TRAJECTORY DESIGN FOR BEPICOLOMBO BASED ON NAVIGATION REQUIREMENTS

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Abstract: *The BepiColombo baseline trajectory foresees a launch in July 2014 and a capture in a Mercury orbit in November 2020. Between the seven flybys (one at the Earth, two at Venus and four at Mercury), there are extended low-thrust arcs providing a total ΔV of nearly 4 km/s. This optimum trajectory, however, has two Mercury flybys which are separated only by 40 days and a chemical trajectory correction manoeuvre of up to 32 m/s may be needed right after the first flyby in order to guarantee a successful second flyby. An alternative trajectory is presented which avoids this critical phase by adding one Mercury revolution between the two flybys. Since the original baseline orbit had one "spare" revolution in its final part (to avoid a solar conjunction at arrival), the alternative trajectory is able to maintain the November 2020 arrival date and the increase in transfer ΔV is marginal. Also the problem of "last-minute" pericentre raise manoeuvres with very unfavorable solar aspect angles demonstrates that navigation issues have an influence on the trajectory design.*

Keywords: *interplanetary navigation, low-thrust propulsion, trajectory design, Mercury*

1 Introduction

BepiColombo will be the first European mission to Mercury and the first mission ever to use solar electric propulsion (SEP) to reach an inner planet. The interplanetary trajectory, consisting of a combination of low-thrust arcs and seven flybys (one at the Earth, two at Venus and four at Mercury), is a challenge in terms both of mission design and navigation. At the end of the transfer, a gravitational capture at the weak stability boundary of Mercury is performed [1]. Several aspects have to be considered when analysing the feasibility of an interplanetary trajectory from a navigation point of view:

- Solar electric propulsion increases the flexibility and number of possible transfers, also allowing partial redesign of the trajectory at very low propellant costs. On the other hand it is also a source of noise for the spacecraft dynamics that can negatively affect the orbit determination from Earth. Because of this, 30-day coast arcs (without low-thrust propulsion) are introduced prior to all flybys to minimise the risks during critical phases of the mission.
- The low altitude of the Venus and Mercury gravity assists (minimum altitudes of 300 and 200 km respectively), and the gravity capture at arrival all introduce critical phases requiring a reliable navigation.
- Ground station coverage should be minimised for cost reasons.
- The event time scales of inner solar system missions are considerably smaller than for missions to the outer planets, which means that planetary encounters will take place closer to each other. This reduces the length of routine phases, and the available time for precise determination and correction of errors between events.
- The duration of solar conjunctions is smaller for similar reasons, but at the same time they happen more often (one superior conjunction every approximately 120 days in the orbit of Mercury). During a few days radiometric measurements are severely degraded due to the passage through the solar plasma [2], and no safe up-link of telecommands can be guaranteed.

- Solar radiation pressure (SRP) forces are up to eleven times larger in the vicinity of Mercury when compared to Earth. Depending on the spacecraft design, the torque introduced by the solar radiation pressure can quickly saturate the momentum wheels, requiring more frequent momentum wheel off-loading burns. In the case of an unbalanced reaction control system (RCS), these burns introduce also perturbations in the trajectory.

A suite of software tools were developed in Europe under the guidance of the European Space Operations Centre to find the optimum transfer trajectory to Mercury and to make a detailed navigation simulation (see [3] for more details). For the basic trajectory design DITAN [4] is used. It transcribes the optimal control problem into a nonlinear programming problem (NLP) which is quite recalcitrant if solar aspect angle constraints are imposed, but can usually be solved with SNOPT [5] after thousands of iterations. The next step is a trajectory refinement using MANTRA [6]. It uses a high fidelity numeric orbit integrator and a direct optimisation method to compute the optimal trajectory and manoeuvre parameters that satisfy the mission constraints.

For the navigation analysis, the tool LOTNAV [7] developed by DEIMOS is used. Its Trajectory Reconstruction Module (TRM) uses the autochthonous optimiser OPXRQP [8] developed at ESOC which is currently replaced by WORHP [9]. The Covariance Analysis Tool (CAM) is based on Bierman's work [10]. All these tools were used for the navigation analysis of the current baseline trajectory and of an alternative trajectory. The results are presented below.

2. Baseline Trajectory with Launch in 2014

The BepiColombo spacecraft leaves the Earth on 19 July 2014 (beginning of a 30-day launch window) with an escape velocity of 3.36 km/s with an Ariane 5 launcher. After one year the spacecraft comes back to the Earth and is deflected towards Venus. The spacecraft travels first inwards and then outwards with respect to Earth in the Earth-to-Earth phase.

