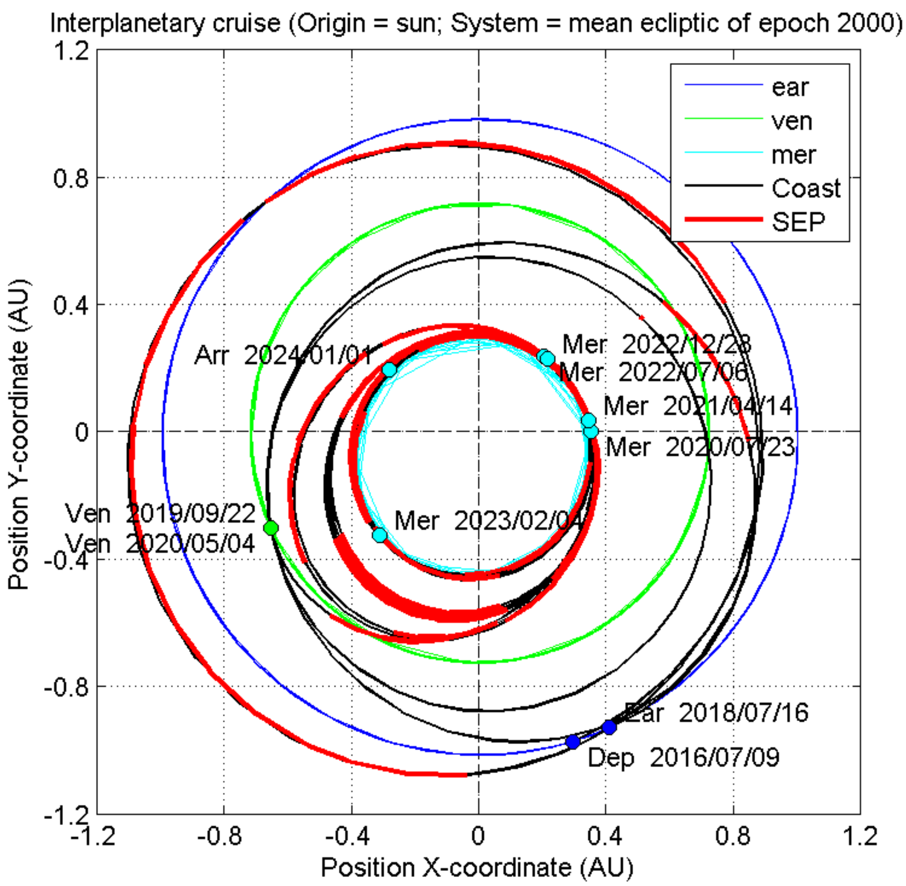

Figure 1: BepiColombo transfer trajectory with a launch on 9 July 2016 and arrival on 1 January 2024.

Figure 2 shows the thrust profile as function of time. The trajectory is calculated with a maximum thrust level of 290 mN minus 10% accounting for thrust outages due to e.g. safe modes and for navigation requirements. Therefore the maximum thrust is 261 mN.

