Operational Navigation Concepts for Low-Thrust Missions

LIONS

Executive Summary

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1. INTRODUCTION

1.1. Purpose and Scope

The purpose of the document is the presentation of a brief summary of the work done during the study '*Operational Navigation Concepts for Low-Thrust Missions'* (LIONS).

This ***Operational Navigation Concepts for Low-Thrust Missions*** study has addressed operational aspects of the low-thrust missions that were not formerly analysed in the frame of mission analysis tools. Some of those operational considerations are:

- Constraints on the use of the low-thrust system and convenience of substituting manoeuvres by chemical burns
- Constrains on thrust direction
- Additional ground segment induced constraints impacting the mission design (introduction of patterns of thrust-coast arcs, as done for Deep Space 1)
- Combination of different types of measurements at different moments in the trajectory
- Implementation of trajectory re-optimisation and linear feedback for guidance/control
- Consideration of system failure modes affecting the trajectory design and the recovery options

1.2. Organisation of the Document

Contents of this document have been structured in the following major sections:

- Chapter 1 is this Introduction
- Chapter 2 is a brief summary of navigation concepts
- Chapter 3 reports the contingency analysis done for BepiColombo trajectory
- Chapter 4 summarises the Navigation and Guidance analysis of BepiColombo trajectory. This analysis has been done with Lotnav Simulation Utility (MonteCarlo)
- Chapter 5 provides similar analysis for the case of the Dawn trajectory
- Chapter 6 reports the navigation and guidance analysis of the BepiColombo trajectory based on Re-optimisation process.
- Chapter 4 provides a summary of the reported information

1.3. Acronyms and Abbreviations

The acronyms and abbreviations used in this document are the following ones:

Table 1: Table of Acronyms and Abbreviations

Acronym	Meaning
AD	Applicable Document
BVP	Boundary Value Problem
CCN	Contract Change Notice
DITAN	Direct Interplanetary Trajectory Analysis
DDOR	Delta Differential One-way Range
DOR	Differential One-way Range
EP	Electric Propulsion
ECRV	Exponentially Correlated Random Noise
ESA	European Space Agency
ESOC	European Space Operations Centre
ESTEC	European Space Technology and Research Centre
FB	Fly-by
GAM	Gravity Assist Manoeuvre
LOTNAV	Low Thrust Navigation Tool
LT	Low Thrust
MOI	Mercury Orbit Insertion
OD	Orbit Determination
RBVB	Refined Boundary Value Problem
SAA	Solar Aspect Angle
SEP	Solar Electric Propulsion
SoW	Statement of Work
SRP	Solar Radiation Pressure
S/W	Software
S/C	Spacecraft
SOI	Sphere of Influence
SRP	Solar Radiation Pressure
TBC	To Be Confirmed
TBD	To Be Defined
TBW	To Be Written
TCM	Trajectory Correction Manoeuvre
WP	Work Package
w.r.t.	with respect to

1.4. Related Documents

Table 2: Applicable Documents

Ref.	Code	Title	Issue	Date
[AD.1]	AO 1-5221/07/F/VS -LI	Invitation to Tender AO 1-5221/07/F/VS “Operational Navigation Concepts for Low-Thrust Missions” – Letter of Invitation	-	05/03/07
[AD.2]	AO 1-5221/07/F/VS-WS	Invitation to Tender AO 1-5221/07/F/VS “Operational Navigation Concepts for Low-Thrust Missions” – Statement of Work	-	05/03/07
[AD.3]	AO 1-5221/07/F/VS-CC	Invitation to Tender AO 1-5221/07/F/VS “Operational Navigation Concepts for Low-Thrust Missions” – Draft Contract	-	05/03/07
[AD.4]	AO 1-5221/07/F/VS-TC	Invitation to Tender AO 1-5221/07/F/VS “Operational Navigation Concepts for Low-Thrust Missions” – Special Conditions of Tender	-	05/03/07
[AD.5]	LIONS-DMS-COM-PRL01-R	Proposal for Operational Navigation Concepts for Low-Thrust Missions, in response to ESA ITT AO 1-5221/07/F/VS.	1.0	13/04/07
[AD.6]	LIONS-DMS-PMD-MOM01	Minutes of the Negotiation & Kick-off Meeting	1.0	03/07/07
[AD.7]		Contract Change Notice To Contract 20735/07/F/VS “Operational Navigation Concepts for Low-Thrust Missions”		18/06/08

Table 3: Reference Documents

Ref.	Reference Documents	Date
[RD.1]	Technical Note on Operational Navigation Concepts for Low-Thrust Missions, ESA/ESOC (provided at Kick Off Meeting)	June 2007
[RD.2]	Cano J.L., Bello M., Software tool for low-thrust navigation in interplanetary space (LOTNAV tool), Final Report of ESA/ESOC study contract 16650	Nov 2004
[RD.3]	Bernelli F., Vasile M., Fornasari N., Masarati P., Design of Interplanetary and Lunar Missions Combining Low Thrust with Gravity Assists, Final Report of ESA/ESOC study contract 14126	Sept 2002
[RD.4]	BepiColombo Mercury Cornerstone Consolidated Report on Mission Analysis, MAO Working Paper No. 525BC-ESC-RP-05500, Issue 3.1	08/10/2009
[RD.5]	Sánchez-Ortiz, N., Cano-González, J.L. *LIONS Technical Note 1: Analysis of Navigation Concepts,* LIONS-DMS-TEC-TNO01, v1.1	03/12/2007
[RD.6]	Sánchez-Ortiz, N., Cano-González, J.L., *LIONS Technical Note 2: Redefinition of the Low-thrust Trajectories*, LIONS-DMS-TEC-TNO02	27/02/2008
[RD.7]	R.H. Battin, *An introduction to the Mathematics and Methods of Astrodynamics*, Revised Edition, AIAA Education Series,	1999
[RD.8]	M.Belló-Mora, M. Baeza-Martín; *Software tool for Interplanetary Navigation (INTNAV) Final Repor*t, ESA contract Nº. 9715/91/D/IM	22/12/1993
[RD.9]	R. Maddè, T. Morley, ESA Delta DOR: from implementation to operation	16/03/2007

Ref.	Reference Documents	Date
[RD.10]	Yevdochenko, S., Feasibility mission analysis, Trajectory & Performance study, EXOMARS mission On A5-ECA, v1.0, A5-NT–1–H–018–AE	18/01/2007
[RD.11]	Sánchez, N., Cano, J.L., Martín, L., Belló, M.; Final Report of UMAST Project: Upgrade of Mission Analysis Software Tools to study Low-Thrust Planetary Exploration Missions, v0.1	23/11/07
[RD.12]	Sánchez, N., Cano, J.L., BepiColombo Navigation Analysis, LIONS-DMS-TEC-TNO05, v1.1	20/01/2010
[RD.13]	Sánchez, N., Cano, J.L.,, BepiColombo Navigation Analysis, LIONS-DMS-TEC-TNO06, v1.0	02/07/2010
[RD.14]	Sánchez, N., Cano, J.L.,, BepiColombo Navigation Analysis (Option with 5 Mercury Flybys), LIONS-DMS-TEC-TNO07, v1.1	13/10/2010
[RD.15]	CReMA (BC-ESC-RP-05500-03-01) signed.pdf	

2. ANALYSIS OF NAVIGATION CONCEPTS

This section provides a review of the past and planned low-thrust missions and possible navigation concepts for low-thrust trajectories.

So far three interplanetary missions have been flown in interplanetary space:

- ESA's **SMART-1** to the Moon, departing from a GTO
- NASA's **Deep Space 1**, in direct escape towards successive flybys of asteroid Braille and comet Borrelly
- JAXA's **Hayabusa**, in direct escape towards a first Earth swingby and then towards asteroid Itokawa, with which it rendezvoused and performed close operations before returning to Earth
- NASA's **Dawn** mission to Vesta and Ceres

The following navigation approach was followed in each of those missions to achieve the mission goals:

Table 4: Summary of flown missions

Feature	Mission			
	Dawn	DS1	SMART1	Hayabusa
Trajectory Type	Interplanetary (asteroid and comet flyby)	Interplanetary (asteroid and comet flyby)	Earth-Moon	Interplanetary (asteroid orbiting, touch down and back to Earth)
Mission Timeline	Sept- 2007 – July 2015	Oct 98 – Dec 01	Sept 03 – Aug 06	May 03 – June 10
Type of electric Propulsion System	Xenon Ion Propulsion System	**Xenon Ion Propulsion System**	Xenon Stationary Plasma Hall-effect (PPS-1350)	Xenon Ion Propulsion System
	90 mN	92 mN	70 mN	20 mN x 4 thrusters
Navigation Scheme	-	Autonomous Navigation with onboard camera + traditional radiotracking	Non-autonomous Radiotracking	Autonomous Navigation in proximity operations
Control Law	-	Linear feedback with MLS on thrust arcs with coast arcs for control	Full trajectory re-optimisation	-

It is known that for ballistic trajectories the design approach and the design of the control method (typically based on the use of TCMs) are performed independently. The navigation delta-V budget is inherently independent of the trajectory design delta-V budget. **In low-thrust however, trajectory**

design and navigation are coupled due to the need of using the same means for both goals (although some chemical TCMs can be also devised for navigation). In that sense, the thrust law is steered to meet the design and the control, but margins in thrust are require to accommodate the control needs (as it is well known, modulation of the thrust angles alone is not enough to achieve efficient trajectory control). In summary, the problem of low-thrust navigation is that the margins are coupled with the design.

If the design optimisation of the low-thrust trajectory is properly done, the optimum solution has no margin for navigation corrections needed to correct injection errors, dynamic errors, swingby errors, etc. Therefore, the incorporation of margins at mission design level is needed. Those margins can be:

- Margin in thrust level to accommodate "guidance" modifications, as already performed in current BepiColombo studies, with a design at 90% level of the nominal thrust for most of the trajectory.
- Margin posed by the coast segments already present at mission design in the trajectory, and some introduced to allow further corrections (e.g. in areas of long thrusting)
- Margin by introducing small coast arcs within the thrust periods, to account for guidance by modifying the thrust angles and the durations of the coast arcs. This was in fact the approach used on NASA’s Deep Space 1

Operationally speaking, the two last options are the recommended solutions to allow always thrusting at maximum level (in the first case the margin is imposed on the thrust modulus).

In addition to the previous, a method has to be employed to perform the control using such coast arc margins. Two options appear as promising: **re-optimisation** and linear variations to the existing thrust laws **-linear feedback-** (for example using a LQC over the design guidance profile or minimum least squares).