Since the maximum deflection angle is 44° for a Venus flyby at 9.3 km/s, two Venus flybys (separated by one Venus year, i.e. 225 days) are necessary to rotate the v-infinity vector into the optimum direction (mainly backwards with respect to the velocity of Venus to reduce the perihelion to Mercury distance). After 2.5 orbits a sequence of 4 Mercury flybys follows (passing through a 3:2 and 5:4 resonance and a 180° singular transfer). The last two Mercury flybys take place within 40 days (the first close to Mercury's perihelion and the second one 180° later) as proposed by Langevin [11] and propel the spacecraft into the required orbital plane and reduce the relative velocity down to 1.9 km/s. Six final thrust arcs further reduce the relative velocity such that the spacecraft will be weakly captured by Mercury on 13 November 2020 even if no orbit insertion manoeuvre takes place. The total solar electric propulsion ΔV is 3717 m/s (without margin). The trajectory details can be found in [12].

Solar aspect angle constraints are imposed along the whole interplanetary trajectory. The Sun must not shine on the Mercury Magnetospheric Orbiter which sits on top of the spacecraft stack and it must not heat up too much the bottom side where the thrusters are located. The worst case of possible thruster failures is assumed which leads to solar aspect angle interval of [67.2°, 112.6°] outside 0.8 AU and to [67.2°, 94.6°] inside 0.8 AU. Figure 1 shows the trajectory which was 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 level used for the trajectory design is 261 mN.

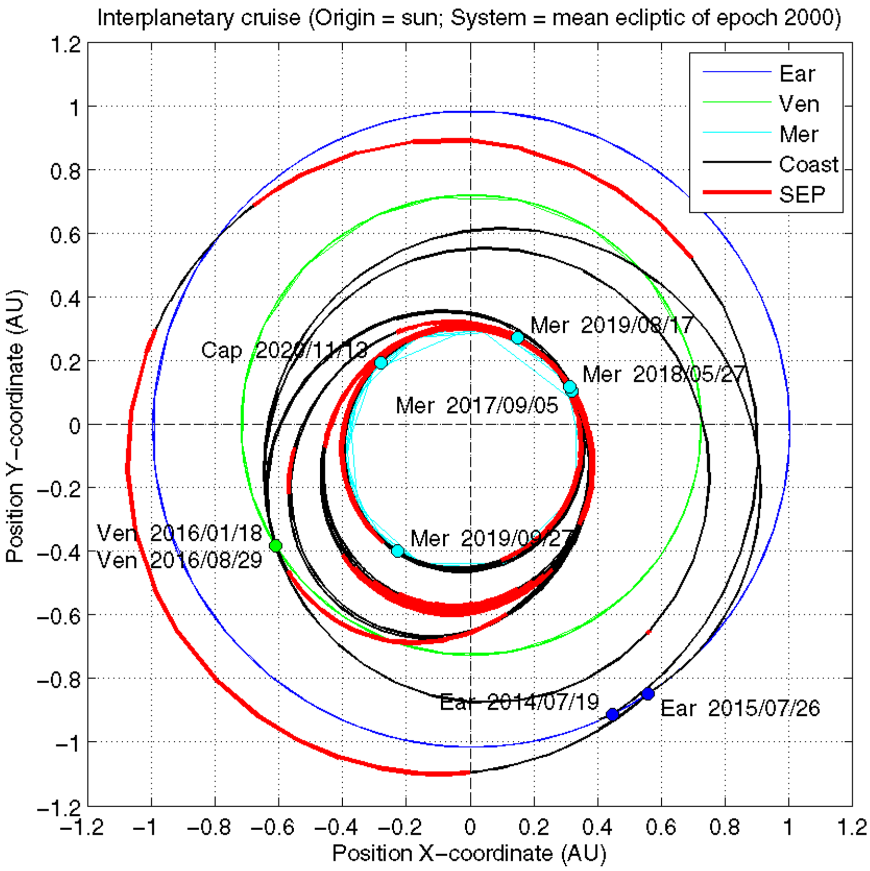

Figure 1. The BepiColombo baseline trajectory with a launch on 19 July 2014 and arrival on 13 Nov 2020. Red arcs indicate the parts of the trajectory where the solar electric propulsion is switched on.