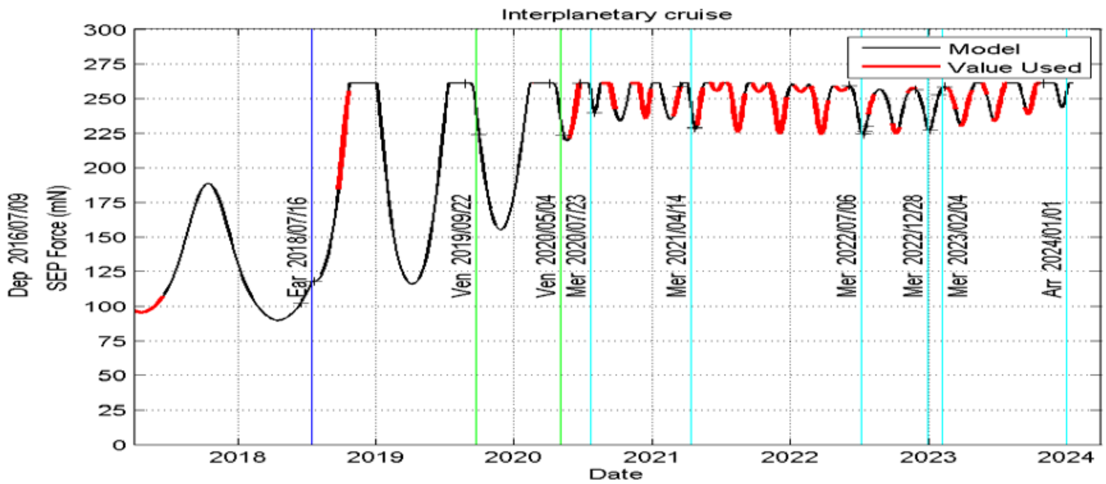

Figure 2: BepiColombo thrust profile during the 7.5-year transfer

Figure 3 shows the trajectory in a Sun-Earth fixed coordinate system. There is a superior conjunction ending 15 days before Venus 1 flyby. This is not a major concern because there is no nominal thrust arc before and also hardly any thrust required in the subsequent Venus-to-Venus arc which facilitates the interplanetary navigation. Mercury 2 flyby coincides with the beginning of a 8-day conjunction and therefore the coast arc after the flyby is extended to 15 days, i.e. providing 7 days for "clean" orbit determination after leaving the conjunction. There is plenty of time to correct the errors of this flyby in the following 15 months before the next flyby and since this correction can be done with Xenon it is very cheap.

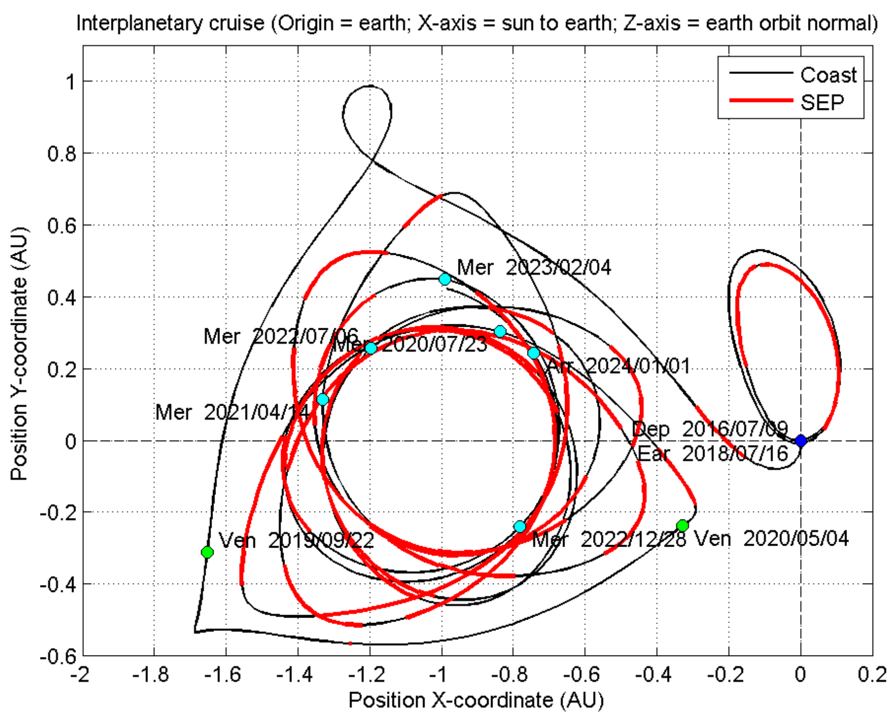

Figure 3: Nominal transfer trajectory plotted in a Sun-Earth fixed coordinate system.

4. Alternative Trajectories with the same Earth Flyby

4.1. Day-time launch on 12 July 2016

As indicated in the introduction the Earth flyby in July 2018 can be reached with various different launch scenarios. The first alternative presented here is a day-time launch with a radially outward escape trajectory. Due to the outward launch component the spacecraft will initially be in a trailing orbit. Figure 4 shows the trajectory in a Sun-Earth fixed coordinate system. The 30-day launch window opens 3 days later on 12 July 2016 and is 85 m/s cheaper (transfer ΔV = 4.169 km/s). The main advantage, however, is that the Earth is always in the coverage field of either the HGA or MGA (high and medium gain antenna). Another advantage is that there is no eclipse during launch (in the baseline scenario there is a 23 minute eclipse at launch). The disadvantage of having a 25-minute eclipse at the Earth flyby is not important, also to have the station coverage from Cebreros initially during night time at the control centre in Darmstadt is not seen as a major drawback. Therefore this option is currently under scrutiny to possibly become the new baseline.