The re-optimisation technique was successfully implemented in ESA’s SMART-1 case, where regular updates of the control where computed and uploaded to the spacecraft for operations. In the case of Deep Space 1, the option used was that of introducing regular coast arcs in each of the large thrust segments with a given pattern to allow performing a linear feedback based on a minimum least squares solver. The option of using a LQC to solve for the linear feedback was already used in LOTNAV but based on changes over the thrust angles and the thrust modulus, option that is not optimal in operational practice. However LQC can be also used to solve the guidance problem with the discretised version of the trajectory with regular coast arcs.

The main problem associated to low-thrust in Obit Determination (OD) is related to the **performances of the engine**, which might be quite irregular along time. The experience in SMART-1 mission has shown how such variability can be quite high and the need to ascertain the thrust excursions as much as possible by estimation and use of telemetry data. It is therefore necessary to put special attention to the inclusion in the estimation process of the thrust parameters to enable appropriate performances of the OD process.

In summary, we have already seen that the problem of low-thrust navigation is that the margins are coupled with the design. Initially, those margins have to be estimated to be incorporated in the mission design. Then, simulations must be performed to check the trajectory robustness in an iterative way, while with chemical propulsion this is performed independently and in a straightforward way.

A proposed generic approach to the definition of the optimal concept for navigation applied to a space mission is provided in Figure 1 where such an iterative scheme is represented. This is analysed in the following:

- Firstly, an analysis of the initial available trajectory "as is" is needed to investigate which operational constraints will be required to introduce. In that sense it is already important to distinguish between two cases: **trajectories with regular coast arcs** (as for SMART-1) and **trajectories with sparse coast arcs** (as DS1 originally or as BepiColombo). The way to follow in each case is different.
- In case of a trajectory with frequent coast arcs, it will be possible to use the margins in time represented by them to accommodate control changes in the trajectory profile. It would then be required to introduce any operational constraint directly in the profile (e.g. thrust solar aspect angle constraints, etc. in case they were not already considered in the design) and re-optimise. The result is a new trajectory having taken consideration of the operational constraint in the trajectory profile.
- In case of a trajectory with infrequent or sparse coast arcs, two ways can be followed:
  - Introduce sparse coast arcs in areas of long thrusting to give margins for guidance/control and re-optimise also counting on other operational constraints
  - Introduce regular small coast arcs in the thrust phases (as for DS1) to give margins and re-optimise also counting on other operational constraints

  In both cases the result is a new trajectory profile considering the operational constraints in the trajectory design.
- Once the trajectory is re-defined, the navigation analysis can be performed. In all the cases any of three possible options solutions can be employed, with different levels of applicability:
  - Navigation with re-optimisation
  - Navigation with linear feedback and linear quadratic control
  - Navigation with linear feedback and minimum least squares
- Having performed the navigation analysis over the proposed trajectory profile some other profiles and options can be analysed in order to perform robustness comparisons between the different possible solutions and iteratively find an optimum navigation solution for the low-thrust mission.

The proposed approach is believed to represent a thorough representation of the needed actions to achieve a complete perspective of the solutions for navigating a low-thrust mission and the performances of each of them for ulterior selection of the best option.

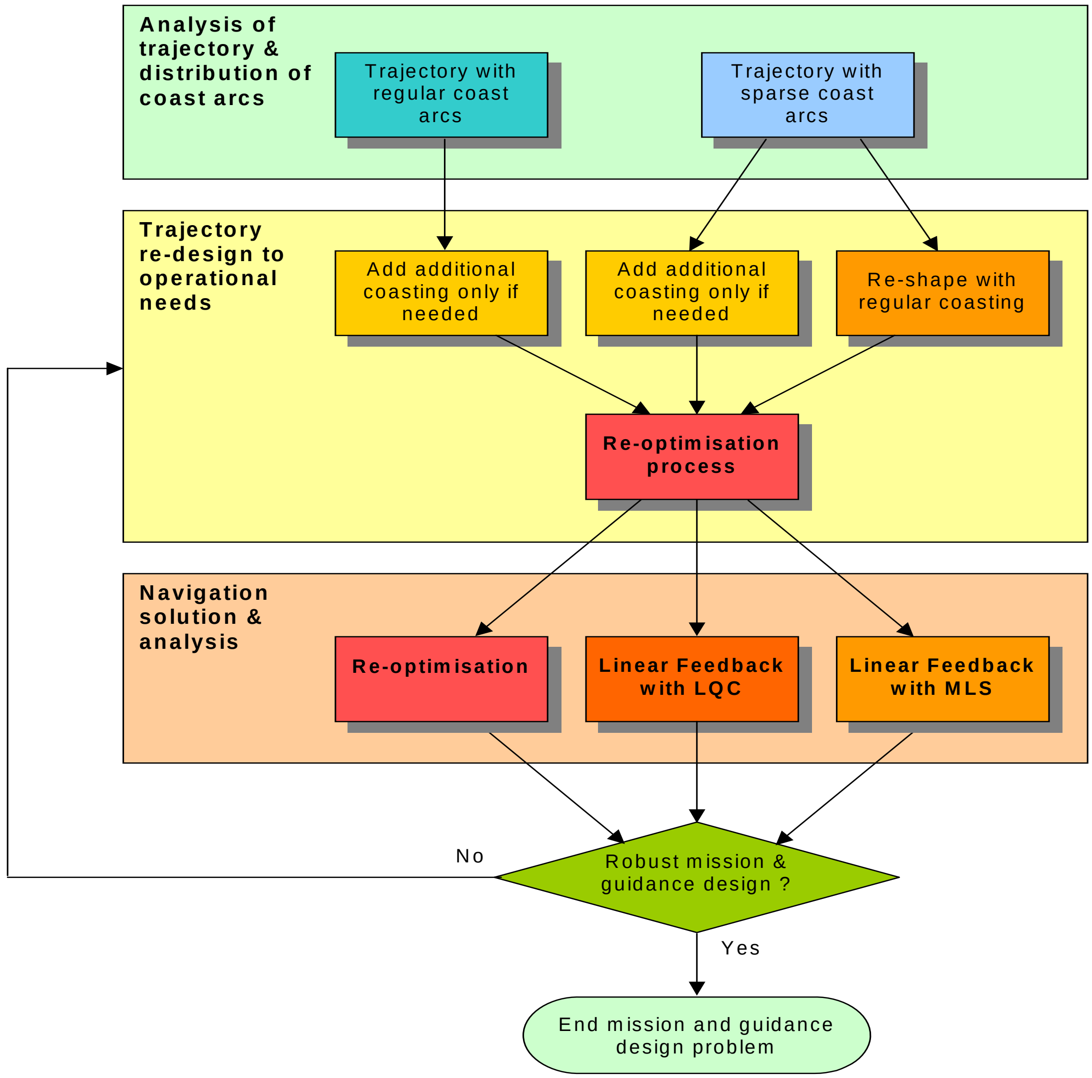

Figure 1: Approach to the design of optimal navigation concept for a mission

After a given low-thrust mission basic design a need for robustness assessment at mission level is identified. Such assessment shall imply a number of changes in the mission design compatible with some requirements on thrust-missed and thrust underperformance. The resulting mission design will then be different from the basic design. Such design will then be the subject of the analysis of robustness in operations and navigation.

Once the trajectory is defined accordingly to some margins policy (with operational constraints - regarding the duty cycle- or without them) it is evaluated in terms of miss-thrust or thrust underperformance. If such an analysis results in a non-robust mission, some modifications of the trajectory (non-optimum coast arcs, swing-bys) or relaxation of some constraints (coast arcs before fly-bys for navigation purposes) can be undertaken. With this new definition of the trajectory, the analysis can be repeated. Is this is not enough to obtain a robust mission, then the mission should be relaxed in terms of targets modification or system margins diminution. This process is shown in Figure 2.

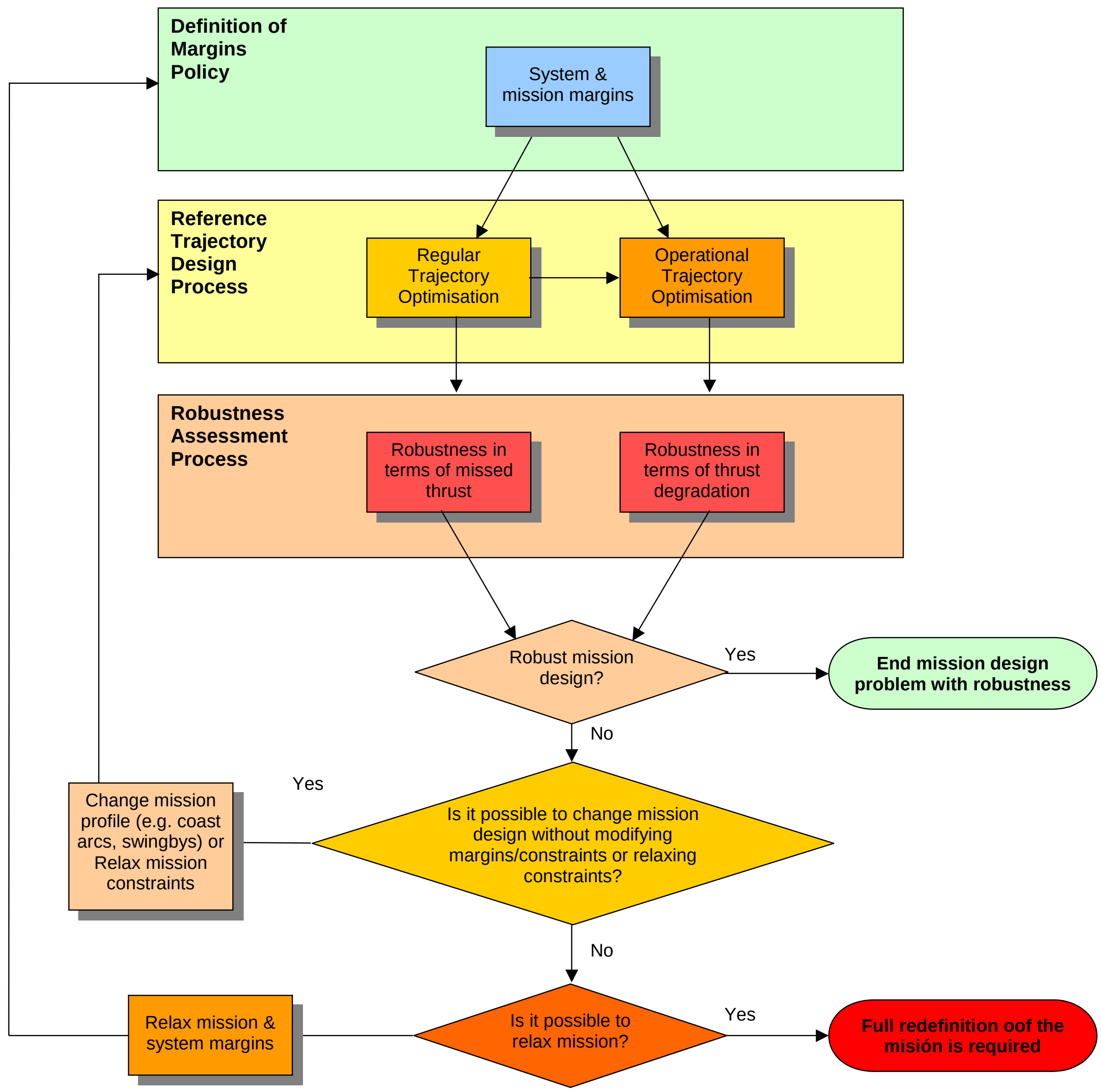

Figure 2: Approach to the mission robustness design

3. CONTINGENCY ANAYSIS OF BEPICOLOMBO TRAJECTORY

The purpose of this section is the presentation of the work done regarding the analysis of contingency casesof a BepiColombo trajectory. Three different types of failures are simulated, both of them are thrust outages at the end of the thrust arc (14 and 28 days respectively) and the third one is a thrust underperformance of a 10% lasting all the arc.