3. Navigation Budget of the Baseline Trajectory and Critical Phases

For the navigation analysis, two-way X-band (8.4-Ghz) Doppler and range data are assumed to be acquired once a week from a single ground station (Cebreros), and ΔDOR measurements (Cebreros - New Norcia) are baselined before planetary flybys when required (before critical flybys like the second Venus flyby and the third Mercury flyby also a second baseline Cebreros - Malargüe in Argentina is required). Intense measurement campaigns begin 30 days prior to each flyby (lasting until a post-flyby cleanup manoeuvre is performed). During these phases measurements are taken at every ground station passage.

Several error sources are accounted for in the Covariance Analysis Module of LOTNAV, either as exponentially correlated random variables (ECRV, for the solar radiation pressure, non-gravitational accelerations, and SEP thrust modulus and direction), Gaussian errors (for the implementation of trajectory correction manoeuvres (TCM), and measurement noises) or as considered biases (in the ground station location and range measurements). A more detailed description of the assumptions can be found in [13].

The initial dispersion and a-priori uncertainties for the spacecraft initial state vector at each phase of the trajectory (the BepiColombo trajectory is split in 8 phases) depends on the navigation results of the previous phase. Figure 2 shows the dispersion of the state vector from the time of the second Mercury flyby to the fourth flyby. The spacecraft can deviate from its nominal position by more than 100 000 km (1-sigma), but the main error is in the along-track component and because of the regular navigation the dispersion can always be reduced close to the level of knowledge which is shown in Figure 3. Due to the large system noise during the thrust arcs (light blue shaded) the position knowledge degrades to several hundred kilometres, whereas during coast arcs the knowledge improves at each time when new measurements are taken (see the jig-saw pattern). Towards a flyby the knowledge of the position vector improves rapidly by orders of magnitude ("gravitational focussing effect").

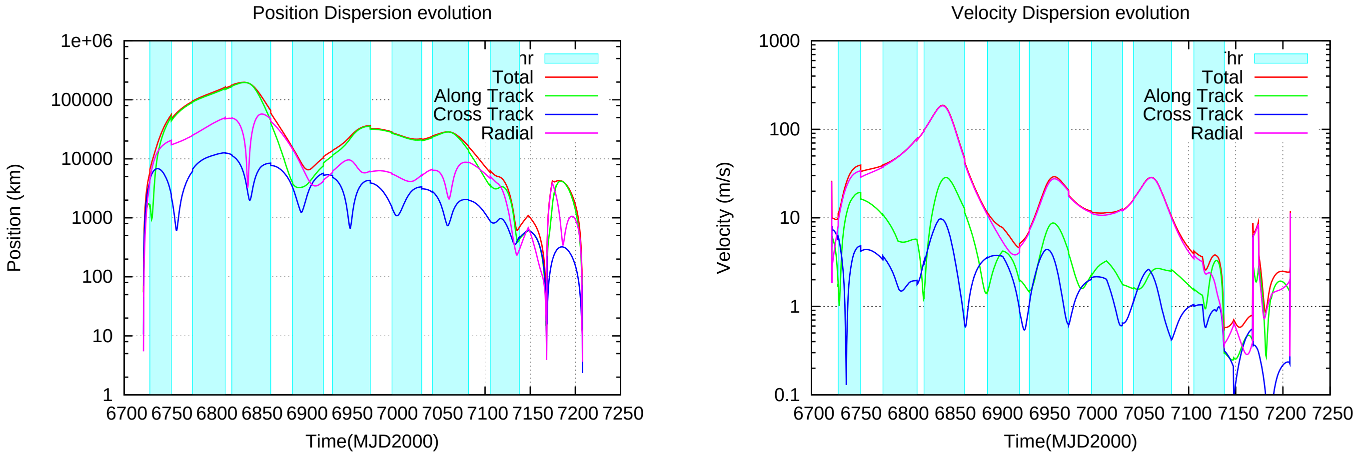

Figure 2. One-sigma position and velocity dispersion between second (on MJD=6721) and fourth (on MJD=7209) Mercury flyby.

