LOW-THRUST NAVIGATION TOOLS AT ESOC MISSION ANALYSIS SECTION

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ABSTRACT

Software able to simulate the guidance and navigation process is essential for the design of complex interplanetary missions. The main tasks are the guidance cost estimation and the measurement requirements establishment for the orbit determination; additional analyses can also be conducted with such software, concerning for example orbit prediction or sensitivity analyses in general. In this context one of the most complete tools available at ESOC Mission Analysis Section was used to conduct navigation analyses for the BepiColombo mission. The fact that the spacecraft uses solar electric propulsion as a main mean of propulsion is indeed greatly affecting the navigation analysis and ad hoc tools and simulation strategies were required.

1. INTRODUCTION

In the context of deep space missions design a crucial aspect to be investigated and simulated is the guidance and navigation of the spacecraft. As a consequence the ESOC Mission Analysis Section has different tools available, apt to numerically reproduce and simulate such an aspect.

Moreover the mission type and the most important design choices for the spacecraft greatly influence the study of the guidance and navigation; particularly if the spacecraft rely on low-thrust propulsion, as for the BepiColombo case, the navigation analysis tool adopted for the study should be able to represent accurately the low-thrust trajectory, should have dedicated low-thrust guidance algorithms and also cope with hybrid propulsion systems. For these reasons the low thrust navigation tool LOTNAV [1] was selected as the core tool for the BepiColombo mission.

The overall setup should also be considered, in order to guarantee internal and external consistency: for example the nominal trajectory of the spacecraft, input to the navigation analysis obtained with dedicated optimization tools, should be reproduced accurately and be consistent within the navigation tool modelling itself.

In section 2 the navigation tool setup used for low-thrust missions is detailed and the specific software structure is presented, highlighting the major assumptions used in the simulation.

In section 3 the BepiColombo case study is presented, describing the assumptions taken for the navigation inputs and showing the results of analysis on the latest baseline trajectory, with launch scheduled in April 2018.

2. SIMULATION TOOLS

The navigation analysis setup used for the BepiColombo mission is not a single input-output software: two separate tools are used in series to generate the overall results of interest, in some cases in subsequent back and forth iteration. The complete setup and the major assumptions made to be able to use the different tools together are explained in subsection 2.1, while the single components are briefly described in subsections 2.2 and 2.3.

2.1. Overall setup

The work-flow for the BepiColombo navigation analysis can be summarized in four steps:

1. The optimized nominal trajectory (generated with MANTRA [2]) is re-optimized with a dedicated LOTNAV module in order to be internally consistent with the navigation tool. Differences between the two trajectories are checked to be below the acceptable level for the needed purposes.
2. A full simulation is performed with LOTNAV for the overall interplanetary trajectory, given the selected assumptions for the orbit determination and guidance process.
3. [Eventual] re-iteration of the guidance and navigation process (step 2) is performed, in order to compare different strategies of guidance targeting and/or measurements schedule.
4. The cost to re-optimize the trajectory after each planetary flyby is computed, given the dispersion at each flyby obtained at step 2/3.

The first step is necessary due to the fact that small differences in dynamics modelling and optimization in general are present between the two tools, but an internally consistent reference trajectory is needed by LOTNAV: otherwise the internal propagation would not be consistent with the trajectory itself causing discrepancies to arise, leading to errors in covariance propagation and guidance cost computation.

The fourth step is necessary since it is exactly what would be done in the real mission scenario: after each planetary

flyby the spacecraft will not be forced to regain at all cost the previous reference trajectory, but a newly optimized trajectory will be generated, usually saving a significant amount of propellant mass.
In some conditions an additional iteration can be necessary if the resulting re-optimization cost is above what is considered to be admissible or if particular constraints apply.
This work-flow scheme relies on two major assumptions:

a) chemical clean-up manoeuvers inserted after each planetary flyby are not accounted for in the ΔV budget;
b) variations of the interplanetary trajectory after the post-flyby re-optimization are considered negligible for navigation analysis purposes.