The analysis is intended to assess which type of thrust arc pattern allows a better recovery from failures. Two studied patterns are studied, the first one with equidistant coast arcs distributed along the thrust arcs and the second one locating all the coast buffer at the end of the thrust arc.

3.1. BepiColombo Trajectory

The trajectory analysed in this section of the document is that corresponding to the following details:

- Launch will take place in July 2014 with an excess velocity of 3.8 km/s.
- In Aug 2015 there will be an Earth flyby to deflect the spacecraft towards Venus.
- The two Venus flybys will take place in January and August 2016 followed by 4 Mercury flybys.
- Final approach at Mercury through the weak-stability region will take place in May 2020.
- An initial spacecraft mass of 3700 kg will be assumed, a specific impulse of 4500 s, and a thrust law as specified in Mission Analysis working paper 525.
- The constraints on solar aspect angles (SSA) are:
    - SSA > 66.3° if distance to the Sun > 0.7 AU and
    - 66.3° < SAA < 99° if distance to the Sun < 0.7 AU

A continuous trajectory must be obtained for further contingency and navigation analysis. The first guess for such a continuous solution is obtained with DITAN. The DITAN trajectory is obtained for a 90% of available thrust, accounting for the rest 10% for navigation and contingency budget (5% for each of those issues).

3.2. Assumptions for Contingency Analysis

The contingency analysis of the Bepi Colombo trajectory is intended for the assessment of the best way to locate coast arcs within a thrust arcs. These coast arcs are used as buffer for the case of contingencies.

The contingency analysis here presented is performed by means of several modules of the LOTNAV tool:

- **Trajectory Reconstruction Utility (TRU)**: This module computes the best continuous solution ffitting the user defined boundaries. BVP solver is used for the optimisation of the different trajectory cases. Since the RBVP optimisation requires larger execution times. The TRU is used in several cases:
  - For the generation of the trajectory resembling the DITAN solution (95% of thrust level for continuous thrust arcs)
  - For the optimisation of the trajectory once the patterns are applied by means of the Trajectory Transcription Utility.
    - Thrust level is set at a 95% (the pending 5% is devoted for navigation activities)
    - 5% of the thrusting time is reserved for buffer coast arcs.
  - For the optimisation of the trajectories with simulated failure.
- **Trajectory Transcription Utility (TTU)**: This tool takes a 'continuous-thrust' solution from the TRU and create the appropriate initial guesses of `patterned-thrust' trajectory for further optimisation. The applied patterns during these study are the following:
  - P1: Equidistant coast arcs of equal duration are inserted into a continuous thrust arc
  - P2: All the coast buffer is kept at the end of the nominal thrust arc

  The generation of the patterned-trajectory allows assessing the impact of the two patterns when compared with the initial continuous trajectory. Additionally, these trajectories represent somehow operational conditions (thus the thrust level shall be equal for all thrust arcs). Some thrust arcs are not analysed for contingency, but the thrust level is set up to 95% and thus, the thrusting time has to be reduced by a 5% for consistency with the original continuous thrust trajectory. Those arcs that will not be analysed for contingency apply the 5% of forced coasting time with pattern P1. (Several other options are attempted but without success in the optimisation process)
- **Contingency Analysis Utility (CAU)**: This module takes a former optimised trajectory and applies different failures, creating the initial guess for further optimisation of the recovery trajectory. The Failures applied for this contingency analysis are the following:
  - F1: Thrust outage to occur 14 days before the end of thrust arc and lasting till the end of the arc
  - F2: Thrust outage to occur 28 days before the end of thrust arc and lasting till the end of the arc
  - F3: Thrust underperformance of a 10%.

  For F1 and F2, failures are applied at the end of the thrust arcs, since this event is the most difficult case to recover, whereas for F3, the failure occurs at the beginning of the failure arc. The failure time will be different for the two patterned trajectories, since the nominal end of the thrust arc is different for every obtained trajectory. For the case of pattern 2, the failure occurs right at the end of the thrust arc and then before the coasting buffer. On the contrary, for pattern 1, the failure also occurs at the end of thrusting period, and the thrust outage time can include coasting buffer arcs (see Figure 5).

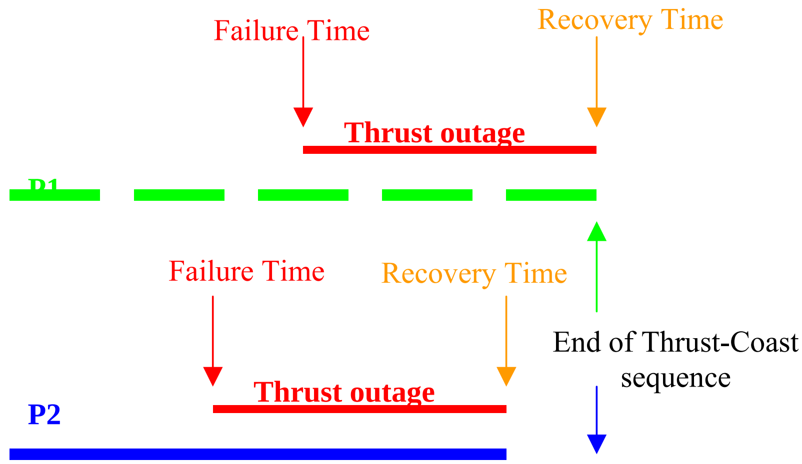

Figure 3: Scheme of Failure and Recovery Time for Thrust Outage

After failure, re-optimisation is computed with full and continuous thrust (accounting for the navigation margin) up to the swing-by following the contingency event (the contingency margin is kept after that fly-by until the end of the optimised trajectory).

Once the failure is applied, the trajectories are re-optimised and the obtained solutions are analysed in order to assess the penalty in mass and the following flyby features. In case of severe contingencies, where optimisation process does not provide appropriate results, the constraints of 30-days coast arcs before every fly-by can be relaxed down to 10 days.

This process is shown in Figure 4, with indication of the modules to be used, and the input and output trajectory cases for every module.

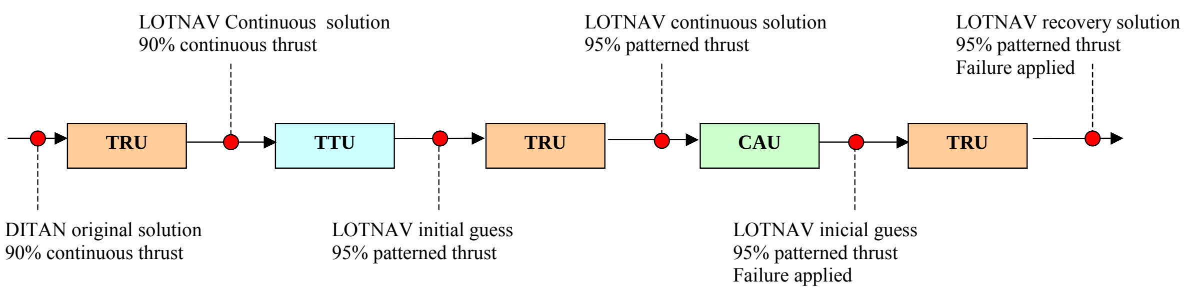

Figure 4: LOTNAV modules used during the analysis of every contingency case

Due to the large number of arcs in the complete trajectory, especially when the pattern 1 (equidistant coast arcs) is applied, the complete BVP trajectory is split in two parts. Phase A contains the arcs from Earth departure up to Mercury GAM2, whereas phase B contains the trajectory from Mercury GAM1 up to Mercury Arrival. It can be seen that Mercury GAM 1-Mercury GAM2 is included in the two phases. Thus, once failure is applied in Phase A, the following re-optimisation process is performed up to Mercury GAM2, whereas, when failure is applied in Phase B, the re-optimisation process is executed up to Mercury Arrival.

As it will be explained in section 3.3, only the thrust arc right before the Mercury GAM1 is analysed for contingency in Phase A of the trajectory. In this case, the re-optimisation process is executed with continuous thrust without keeping coasting buffer up to the Mercury GAM1, and keeping this buffer in the segment between the two first Mercury swing-byes.

For the case of Phase B, several arcs are analysed for contingency, all of them within the segment from Mercury GAM2 up to Mercury GAM3 (see section 3.4.1 for further explanations of the arcs to be analysed). Once the failure is applied in these arcs, the further re-optimisation process is executed so that the thrust is continuous up to the following swing-by (Mercury GAM3) but the pattern is applied within the segment between Mercury GAM4 and Mercury arrival.

3.3. Contingency Analysis for Phase between Earth and Mercury GAM1 (Phase A)

As it has been said, the trajectory is split in two parts for the contingency analysis. These two parts are converged with LOTNAV TRU in order to obtain the best continuous solution for further analysis. Since the events and arcs of the two generated phases are slightly different to those coming from the continuous trajectory, the obtained solution is here presented.

3.3.1. Comparison of continuous thrust trajectory and patterned cases

Once obtained a continuous thrust trajectory for the Phase A, the two trajectories with appropriate pattern (P1 and P2) in arc 13 are applied. The rest of thrust arcs are split with pattern 1, so that the thrust level of the complete phase is set to 95% of the available thrust, and the time and thrust conditions are compatible with those from the initial trajectory.