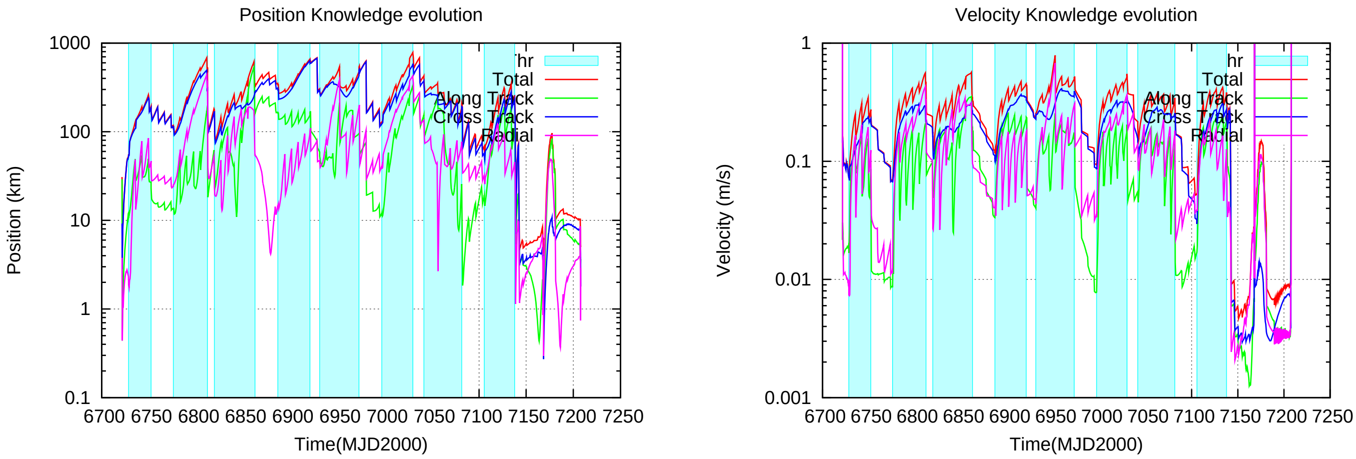

Figure 3. One-sigma position and velocity knowledge between second and fourth Mercury flyby.

A particular critical phase is the arc between the third and fourth Mercury flyby. They are only 40 days apart and in case the third Mercury flyby has a significant error, it must be corrected quickly in order not to miss the fourth flyby. Even with two ΔDOR baselines, the 3-sigma error in the B-plane of the third Mercury flyby is 31 x 10 km. Since solar electric propulsion may not always be available, the safest approach is to schedule a chemical correction manoeuvre after the post-flyby orbit determination is performed. This may take typically 7 days. Figure 4 shows the size of the correction manoeuvre 7 days after the third Mercury flyby as function of the error in the B-plane. It can be seen that in the worst case (i.e. 3 sigma) about 32 m/s are required.

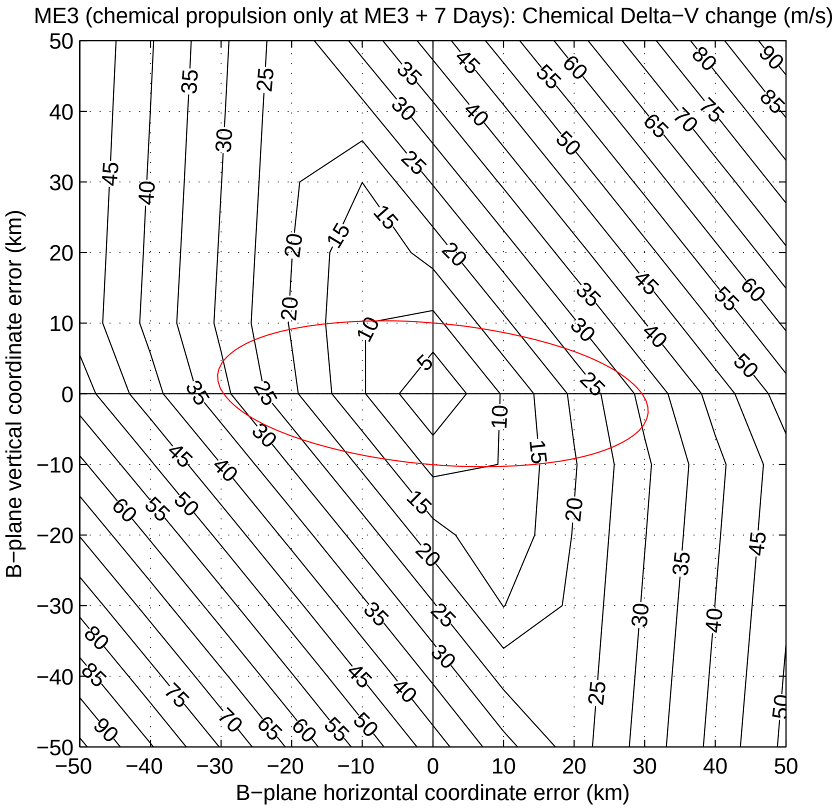

Figure 4. Size of chemical cleanup manoeuvre as function of errors in the B-plane at the third Mercury flyby. The labels give the values in m/s and the red ellipsoid shows the 3-sigma navigation error for two Delta-DOR baselines.