The first assumption is made because such manoeuvers would not be really executed during the mission: they are inserted in the simulation just to lower the dispersion level with respect to the nominal trajectory (but still retain a way to assess the cost of such a process).
The second assumption is linked to the first one: if the re-optimized trajectory is considered to be similar enough to the reference trajectory, it is possible to use the same trajectory for the whole navigation analysis, only introducing ad hoc chemical manoeuvers (not really applied in the actual mission) to lower the dispersion whenever in real life a re-optimization would take place. This plausible assumption allows to run the two analyses almost independently, leading to a more straightforward and less computationally demanding simulation.

2.2. LOTNAV

The Low-Thrust Interplanetary Navigation Tool, LOTNAV [1], is a mission analysis tool developed under ESA contract by Deimos Space S.L. Its main functions are:

- reproduction of low-thrust trajectories including encounter with massive and minor bodies,
- simulation of measurement systems used for orbit determination,
- covariance analysis,
- simulation of full Monte Carlo process on the navigation and guidance activities.

One or more modules of the tool are dedicated to each of the functions listed; additional functions are also present in the tool, but were not used in the current analysis.
Two modules are used to reproduce an optimized low-thrust trajectory, with an increasing degree of accuracy. The reference trajectory for the BepiColombo case is in fact obtained with MANTRA and only afterwards reproduced in LOTNAV for the navigation analysis.
Given the internally consistent trajectory, measurements can be simulated with a selected schedule, variable according to the different phases of the mission.
The core of LOTNAV is then the covariance analysis module for theoretical analysis of the estimation process and the MonteCarlo module for the actual computation of estimation and guidance process. A batch-sequential Square Root Information Filter (SRIF) based on Bierman's formulation [3] is used to process the measurements. Several error sources can be accounted for in the filter, either as exponentially correlated random variables (ECRV), Gaussian errors or as considered biases. Different targeting options are available to the user for the guidance, targeting either directly the spacecraft state at a specific time or instead flyby related quantities (i.e. B-plane parameters).
The results of the simulation are processed with a specific module and statistical results are given for the trajectory correction manoeuvers (TCMs), navigational corrections of the thrust profile and evolution of spacecraft dispersion and knowledge.

2.3. MANTRA

The flight dynamics interplanetary manoeuver optimization software, also known as MANTRA [2], is an optimization tool the key function of which is to compute during operations the orbit manoeuvers required to reach given orbital targets while satisfying given mission constraints and minimizing a given cost function. The software is also intended for use in the context of mission design and preparation studies: typical applications are launch window definition or verification, trade-off studies and sensitivity analyses.
Among other capabilities, the MANTRA software is able to evaluate the cost of low-thrust trajectory re-optimization; specifically for a trajectory which includes flybys, it is possible to study how a different B-plane crossing point at a given flyby affects the optimization of the downstream trajectory.

3. BEPICOLOMBO CASE STUDY

BepiColombo is a joint ESA/JAXA mission to the planet Mercury, with baseline launch in April 2018 [4]. The two separate modules, Mercury Planetary Orbiter and Mercury Magnetospheric Orbiter, will share the transfer to Mercury thanks to the Mercury Transfer Module, equipped with a solar electric ion drive engine.
The navigation analysis reported in this document refers to the interplanetary cruise between Earth departure and final approach to Mercury.

3.1. Assumptions

The analysis performed is based on several assumptions, which can be divided in five classes:

- trajectory,
- measurements,
- orbit determination,
- guidance strategy,
- re-optimization.

The reference trajectory considered is the current baseline, with launch in April 2018 and arrival in December 2024; it includes six planetary flybys, two at Venus and four at Mercury. The navigation analysis is performed from Earth departure up to Mercury arrival minus 63 days. Figure 1 shows the interplanetary reference trajectory.