Following figures provide the evolution of mass, thrust module and thrust angles for the three trajectories. It can be observed in Figure 5 the small impact in mass at the end of this phase of locating the 5% of coasting time well distributed along or at the end of the thrust arc. The mass at Mercury GAM2 for the continuous thrust trajectory is **3632.7 kg**, whereas the obtained values for the mass at that event are **3631.1 Kg** and **3630.2 kg** for the trajectories with pattern 1 and 2 respectively (see Figure 6). It has to be recalled that the pattern 2 (which impose a larger penalty) is only applied to the arc number 13 (numbering of the continuous trajectory) and not for all the thrust arcs.

Figure 7 shows clearly the two different levels of thrust in these simulated cases. For the case of the continuous thrust trajectory, the thrust level is set up at the 90% of the available thrust whereas for the other two cases, it is set up at 95%.

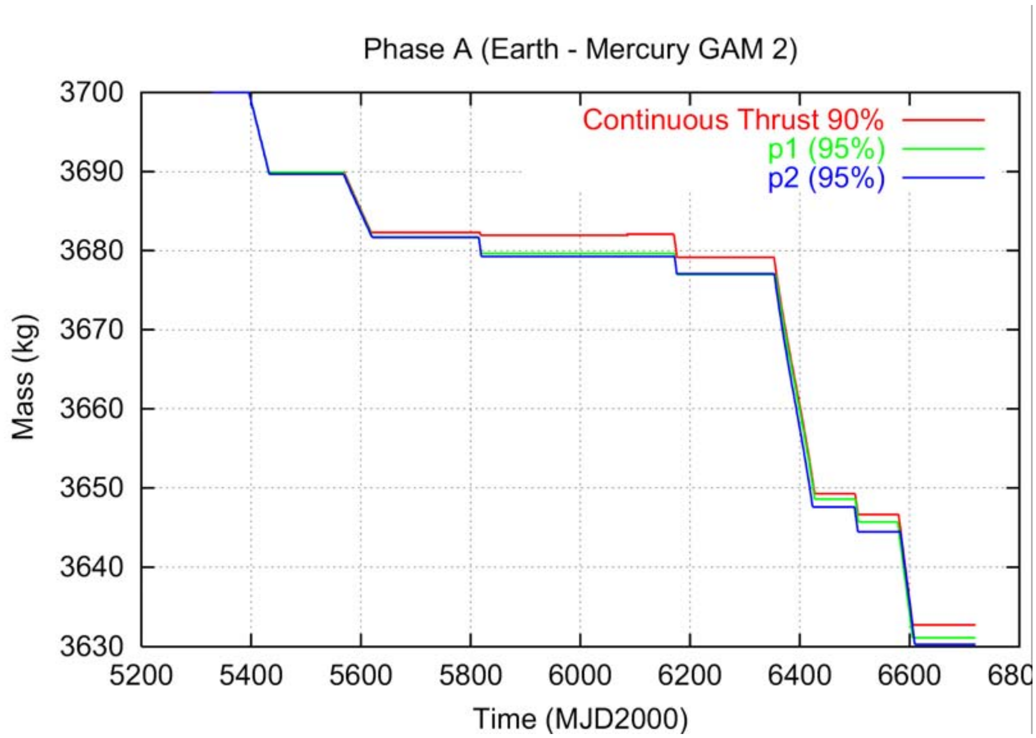

Figure 5: BepiColombo Phase A Mass evolution for continuous thrust trajectory and patterned thrust trajectories

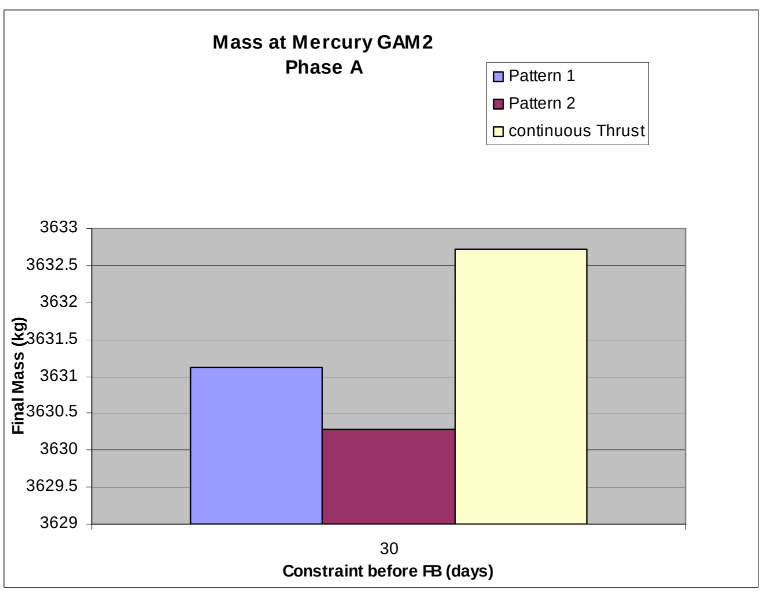

Figure 6: BepiColombo Phase A Mass at Mercury GAM2 for continuous thrust trajectory and patterned thrust trajectories

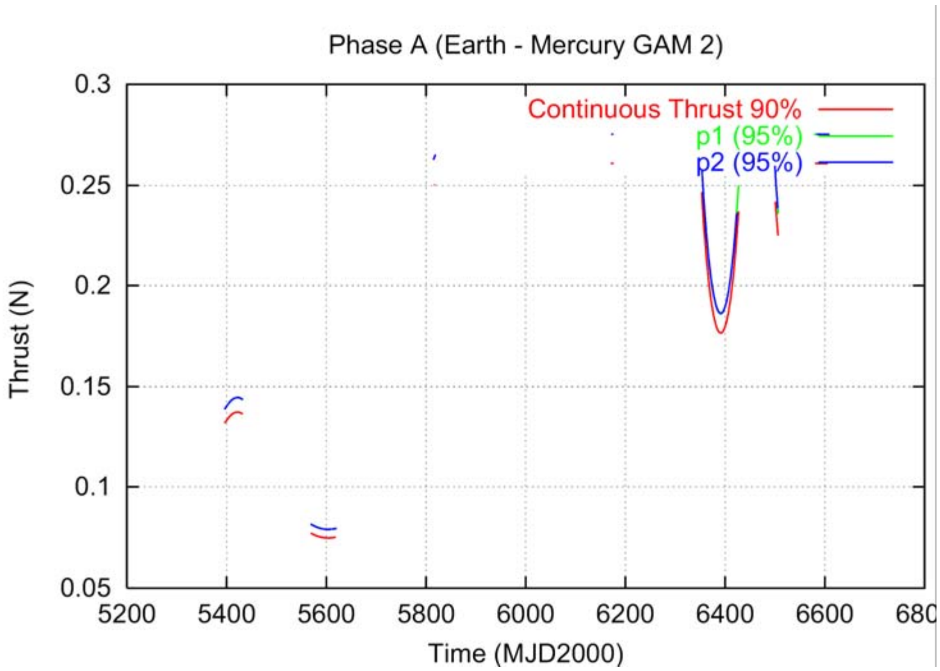

Figure 7: BepiColombo Phase A Thrust modulus evolution for continuous thrust trajectory and patterned thrust trajectories

3.3.2. Contingency Analysis of Arc A13

3.3.2.1. Thrust outage to occur 14 days before the end of thrust arc and lasting till the end of the arc (F1)

3.3.2.1.1. Equidistant Coast Arcs

The optimisation of the resulting trajectory after the simulation of a thrust outage of 14 days at the end of the thrust arc number 13 imposes the relaxation of the constraint of 30 days of coast arc before Mercury GAM1. As it has been said, arc 13 is followed by a forced 30 days coast arc; then, a thrust outage of 14 days to occur during the last 14 days of this arc imposes the start of the recovery of thrust capabilities just 30 days before the fly-by. For pattern 1, in case the constraint cannot be relaxed, no time for thrusting is available and the optimisation of the resulting trajectory is not possible (the TRU does not provide a continuous trajectory fulfilling the imposed boundaries).

As a consequence of this fact, the mentioned constraint is relaxed down to 10 days. No convergence is achieved for the cases of forced coast arc of 30, 25, 20 and even 15 days. The difficulties in the optimisation process are larger for those cases with larger constraint. Discontinuity for case of 30 days are obvious, whereas for the case of 15 days constraint, the mass evolution seems to be almost continuous; in this last case, the residuals from the optimisation process are large, and the solution is not converged.

When the forced coast arc is reduced down to 10 days, the constraint is not imposed; the TRU provides a coast arc before the flyby lasting about 12 days (the same solution is obtained when this value is used for such a constraint). The mass penalty for this case when compared to the nominal P1 case is 3.1 kg. The mass penalty for the case of reducing the constraint down to 13 days is 3.8 kg.

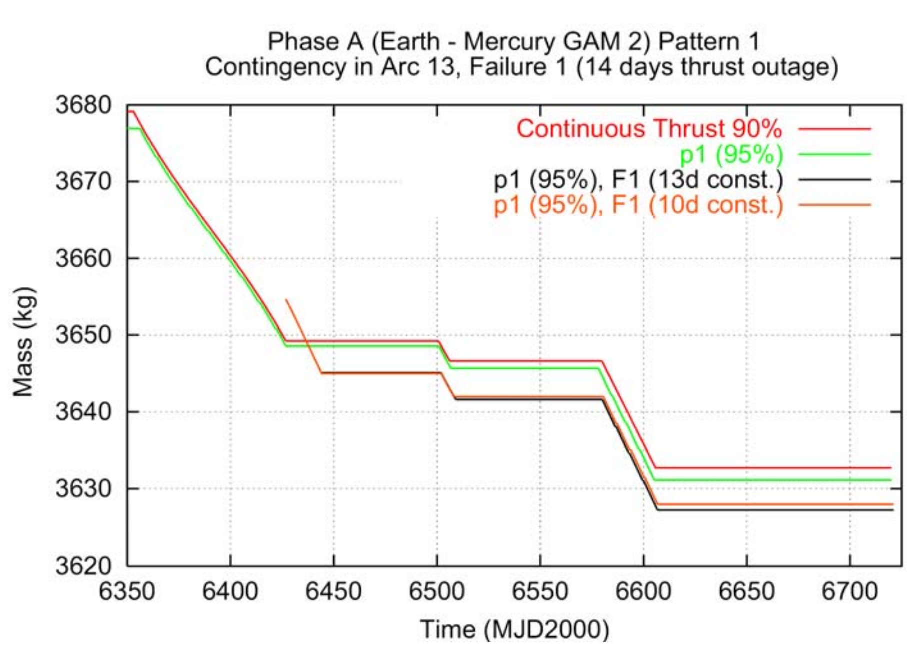

Figure 8: BepiColombo Phase A Mass evolution after 14 days of thrust outage in Arc 13 with Pattern

3.3.2.1.2. Coast Buffer at the End of the Thrust Arc

For pattern 2, in case the constraint cannot be relaxed, the buffer of 3.75 coasting days kept at the end of thrust arcs is available for thrusting and the optimisation of the resulting trajectory has larger margin than the case of pattern 1. In spite of that, the TRU does not provide a continuous trajectory fulfilling the imposed boundaries.