The 32 m/s TCM requires 40 kg of fuel and constitutes half of the available chemical navigation fuel budget. The other chemical trajectory correction manoeuvres which are nominally 20, 10 and 2 days before each flyby amount to 38 m/s including a very small TCM 90 days after the first Venus flyby which is not listed in Tab. 1. Hence in total 70 m/s chemical ΔV is required. A detailed break-down is given in Tab. 1. The low-thrust navigation ΔV which is usually spent during regular thrust arcs as well as for flyby clean-up manoeuvres is 220 m/s (see [13] for more details). Due to the 14 times higher specific impulse this corresponds to only 20 kg of Xenon.

Table 1. Chemical Navigation Fuel Budget

	Earth	Venus 1	Venus 2	Mercury 1	Mercury 2	Mercury 3	Mercury 4
Date	26.07.2015	18.01.2016	29.08.2016	05.09.2017	27.05.2018	17.08.2019	27.09.2019
Flyby velocity (km/s)	4.32	9.26	9.27	5.58	5.31	2.82	1.89
Navigation error (km x km)	10 x 5	69 x 15	61 x 26	66 x 10	36 x 4	31 x 10	20 x 6
TCM flyby –20 days (m/s)	3.93	8.63	1.41	3.44	12.63	2.86	0.81
TCM flyby –10 days (m/s)	0.11	0.26	0.10	0.26	0.41	0.19	0.16
TCM flyby –2 days (m/s)	0.05	0.30	0.17	0.39	1.04	0.26	0.21

As it can be seen in Tab. 1, the 3-sigma error ellipsoid at the fourth Mercury flyby is only 20 x 6 km, however if an anomaly occurs much larger errors could be the consequence. Therefore it is desirable to have the option to make a “last-minute” pericentre raise manoeuvre, which has to be performed with chemical thrusters due to the time constriants. At the fourth Mercury flyby the spacecraft approaches Mercury from the South pole with a declination close to 90° and a flyby on the night side. To raise the pericentre requires a manoeuvre in the orbital plane nearly perpendicular to the flight direction. In this geometry it is nearly 180° away from the Sun. Figure 5 shows the last 10 hours of the trajectory before the fourth Mercury flyby. The red lines indicate the directions of the pericentre raise manoeuvres and the numbers next to them, the solar aspect angles.

If there are severe constraints on the solar aspect angle, then the pericentre raise manoeuvre has to be rotated close to the velocity direction and therefore it becomes much larger. Only the radial component of the manoeuvre leads to a raise of the pericentre whereas the tangential component has nearly no effect on the pericentre altitude.

The penalty as function of the solar aspect angle *SAA* for a maximum Sun-incidence angle α_{MAX} is:

$$\text{penalty} = 1 / \cos\,(SAA - \pi/2 - \alpha_{MAX})$$

If the pericentre of Mercury 4 flyby needs to be raised by 50 km three hours before the flyby, a radial manoeuvre of 4.7 m/s is required. However if only a maximum Sun-incidence angle on the spacecraft stack α_{MAX} of 12° is allowed, the manoeuvre becomes 2.56 times more expensive and increases to 13 m/s. The numbers in parentheses in Figure 5 give the penalty for α_{MAX} = 12°.