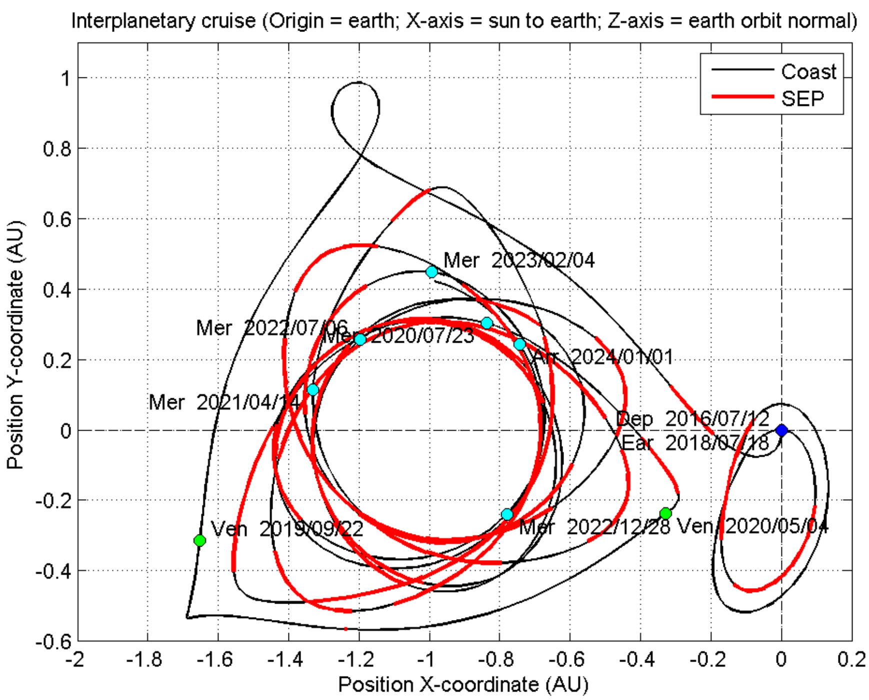

Figure 4: BepiColombo transfer with an outward escape trajectory.

4.2. Launch options in 2017

The two 2016 trajectories described above consist of two revolutions around the Sun before the Earth flyby. The same Earth flyby can be reached if the launch is delayed by six months (reducing the Earth-to-Earth transfer to a 540° arc) or by 1 year (reducing the Earth-to-Earth transfer to the ”normal” 360° arc). Figure 5 shows the transfer delta-V as function of launch date of all options that lead to the same Earth flyby in July 2018. Table 4 summarizes the four launch options of 2017.