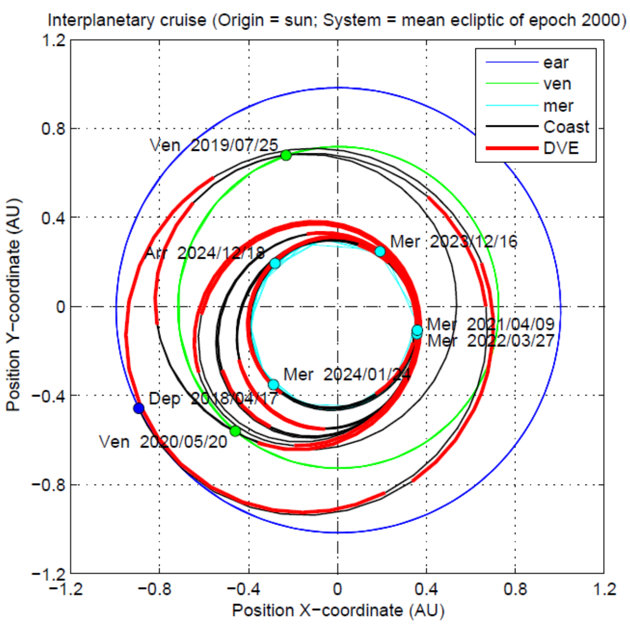

Figure 1. BepiColombo April 2018 trajectory projection in ecliptic plane. Thrust arcs in red.

Measurements are simulated according to the following schedule:

- Range and Doppler measurements taken from a single ground station (Cebreros); range data sampled once every 60 minutes and Doppler data once every 10 minutes; one ground station pass every week is considered for interplanetary arcs, daily ground station passes are considered for last 30 days before each flyby.
- ΔDOR measurements are simulated once every four days during the last 30 days before a flyby. The baseline is Cebreros-New Norcia; a second ΔDOR baseline (Cebreros-Malargüe) is simulated when high accuracy orbit determination is required to obtain an admissible spacecraft dispersion.

Ground station position errors are modelled as consider biases with 0.3 m in every direction; measurements errors, bias and constraints in availability are reported in Table 1.

Table 1. Measurements Errors and Visibility Constraints.

Measurement	Noise (1σ)	Bias	Ground Station Minimum Elevation
Range	10 m	2 m	10º
Doppler	0.3 mm/s	--	10º
ΔDOR	0.2 m	--	15º

Concerning the orbit determination, initial knowledge and dispersion are taken from the launcher performance data and are updated every 0.5 days; the spacecraft residual acceleration is modelled as an exponentially correlated random variable (ECRV) with a 1σ steady state covariance at 10^{-11} km/s^2 and an autocorrelation time of 1 day.
The strategy for the guidance is consistent with the hybrid configuration of the propulsion system of BepiColombo: both low thrust and chemical TCM are simulated.
As a baseline option low-thrust guidance is performed whenever a thrust arc is present and sufficient time is available for the guidance law computation and upload; the guidance law is assumed to be computed and updated every 7 days (reflecting the 7 days schedule of the ground station availability during interplanetary arcs) but conservatively uploaded only every 14 days (accounting for the loss of one upload opportunity). Additionally during the first and last 0.5 days of each thrust arc no guidance is performed. The errors in guidance thrust modulus and direction are modelled as ECRV: a 1σ uncertainty of 1% and 0.5º, respectively is assumed, together with an autocorrelation time of 1 day for both errors.
Chemical TCMs are scheduled as a baseline during the last 30 days before a flyby in order to target the planet encounter precisely: a baseline schedule of three targeting manoeuvers (roughly 20, 10 and 2 days before each flyby) is selected. A clean-up manoeuver is also simulated roughly 5 days after each flyby (as already explained in section 2, this TCM is not accounted in the total budget since it is required only for simulation purposes). Each chemical manoeuver error is modelled as Gaussian with a 1σ uncertainty of 1% in modulus and 0.5º in direction.
A very strong assumption directly related to navigation and orbit determination was already taken into account while the reference orbit was determined and optimized: in order to have a good spacecraft knowledge during the final approach to flybys (to be able to determine precisely the correction