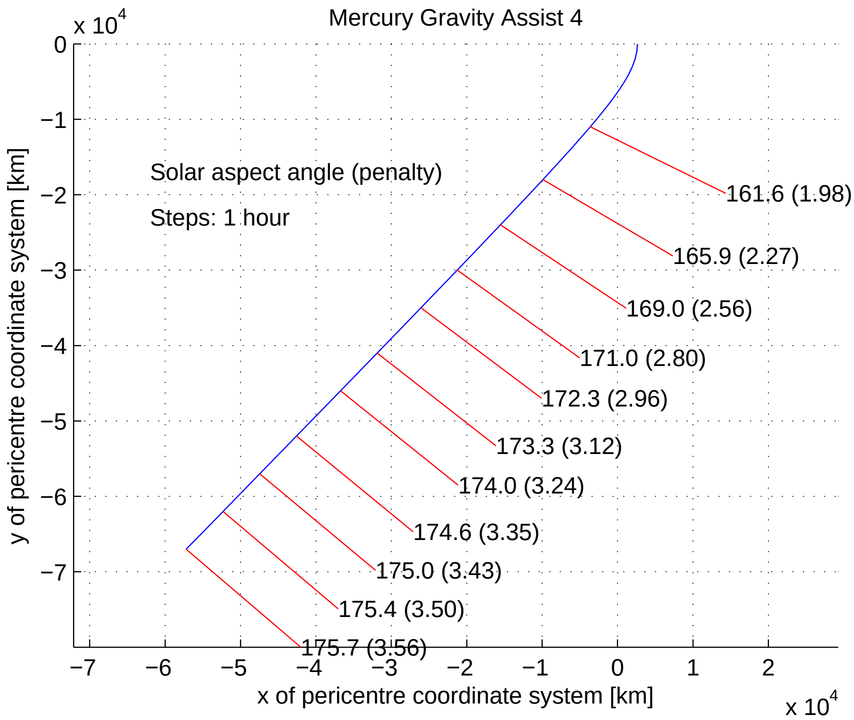

Figure 5. Direction of pericentre raise manoeuvres hours before the fourth Mercury flyby. The numbers indicate the solar aspect angle constraints (and the penalty factors if a maximum Sun-incidence angle of 12° is imposed).

4. Alternative Trajectory with More Relaxed Navigation Requirements

In the previous section it was shown that the chemical navigation fuel budget would be exhausted if a 3-sigma error case had to be compensated at Mercury 3 flyby and no fuel would be left for a contingency pericentre raise manoeuvre at the following flyby. To mitigate this critical situation a different flyby strategy was investigated. Rather than performing the fourth Mercury flyby half a revolution after Mercury 3, it can also be performed one and a half revolutions later. The advantage is that the Mercury 3 cleanup manoeuvre in this case can be done with electrical propulsion because there is enough time even if the propulsion system has temporary problems.

Figure 6 shows the distance to Mercury from the third Mercury flyby until orbit insertion for the baseline trajectory and for the alternative trajectory. One revolution after the third flyby there is a close encounter with Mercury at a distance of 80 000 km. However this is not critical because the dispersion in the position at that time is on the order of 1000 km (see
Figure **7**) even without any special trajectory correction manoeuvres. The spacecraft can practically ignore this very high altitude flyby and continue performing routine operations.
Figure **8** shows the knowledge of the state vector that can be achieved with regular range and Doppler data and ΔDOR measurements from two baselines prior to Mercury 3 flyby. Comparing the knowledge with the knowledge of the state vector of the baseline trajectory (see Figure 3) there are little differences.

The total transfer ΔV of the alternative trajectory is 3782 m/s which is only an increase of 65 m/s (corresponding to 6 kg of Xenon) and the arrival date on 13 Nov 2020 remains unchanged. The reason why there is no delayed arrival is due to the fact that already in the baseline trajectory there was an extra revolution around the Sun because the geometry of a superior solar conjunction (which would disturb the ground contact) prevented an arrival in August 2020.

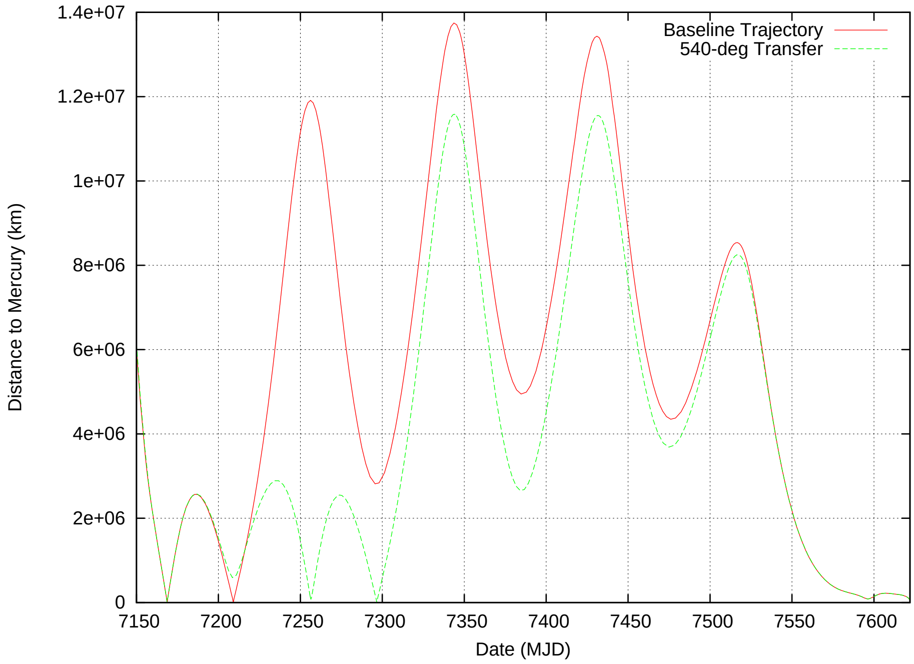

Figure 6. Distance to Mercury for the baseline trajectory and for the alternative trajectory with a 540° transfer between Mercury 3 and 4 flyby. Mercury 3 flyby is on MJD = 7169 and Mercury 4 flyby on MJD = 7209 (baseline) or MJD = 7297 (alternative).