Similarly to the case of pattern 1, the mentioned constraint is relaxed down to 10 days. No convergence is achieved for the cases of forced coast arc of 30, and 25 days. The difficulties in the optimisation process are larger for the case with larger constraint.

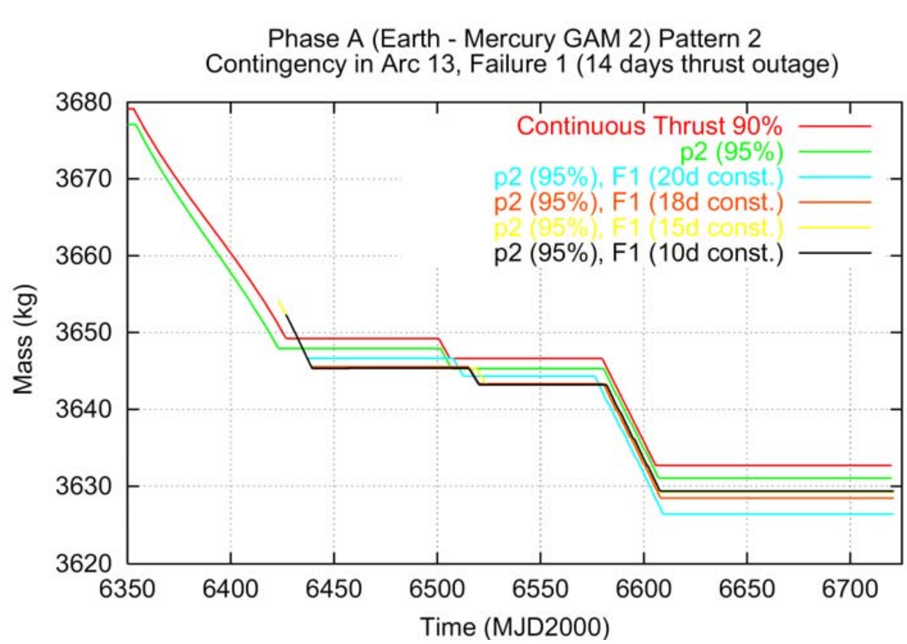

Figure 9: BepiColombo Phase A Mass evolution after 14 days of thrust outage in Arc 13 with Pattern 2

3.3.2.1.3. Summary

Pattern 2, and due to the buffer of coast arc at the end of the thrusting period, provides better capabilities for the recovery of the simulated failure of thrust outage lasting 14 days. For pattern 1, the constraint in the forced coast arc before Mercury GAM1 has to be reduced down to 13 days, whereas for the case of pattern 2 appropriate solutions are achieved for a forced coast arc of 20 days, with a reduced penalty when reducing such a constraint down to 17 days.

The unique cases where the behaviour of pattern 1 and 2 against contingency can be compared are those of the constraint reduced down to 10 and 13 days (since the rest of cases for Pattern 1 have large residuals and thus, no continuous trajectories are obtained after optimisation). For such cases, the solution with pattern 2 provides a mass at Mercury GAM2 larger than that for pattern 1 by 2.1 kg (coast of 10 days) and 2.9 kg (coast of 13 days).

The design of the trajectory with pattern 2 only penalises the final mass by 20 gr, and is much more robust for this kind of failure. In case of this kind of failure, the use of pattern 2 in this arc allows to have mass at Mercury GAM2 of about 3628.45 kg with a forced coast arc of 18 days before the flyby; whereas the use of pattern 1 implies a reduction of that coast arc down to 10 days in order to have a similar mass at that swing-by (3627.9 kg).

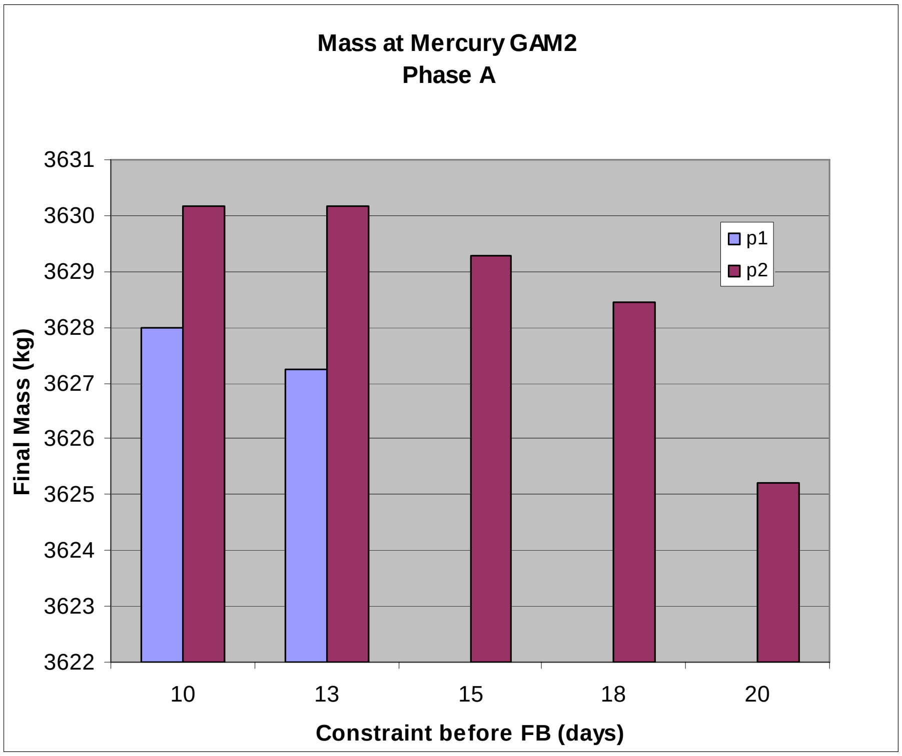

Figure 10: BepiColombo Phase A Mass at Mercury GAM2 after 14 days of thrust outage in Arc 13

3.3.2.2. Thrust outage to occur 28 days before the end of thrust arc and lasting till the end of the arc (F2)

3.3.2.2.1. Equidistant Coast Arcs

The optimisation of the trajectory resulting from the application of a 28 days- thrust outage to occur at the end of the arc 13 does not provide appropriate results (for the pattern with equidistant coast arcs). Trajectories from the LOTNAV TRU are not converged even for the case of relaxing the constraint of forced coast arc down to 10 days before the first Mercury flyby. In the extreme case (constraint of 10 days), the pending 20 days for thrusting do not allow to recover the missing 28 days of simulated outage.

3.3.2.2.2. Coast Buffer at the End of the Thrust Arc

Arc designed with pattern 2 presents a better behaviour for this kind of failure than pattern 1. Anyhow, this contingency is very severe, since the outage period is almost as large as the remaining coasting arc before the flyby and only the more relaxed trajectory provides a continuous solution (see Figure 11). As pattern 2 keeps a buffer of 3.75 days after the thrusting period (in addition to the 30 forced coast arc for navigation prior to the swing-by), the recovery from failure can make use of this buffer, together with the time from the relaxation of the constraint.

With such circumstances, a continuous trajectory can be achieved by optimisation of the case with a relaxed constraint down to 10 days. In this case, the available thrusting period (to recover from the 28 days outage) is 24.2 days (20 days coming from the relaxation of the constraint, 3.75 days from the buffer and additional 0.45 days due to the delay of Mercury flyby). Thus the trajectory can be recovered after the simulated contingency, but the penalty in mass is very large and grows up to 10.9 kg (final mass at GAM2 of 3619.3 kg.). For smaller reductions of the coast constraint, the trajectory cannot be recovered.

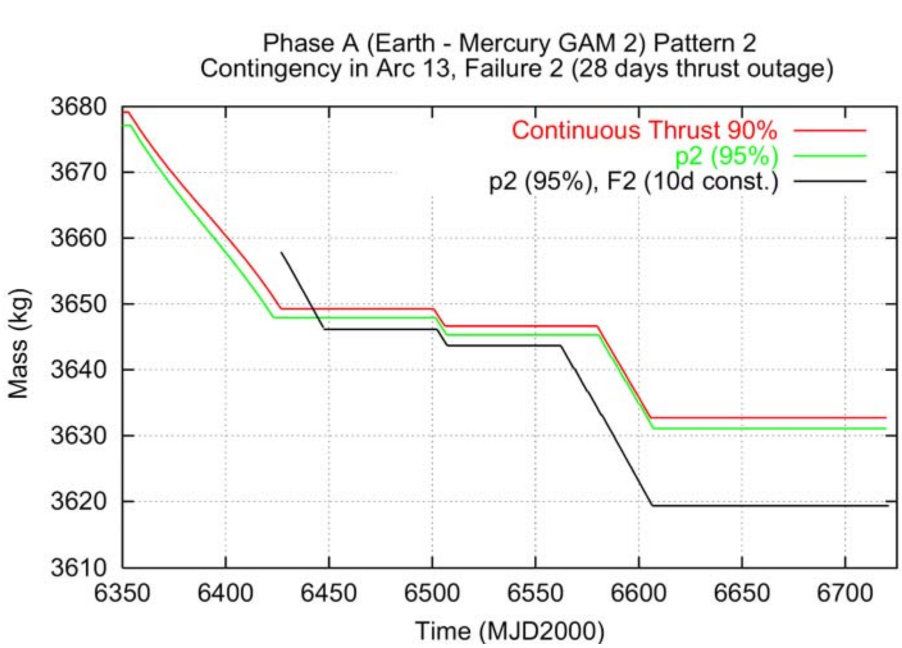

Figure 11: BepiColombo Phase A Mass evolution after 28 days of thrust outage in Arc 13 with Pattern 2

3.3.2.2.3. Summary

As expected, arc designed with pattern 2 presents better behaviour for this kind of failure than pattern 1. Pattern 1 does not allow recovering the initial trajectory whereas, for pattern 2, the trajectory can be recovered after the simulated contingency when reducing the coast constraint before Mercury GAM1 down to 10 days. In this case, the penalty in mass is very large (10.9 kg) providing a final mass at Mercury GAM2 of 3619.3 kg. For smaller reductions of the coast constraint, the trajectory cannot be recovered.