manoeuvers to be executed), coasting was imposed in the last 30 days before every planetary encounter; without this constraint the activation of the electric propulsion module would have led to a strong increase in the spacecraft state uncertainty. This degradation can be verified a posteriori, simply examining how the spacecraft state knowledge is affected by the low-thrust propulsion. As an example in Figure 2 and Figure 3 the BepiColombo spacecraft dispersion evolution is plotted for the interplanetary phase between Venus-2 and Mercury-1 flybys.

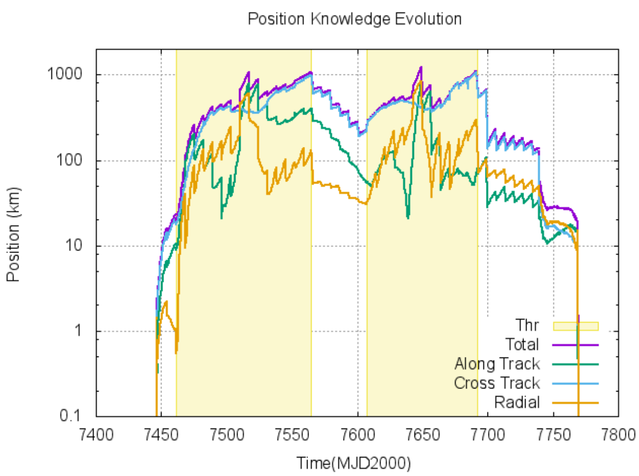

Figure 2. Position knowledge evolution, Venus-to-Mercury phase. Thrust arcs highlighted.

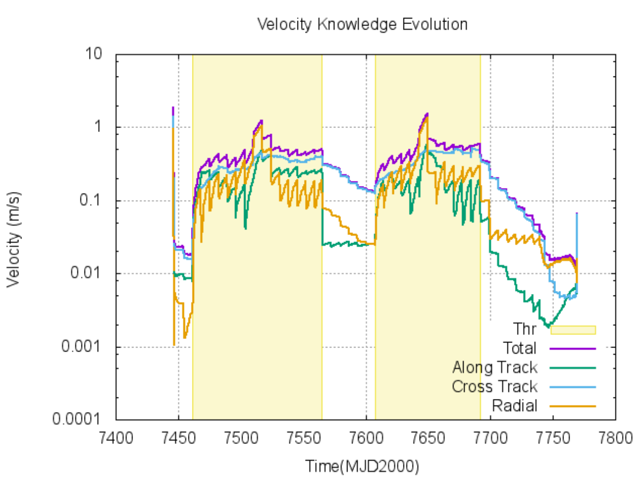

Figure 3. Velocity knowledge evolution, Venus-to-Mercury phase. Thrust arcs highlighted.

The clearly visible knowledge degradation is caused by the intrinsic uncertainty on the electric propulsion module performance: the velocity knowledge is directly affected by the delivered ΔV noise, while the position knowledge is degraded as a consequence of the velocity noise integration.

3.2. Search of best guidance strategy

The baseline strategy for the guidance was first applied to the each interplanetary phase and flyby; the results obtained were then used to tune the manoeuvers number, epoch and targeting (possibly the measurements as well) in order to lower the overall navigation cost and retain acceptable levels of dispersion. The first interplanetary leg, from the Earth departure to the first Venus flyby, is already an interesting case, which requires a deviation from the standard navigation strategy. This interplanetary phase is constituted, as all trajectories considered for the BepiColombo mission, by an initial coast arc of 90 days, used for spacecraft commissioning and electric propulsion system testing, during which only a chemical launcher dispersion correction manoeuver is scheduled few days after launch; before the Venus encounter three thrust arcs are present, two of them are long enough for full low-thrust guidance exploitation; during the final 30 days before Venus flyby (as for every other flyby) a coast arc is present. The arcs duration and events are reported in Table 2.