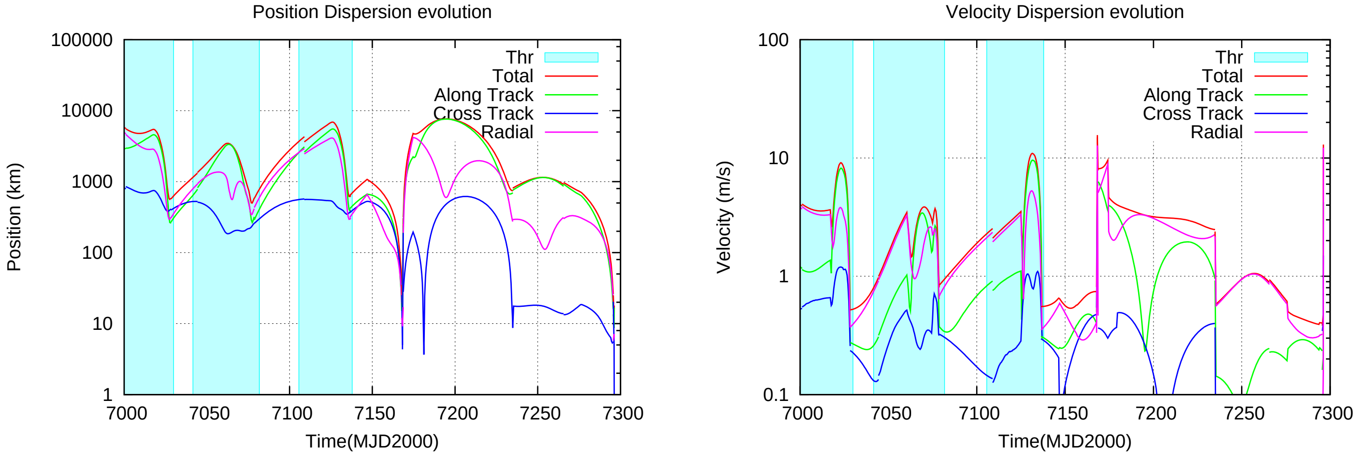

Figure 7: One-sigma position and velocity dispersion 300 days before the fourth Mercury flyby

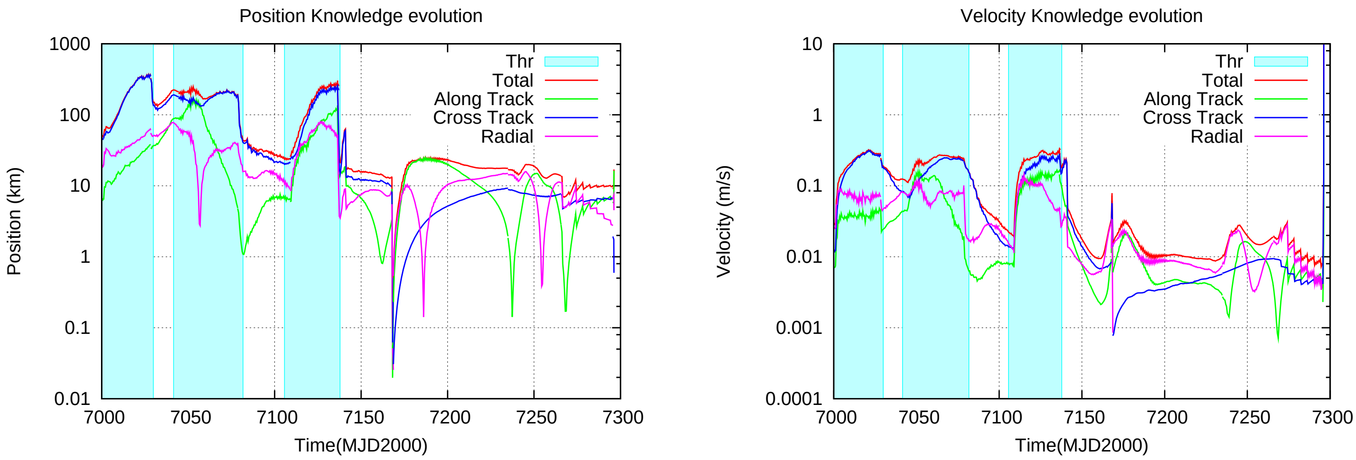

Figure 8: One-sigma position and velocity knowledge evolution 300 days before Mercury 4 flyby.