3.3.2.3. Thrust underperformance (F3)

In the following, the impact of the thrust underperformance at Arc 13 on the mass at Mercury GAM2 is analysed. It has also to be accounted that this failure lasts till the end of the trajectory and thus would impose a penalty in mass for the rest of the trajectory (Phase B). That penalisation is about 14 Kg during the phase B of the trajectory.

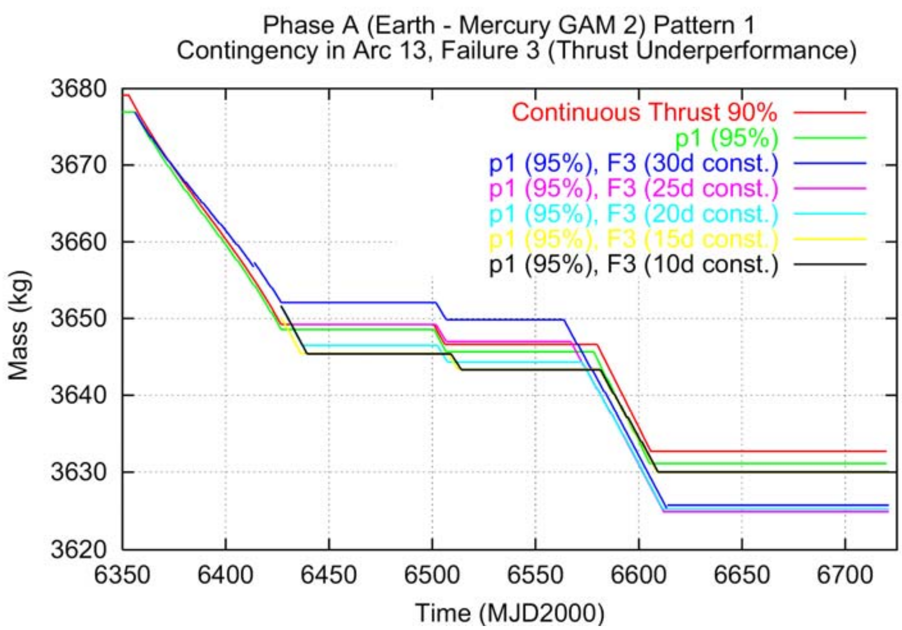

Figure 12: BepiColombo Phase A Mass evolution after a thrust 10% underperformance in Arc 13 with Pattern 1

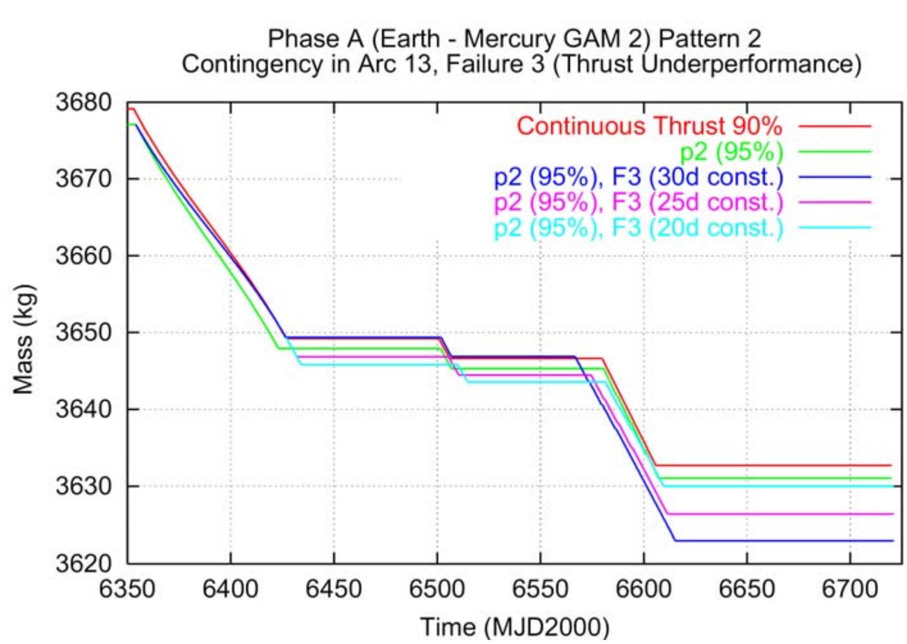

Figure 13: BepiColombo Phase A Mass evolution after a thrust 10% underperformance in Arc 13 with Pattern 2

This type of failure is not really demanding and the resulting penalties are similar for the two studied cases since the failure occurs at the beginning of the arc, and then, it has no impact where the buffer is located (except for the initial conditions at the initial time of the thrust arc).

Converged solutions can be obtained without relaxing the forced coast arc before the Mercury Fly-by and the associated penalties are not so large than those from the other simulated failures.

This is only a partial result, since the rest of the trajectory, up to the Mercury arrival is also modified due to the reduced thrust, and thus the impact on the final mass at arrival may be larger than for the other two simulated cases. Thus the reduction in final mass at Mercury arrival may be larger than for the other type of failures. The additional mass penalty during phase B due to this failure is about 14 kg.

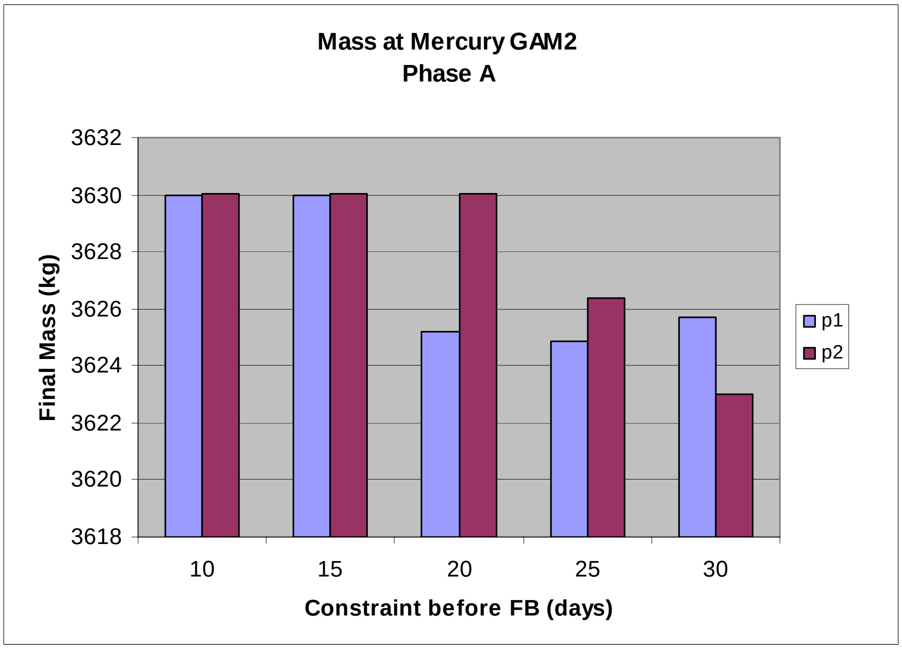

Figure 14: BepiColombo Phase A Mass at Mercury GAM2 after 10% underperformance in Arc 13

3.3.2.4. Summary for Contingency Analysis of Arc A13

For failure to occur at the end of the thrust arc, and as expected, the pattern of locating the entire buffer at the end of the thrust arc provides benefits in terms of both, possibility of recovery and mass penalty. A severe contingency of loosing the thrust during the 28 last days of the thrust arc can only be recovered when designing the trajectory with this mentioned pattern. Additionally, it is required to relax the constraint of forced coast arc for navigation previous to the fly by down to 10 days.

In case of not so severe contingencies at the end of the thrust arc, both patterns allow to recover from the failure, but locating all the buffer at the end of the thrust arc allows to have lower penalties in mass and more flexibility in regards to the relaxation of the forced coast arc.

The simulated thrust underperformance is not a really demanding case, converged solutions can be obtained without relaxing the forced coast arc before the Mercury Fly-by and the associated penalties are not so large than those from the other simulated failures (at Mercury GAM2; as said before it has to be accounted the effect of the thrust underperformance till the end of the trajectory which imposes an additional mass penalty of 14 Kg).

A summary of the final mass at Mercury GAM2 is shown in Figure 15 for the converged cases. This figure shows how a failure type 3 in this arc (thrust underperformance) can be recovered without relaxing the constrain of forced coast arc before Mergury GAM1 for the two patterns. On the contrary for failure type 2 (28 days of thrust outage) the recovery is only possible when designing the arc with pattern 2 and requires the relaxation of the constraint down to 10 days. For the less severe failure 1 (14 days of thrust outage) there are several options for recovery with pattern 2 and it is required to relax the constraint down to 10 days for pattern 1. The nominal final mass for the continuous thrust is 3632.7 kg, 3631.1kg for pattern 1 and 3630.9 for pattern 2.

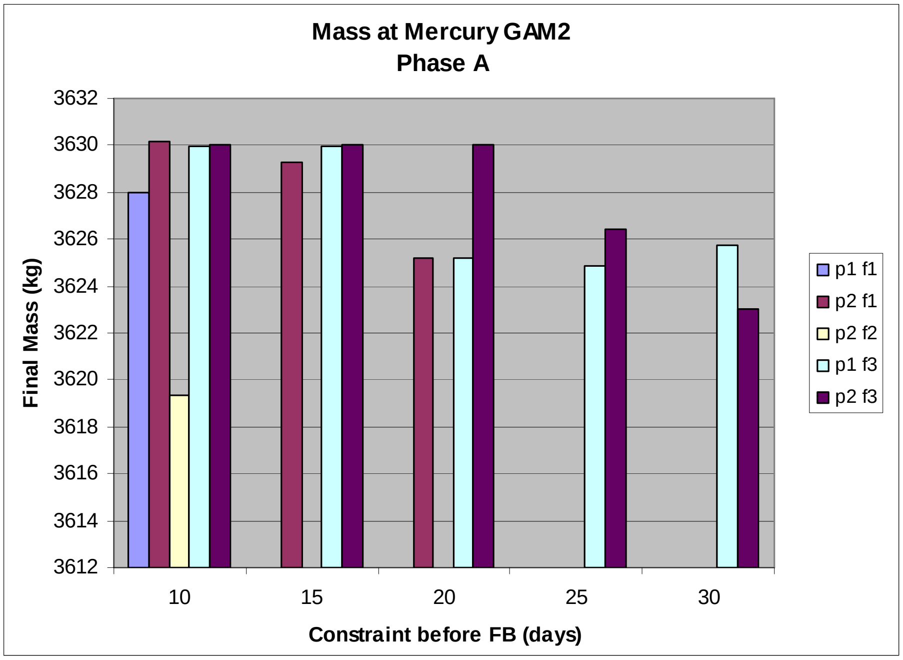

Figure 15: BepiColombo Phase A Final Mass at Mercury GAM2 for different patterns and failures

3.4. Contingency Analysis for Phase between Mercury GAM1 and Mercury Orbit Insertion - 40 days (Phase B)

3.4.1. Summary of Phase Events and Arcs

Considering the thrust arcs duration, the duration of coast arcs after every thrust period and other constraints (as the forced 30 days coast arc before flybys), the arcs to be analysed in regards the contingency are the Arc number 10, 16, 18, 20 and 22 (marked in red). These arc last 39, 40, 24, 42 and 15 days respectively; and they are followed by coast arcs of shorter duration than the associated thrust period (Arc 22 is followed by a constrained coast arc due to the Mercury GAM3). P1 and P2 are applied to those arcs, whereas P1 is applied to the rest of thrust arcs (marked in green), for the further optimisation of resulting trajectories.