Table 2. Earth to Venus phase, Arcs and Events.

Event/Arc	Duration (days)
Earth Departure	--
1-coast	2.76
Earth SOI exit	--
2-coast	87.24
3-thrust	56.78
4-coast	70.74
5-thrust	153.53
6-coast	43.02
7-thrust	18.60
8-coast	31.70
Venus SOI enter	--
9-coast	0.93
First Venus flyby	--

If the baseline strategy for the guidance is used for this phase of the mission, the cost of the first targeting manoeuver before the Venus flyby (20 days before) would be 38.9 m/s (3σ confidence). The cause of such a high cost for the correction manoeuvers is probably due to the presence of a short thrust arc (7-thrust) just before the final approach to Venus. Not only the dispersion present before the low thrust arc is not decreased while thrusting, but also the noise in the thrust itself increases the dispersion magnitude. Several strategies were analysed and it is found that the introduction of two additional TCMs leads to a much lower cost of the guidance: the first additional manoeuver is inserted 1.5 days before the 7-thrust arc, to decrease the dispersion present before the non-guided arc, the second is inserted just after the 7-thrust arc, 29.4 days before the Venus flyby, correcting for the errors introduced by the low-thrust propulsion. The cost of the two additional manoeuvers is 3.1 and 11.1 m/s, respectively, but the targeting manoeuver 20 days before closest approach is reduced by almost 98%, decreasing from 38.9 to 0.85 m/s. The overall guidance cost is hence reduced by more than 50% even though the number of TCMs increases from 3 to 5. Additionally the chemical manoeuvers executed more than 30 days before a flyby could be (and will probably be) substituted in the real mission with an ad hoc modified or newly introduced low-thrust arc. This technique, which goes beyond the capability of the LOTNAV tool, would allow an even lower impact of the guidance process on the overall mission ΔV.

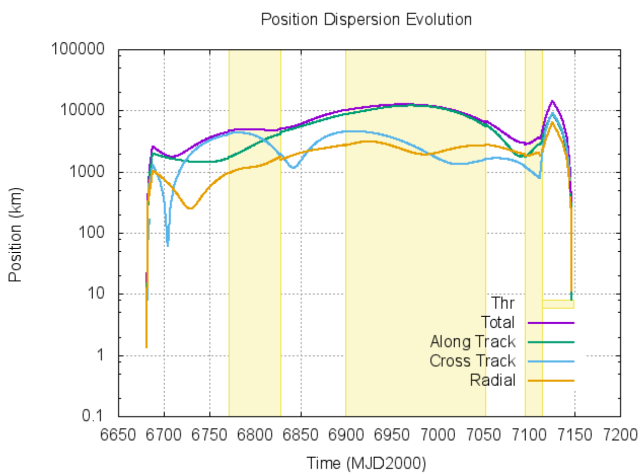

Figure 4. Position dispersion evolution, Earth departure to Venus-1 phase, standard strategy. Thrust arcs highlighted.

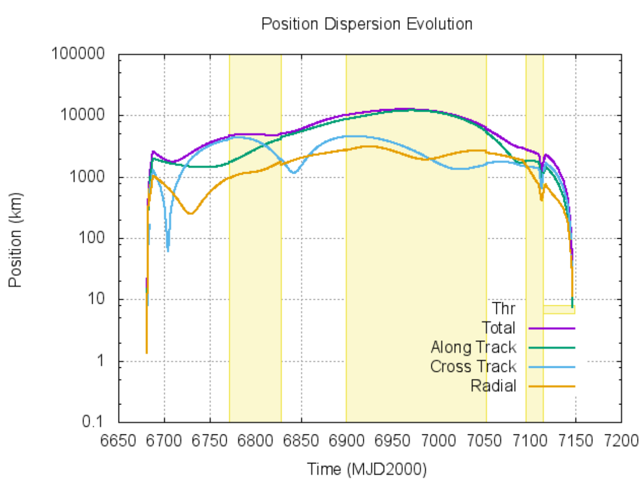

Figure 5. Position dispersion evolution, Earth departure to Venus-1 phase, selected strategy. Thrust arcs highlighted.