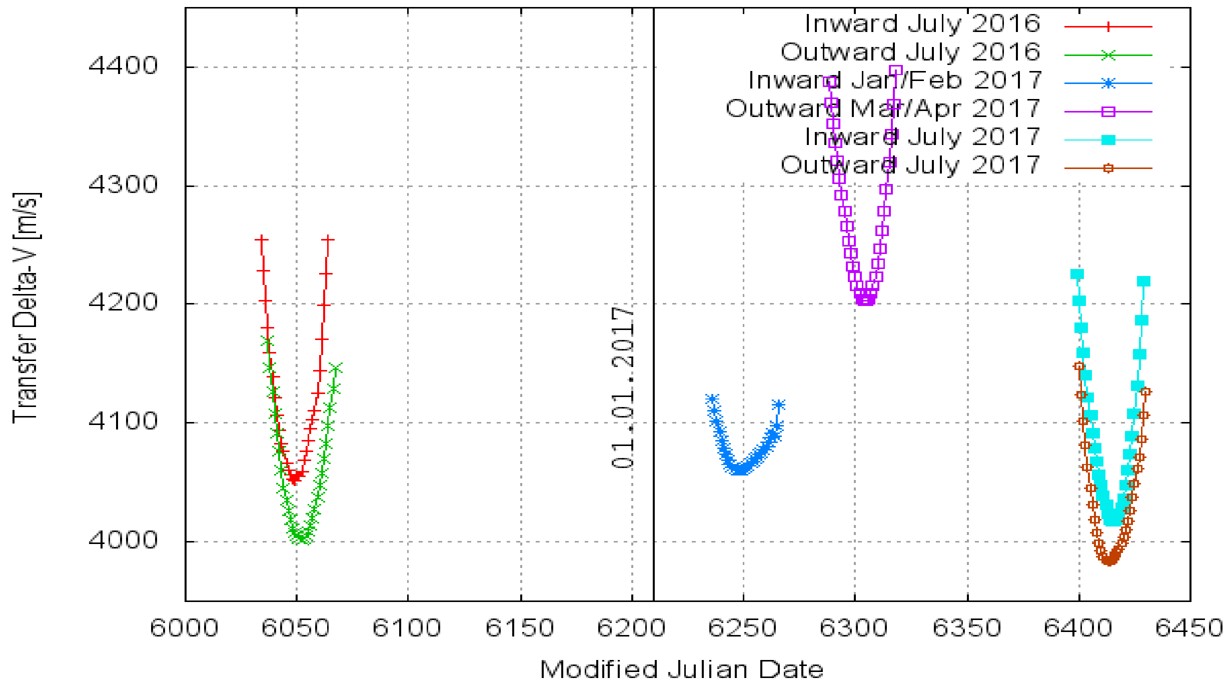

Figure 5: Transfer ΔV of the six launch windows as function of launch date.

Table 4: Launch windows in 2017

Launch Window	Launch hour	Launch type	Max. transfer ΔV
27 Jan- 26 Feb	01:40 - 01:48 UT	inward, 540° arc	4120 m/s
20 Mar - 19 Apr	12:57 - 13:05 UT	outward, 540° arc	4398 m/s
09 Jul - 08 Aug	02:17 - 02:34 UT	inward, 360° arc	4225 m/s
10 Jul - 09 Aug	13:53 - 14:07 UT	outward, 360° arc	4148 m/s

In all cases (also in the nominal scenario), 100 m/s delta-V shall be reserved to allow for the reduction of the thrust load in the Venus-to-Mercury arc and to move thrust to the Venus-to-Venus arc. The optimum thrust load balance in these two arcs can be fine-tuned at a later stage. The trade-off to be made is in which arc more margin is desired.

5. Direct Launch Option to Venus

Y. Langevin proposed a completely different strategy with a direct launch towards Venus. In January 2017 only 2.7 km/s escape velocity at the Earth are required to reach Venus about 110 days later. The departure declination is also favorable and allows a significant increase in payload mass on an Ariane 5. The first Venus flyby on 11 May 2017 will sling the spacecraft into a 1:1 resonance and after the second Venus flyby in December 2017 a 4:3 resonance is achieved. The third Venus flyby is used to reduce the perihelion and to reach Mercury for the first time in May 2020. A series of Mercury resonances and low-thrust arcs are performed to reduce the flyby velocity. The fifth Mercury flyby takes place on 20 Feb 2023 and an optimistic arrival date is 31 Aug 2023 at a Mercury true anomaly of 240°.

There are two open issues in this transfer: The direct launch towards Venus would require a chemical launcher dispersion correction, because relying on low-thrust for this very critical manoeuvre at the very beginning of the mission is considered as being too risky. The second issue is that the third Mercury flyby takes place only 7 days after a solar conjunction and in case of spacecraft anomalies not enough time would be available to navigate the spacecraft through a safe flyby. Raising the flyby altitude to 300 km might mitigate this issue, but it is still a challenge for spacecraft operators. Another (mainly financial) disadvantage is that a direct launch to Venus requires different flight tapes for each launch date. Furthermore, the approach navigation becomes more demanding and the orbit insertion geometry is more complex for an arrival in August 2023, and therefore this transfer option has not been considered in detail so far, given that a 2017 launch is not the current mission baseline.

5. Conclusions

The lack of a suitable flyby option at the Earth during the whole year of 2017 leads to a long 7.5-year transfer time of the nominal BepiColombo trajectory where the launch takes place on 9 July 2016 and the arrival on 1 Jan 2024. The advantage, however, is that 2 backup launch slots exist, that converge to the same transfer trajectory after the Earth flyby in July 2018. If the launch is delayed by about six months, the Earth-to-Earth arc is shortened from 720° to 540° and even a delay of one year can be accommodated (by shortening the Earth-to-Earth arc to the "normal" 360°). In all cases the same orbit insertion sequence as proposed in [8] can be executed.

In the current baseline a nighttime launch with an escape velocity directed towards the Sun is foreseen. However, all three launch windows in 2016 and 2017 can also be converted into a daytime launch where the trajectory is initially outside the Earth orbit and therefore Earth trailing. Since the communication geometry with the Earth is mostly better and the ΔV requirements are not too much different, it is currently under investigation if this strategy should be adopted. There exists also a completely different transfer trajectory which is currently not considered because the launch will be only in Jan 2017.

6. References

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