3.4.2. Comparison of continuous thrust trajectory and patterned cases

Similarly to the case of Phase A, once obtained a continuous thrust trajectory for the Phase B, the two trajectories with appropriate pattern (P1 and P2) in arc 10, 16, 18, 20 and 22 are obtained. The rest of thrust arcs are split with pattern 1, so that the thrust level of the complete phase is set to 95% of the available thrust, and the time and thrust conditions are compatible with those from the initial trajectory.

Following figures provide the evolution of mass, thrust module for the three trajectories. It can be observed in Figure 16 the small impact in mass at the end of this phase of locating the 5% of coasting time well distributed along or at the end of the thrust arc. The mass at Mercury GAM2 for the continuous thrust trajectory is **3417.9 kg**, whereas the obtained values for the mass at that event are **3418.5 Kg** and **3419.0 kg** for the trajectories with pattern 1 and 2 respectively. It has to be recalled that the pattern 2 is only applied to the mentioned arcs and not for all the thrust arcs, and thus the penalty for this more constrained condition is not large (on the contrary, a small improvement in final mass can be observed, but within the margins of convergence of the solutions).

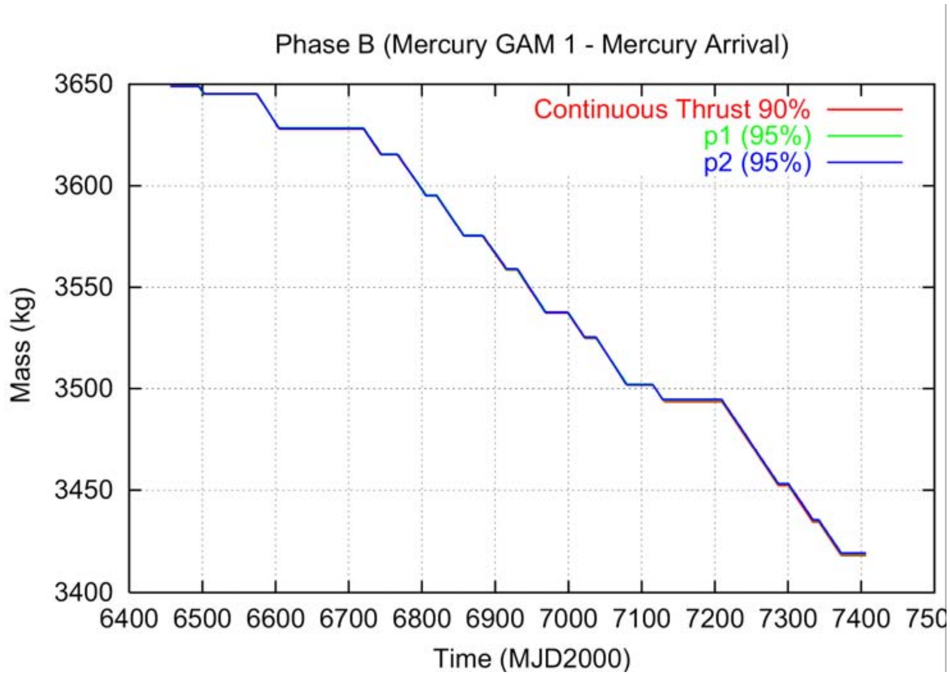

Figure 16: BepiColombo Phase B Mass evolution for continuous thrust trajectory and patterned thrust trajectories

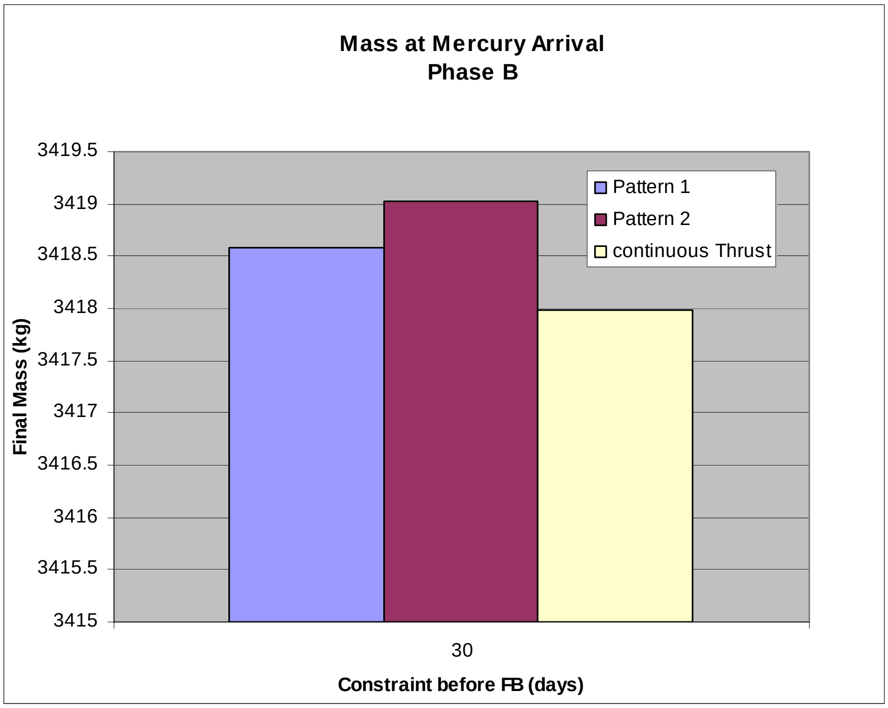

Figure 17: BepiColombo Phase B Mass at MOI–40 day for continuous thrust trajectory and patterned thrust trajectories

3.4.3. Contingency Analysis of Arc B10

3.4.3.1. Equidistant Coast Arcs

Once the failure is applied to the trajectory and relaxed the constraints on coast buffer arcs until the next flyby (no double contingency in the same trajectory segment, contingency buffer for other trajectory are maintained), the resulting trajectories from LOTNAV TRU show that the simulated contingencies are not really demanding on this arc. All the contingency cases can be recovered without relaxing any constraint on the trajectory design (apart of the buffer for contingency within the segment).

The relaxation of this contingency constraint provides the trajectory with a lot of margin, so that for small contingencies (Failure type 1 of 14 days thrust outage), the obtained trajectory does not have a mass penalty with respect to the nominal trajectory. The relaxation of coast buffer for contingency provides with about 6 additional days of thrusting within the segment, which are enough to recover without penalty from this failure.

On the contrary, a more severe contingency (28 days of thrust outage) imposes a mass penalty of 3.5 kg but the constraint on coasting before the flyby can be maintained.

Opposite to the case of the analysed arc in previous section (Phase A, Arc13), the most demanding failure is the type 3 (Thrust underperformance). Since this failure remains till the end of the trajectory, the impact of this event is larger when a large number of thrust arc are included till the end of the trajectory. The total mass penalty till the end of the trajectory for this case rises up to more than 16 kg.

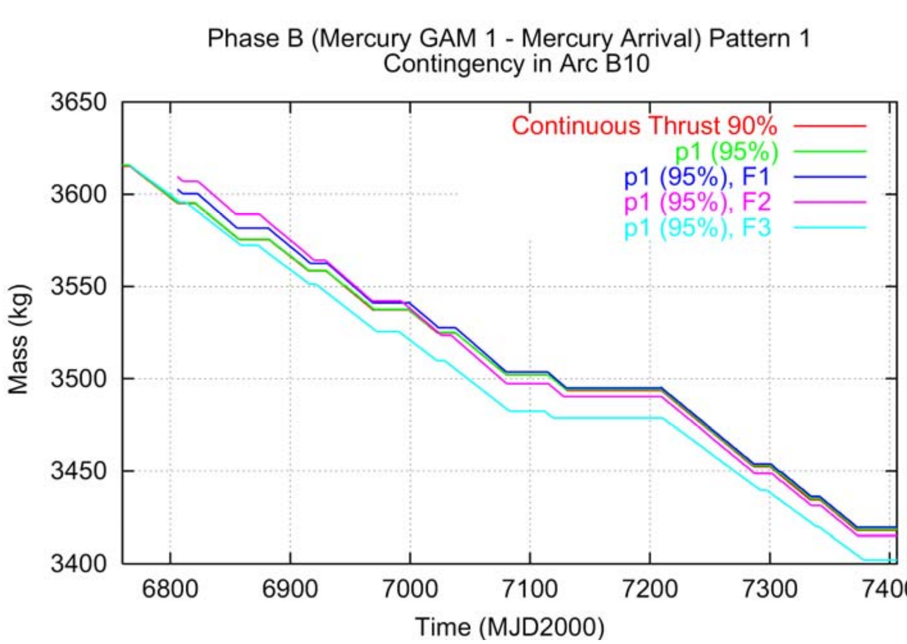

Figure 18: BepiColombo Phase B Mass evolution for different Failure types in Arc B10 with Pattern 1

3.4.3.2. Coast Buffer at the End of the Thrust Arc

Continuous solutions are obtained for all the failure types applied to this arc. The coast buffer is almost maintained for every thrust arc. Mass penalties are slightly larger than those in pattern 1, but they are not relevant and could be related to the convergence margin.