The effectiveness of the two additional TCM can also be seen in the position dispersion evolution. The standard strategy leads to the dispersion shown in Figure 4: the dispersion starts to increase during the last thrust arc and has an even sharper increase at the beginning of the 30 days approach to Venus.

The two additional manoeuvers are able to prevent the dispersion increase in the last part of Earth to Venus phase, as it can be seen in Figure 5 (differences with respect to the standard strategy can be seen after MJD2000 7092).

A crucial factor in the guidance analysis, besides the selection of the number of TCMs and their epoch, is the targeting of each correction scheme. The LOTNAV tool accepts different types of targeting; among those, two are used for the BepiColombo mission navigation analysis: either the spacecraft state at a given epoch or the B-plane parameters at the flyby are selected. The choice of the epoch at which parameters are targeted is not trivial and the related correction efficiency depends on several factors, such as relative orbital geometry between manoeuver epoch and target epoch and dynamical conditions in general. Even though targeting the same parameters at different epochs can lead to a very similar dispersion at a later stage if the same guidance strategy is applied for a given phase, the overall navigation cost can be strongly affected.

As an example, in the interplanetary phase between Earth departure and Venus-1 flyby, if the targeting epoch for clean-up and low-thrust corrections is shifted from the Venus sphere of influence (SOI) entrance to 32 days before (end of last thrust arc before Venus-1 encounter), the cost of the first TCM targeting the B-plane parameters can be decreased from 14.3 m/s to 11.1 m/s, obtaining similar flyby dispersion levels. Several alternatives where tested for each manoeuver in order to determine the most efficient guidance scheme and the eventual linked compromises.

3.3. Dispersion at the B-plane

One very meaningful output of the navigation analysis is the dispersion ellipse mapped on the B-plane. In the case of the first Venus flyby, for example, with the selected guidance strategy a dispersion ellipse of 77x31 km is obtained. This result is not only interesting per se, but can be coupled with the MANTRA results to understand the costs of the trajectory re-optimization. Starting at the Venus flyby, the B-plane crossing point is modified with respect to the reference trajectory over a 200 x 200 km grid, the resulting trajectories are re-optimized and the isolines of ΔV variation are computed. The final result of this procedure can be seen in Figure 6: in this case the re-optimization of the trajectory results in a small increase in the required low-thrust ΔV, given the dispersion at the flyby computed with the LOTNAV tool.

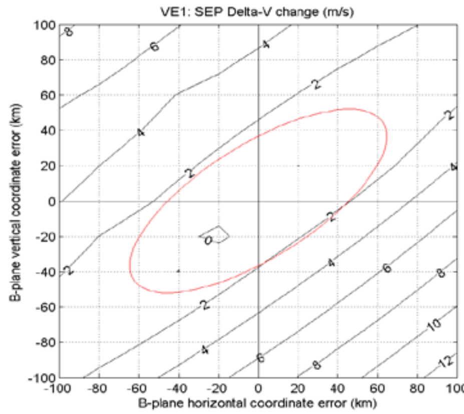

Figure 6. Re-optimization low-thrust ΔV cost for B-plane crossing variation at Venus-1 flyby. Dispersion ellipse in red.

In the Venus-1 case the re-optimization always leads to an increase of the total low-thrust ΔV, but in several flybys (specifically Venus-2, Mercury-1 and Mercury-2) a B-plane crossing variation that leads to a lower closest approach distance to the planet also decreases the overall ΔV budget for the reference trajectory.

The freedom to insert deterministic chemical manoeuvers for the re-optimization is always given to the software: for every flyby of the April 2018 BepiColombo trajectory the optimizer however discards the possibility to use chemical instantaneous manoeuvers because chemical manoeuvres have a much higher fuel consumption than an adaptation of the low-thrust profile.