So the question is: how much navigation fuel can be saved with the alternative trajectory? Figure 9 shows the size of the cleanup manoeuvre of the third Mercury flyby as function of the error in the B-plane. The 3-sigma error ellipse has a size of 37 x 21 km and the maximum correction manoeuvre inside this ellipse requires 43 m/s. However since this can be done now with low-thrust propulsion, the required Xenon mass is only 4 kg. Even if the SEP were not available during the first 14 days after the flyby, the TCM would increase only to 60 m/s (5.5 kg Xenon).

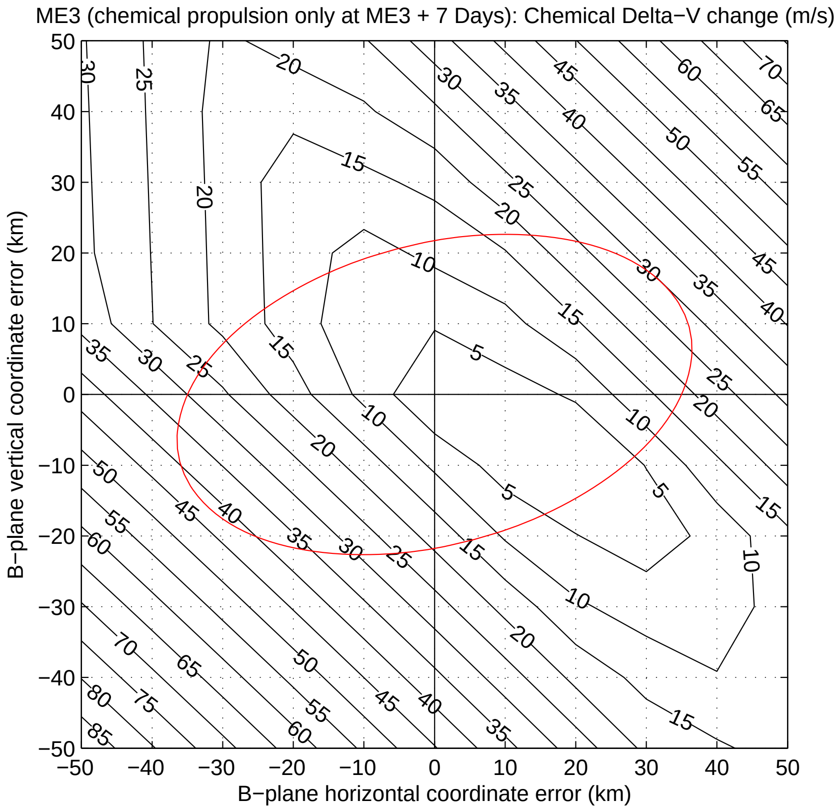

Figure 9: Size of chemical cleanup manoeuvre as function of errors in the B-plane at the third Mercury flyby of the alternative trajectory. The labels give the values in m/s and the red ellipsoid shows the 3-sigma navigation error for two Delta-DOR baselines.

5. Conclusions

Originally the BepiColombo trajectory was designed by minimizing the fuel consumption and the transfer time. However, during a detailed navigation analysis, it turned out that the optimum trajectory was risky from an operational point of view because the third and fourth Mercury flyby are too close to each other. A spacecraft contingency at the third Mercury flyby would require an immediate chemical correction manoeuvre to continue the mission. The cost of this manoeuvre is at the limit or even beyond the current chemical fuel budget.

Therefore an alternative trajectory was designed where the Mercury 3 flyby cleanup manoeuvre can be done with electrical rather than chemical thrusters because the fourth flyby is performed 88 days (1 Mercury year) later. Even if the electrical thrusters had a down-time of 14 days (or even more) there would be enough time to re-optimize the rest of the trajectory after the degraded flyby. Thus the overall design and optimization of the BepiColombo trajectory is strongly influenced by navigation requirements.

Also the huge penalties due to the severe solar aspect angle constraints in a contingency pericentre raise manoeuvre shortly before the fourth Mercury flyby may have an influence on the trajectory design. It is much cheaper to raise the nominal flyby altitude by e.g. 50 km, tolerate a very large flyby error and re-optimize the final trajectory, than to make a last-minute pericentre raise manoeuvre. This option is currently discussed and it is just another example how navigation issues influence the trajectory design.

Acknowledgements

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6. References

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