The dispersion ellipses obtained at each flyby B-plane are reported in Table 3. The semi-major axis angle refers to the angle between the so called T vector (cross product of the planet South pole direction and the incoming infinite velocity vector) and the dispersion ellipse semi-major axis direction. As it can be seen in the table, dispersion ellipses are often in the range of 50x20 km or below. The only exception is the very first flyby which has a dispersion higher than the average: thanks to the long time available before the following flyby and the not so strong sensitivity to the flyby variation (as can be seen in Figure 6) this larger dispersion is not considered critical and can be dealt easily by re-optimizing the reference trajectory. A low sensitivity to the geometrical swing-by conditions is also present in the Mercury-4 case: in this particular case the effect can be attributed to the higher flyby altitude of 1649 km at closest approach.

Table 3. Dispersion ellipses at B-plane.

Flyby	Semi-major axis, 3σ [km]	Semi-minor axis, 3σ [km]	Semi-major axis angle [°]
Venus-1	77.035	30.791	36.398
Venus-2	17.565	8.857	58.322
Mercury-1	41.923	5.274	-84.073
Mercury-2	55.953	17.256	-57.994
Mercury-3	21.434	10.769	-88.654
Mercury-4	32.392	6.105	-0.590

3.4. Total navigation cost

An overview of the overall study results can be seen in Table 4, where the total ΔV budget for the navigation of the April 2018 BepiColombo trajectory is reported.

Table 4. Total navigation cost, 3σ confidence.

Phase	Low-thrust Guidance [m/s]	Chemical TCMs [m/s]	Re-optimization / clean-up cost [m/s]	
			Elec.	Chem.
Dep.-V1	13.726	26.782	-	-
V1-flyby	-	-	< 15	0
V1-V2	6.638	5.504	-	-
V2-flyby	-	-	< 15	0
V2-M1	5.931	4.125	-	-
M1-flyby	-	-	< 15	0
M1-M2	15.109	8.882	-	-
M2-flyby	-	-	< 15	0
M2-M3	17.020	3.635	-	-
M3-flyby	-	-	0	9.557
M3-M4	0	0.474	-	-
M4-flyby	-	-	< 15	0
M4-Arr.	24.597	0	-	-
TOTAL	83.021	49.402	<75	9.557

It can be seen from Table 4 that the major term affecting the chemical navigation manoeuvers is dominated by the launcher dispersion correction (which is 9 m/s by itself) and the guidance for the first interplanetary phase (total of more than 26 m/s), which is affected by the criticalities already analysed.

Another critical part of the BepiColombo navigation is the interplanetary phase following the third Mercury flyby. The short duration of this phase (37 days between the two flybys) is preventing completely the use of low-thrust to re-optimize the trajectory before the following flyby: for this reason it is chosen as baseline to decrease the dispersion accumulated after the Mercury-3 flyby with an actual chemical clean-up manoeuver.

The total 3σ confidence cost for the navigation, split in low-thrust and chemical terms is:

- 158 m/s for the low-thrust guidance
- 59 m/s for chemical TCMs

Both results are within the acceptable ΔV range allocated for the mission, but the chemical part is far more critical because it is close to the pre-allocated value if all losses (geometric efficiency, uncertainty in residual fuel, uncertainty in specific impulse, etc.) are taken into account.

4. CONCLUSIONS

The methodology and software used for the BepiColombo navigation analysis as described in detail in this paper is considered reliable and coherent for the analysis purposes.
The major problems concerning a realistic simulation were highlighted and the obtained results and strategy alternatives were discussed. The final results, obtained with the selected guidance strategy and measurements schedule, confirm that the available navigation fuel budget is adequate. The most critical phases in terms of navigation are the trajectory part from launch up to the first Venus flyby and the part between the third and fourth Mercury flyby, but no major problem for the mission was discovered.

5. REFERENCES

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