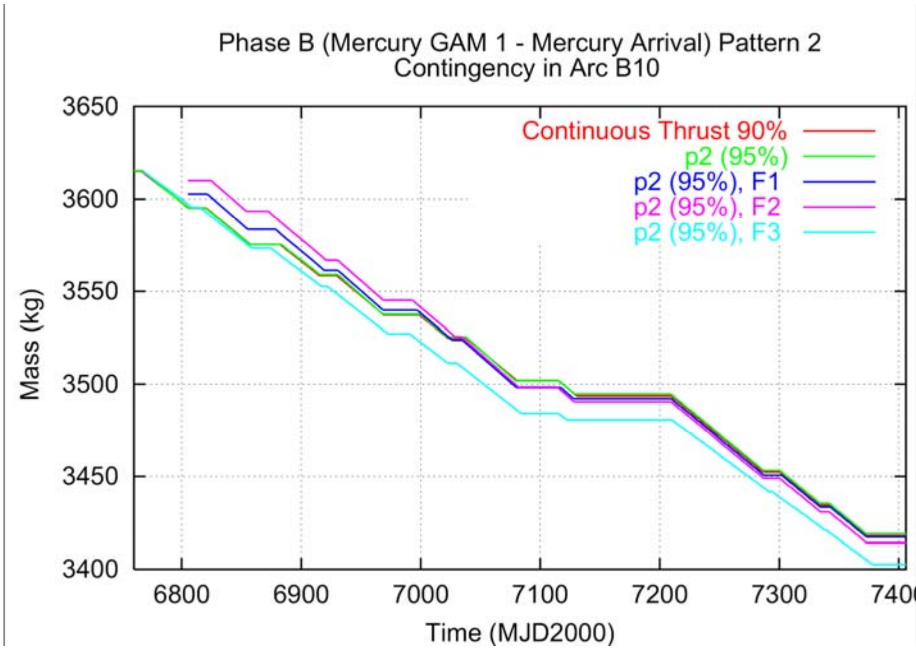

Figure 19: BepiColombo Phase B Mass evolution for different Failure types in Arc B10 with Pattern 2

3.4.3.3. Summary for Contingency Analysis of Arc B10

Opposite to the case of the arc number 13 in phase A of the trajectory, the simulated contingencies can be solved without relaxing constraints on the trajectory design. This is due to large natural coast buffer within this multi-arc phase till next GAM. The results show that this is not a demanding arc for contingency.

Thrust underperformance is the most demanding failure for this arc. This is due to the long duration of thrust periods up to the end of the trajectory. All these arcs are simulated with a 80% of the available thrust module.

The thrust underperformance failure imposes a large mass penalty, mainly caused to the effect on the large thrust arcs between M_4 and MOI-40d. Additional simulation cases are executed with the underperformance lasting only up to M4, instead of up to MOI-40d. The associated mass penalties for these cases (labelled F3b) are much lower than the corresponding F3 cases. Anyhow, the thrust underperformance under this assumption is also the most demanding contingency for this arc.

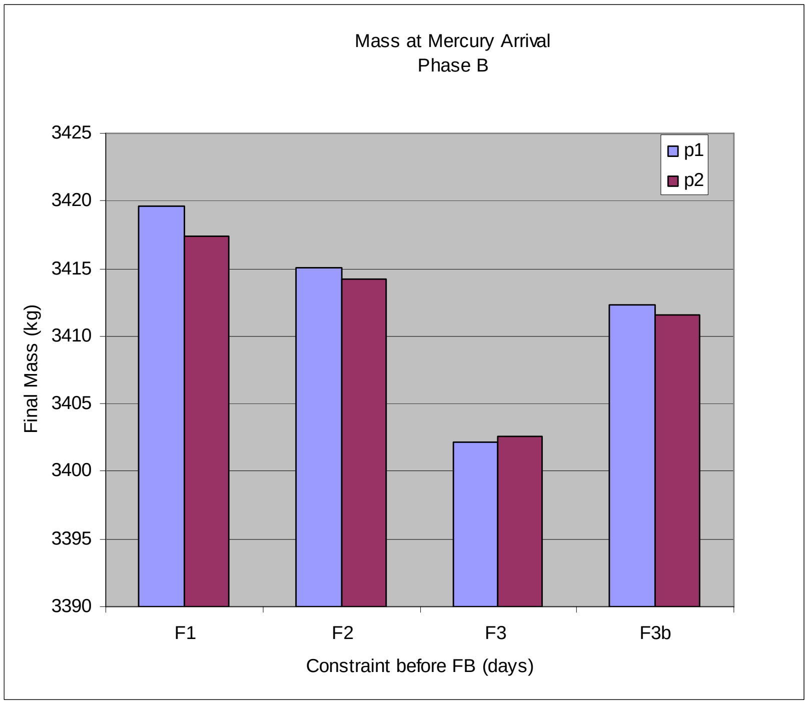

Figure 20: BepiColombo Phase B Final Mass at MOI–40 day for different patterns and failures during Arc B10

3.4.4. Contingency Analysis of Arc B16

This is a 40 days thrust arc followed by 3 other thrust arcs before next Mercury GAM. It is an accelerating arc at Pericenter. All the contingency cases can be recovered without relaxing any constraint on the trajectory design

3.4.4.1. Equidistant Coast Arcs

As mentioned before, all the contingency cases can be recovered without relaxing the design constraints. The mass penalty is about 12, 43 and 20 kg for F1, F2 and F3 respectively.

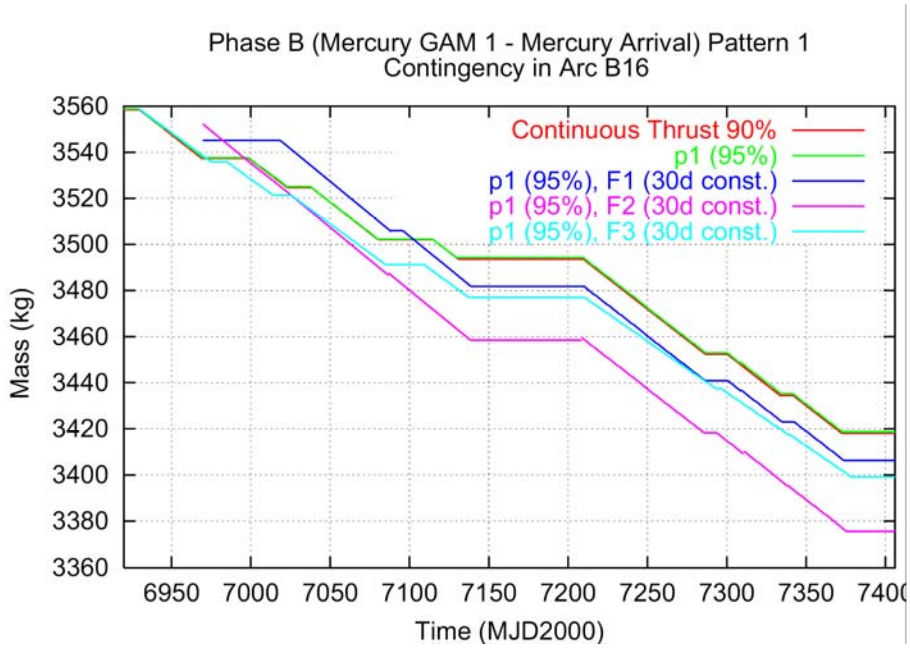

Figure 21: BepiColombo Phase B Mass evolution for different Failure types in Arc B16 with Pattern 1

3.4.4.2. Coast Buffer at the End of the Thrust Arc

All the contingency cases can be recovered without relaxing the design constraints. The mass penalty is about 12, 32 and 6 kg for F1, F2 and F3 respectively.

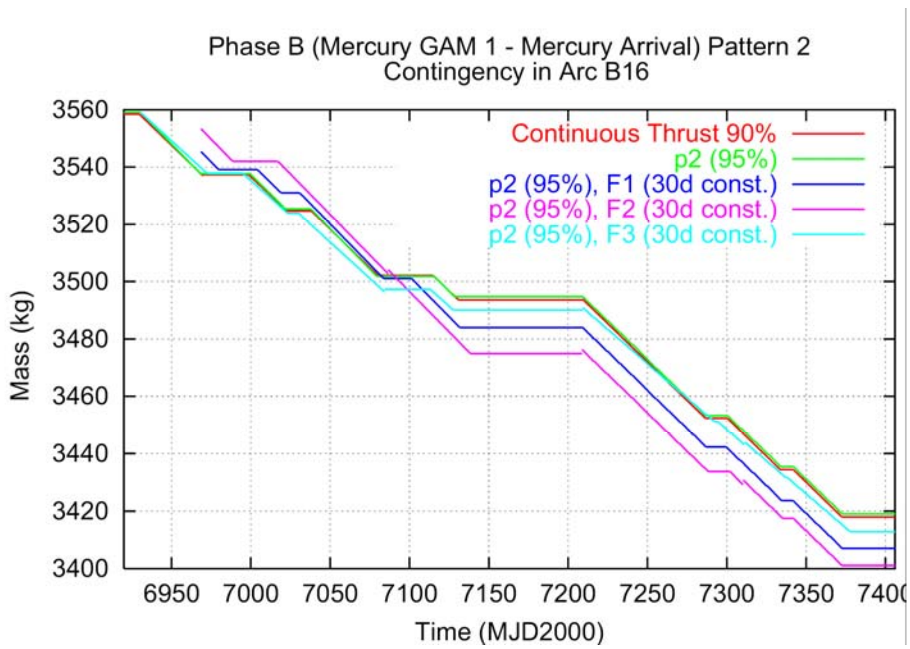

Figure 22: BepiColombo Phase B Mass evolution for different Failure types in Arc B16 with Pattern 2

3.4.4.3. Summary for Contingency Analysis of Arc B16

Large natural coast buffer in this multi-arc phase exist till next GAM. Thus, it is not a demanding case for contingency. Failure type 2 (28 days of thrust outage) is the most demanding failure type. The two patterns have similar behaviours against contingency, although some advantages can be observed for pattern 2, especially for F2.

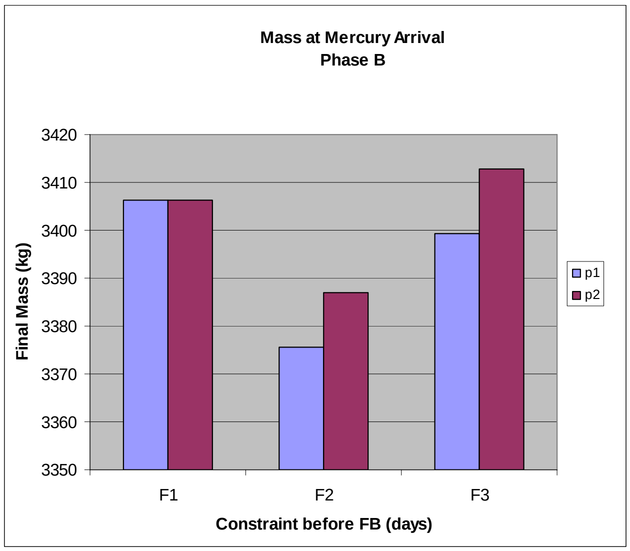

Figure 23: BepiColombo Phase B Final Mass at MOI–40 day for different patterns and failures during Arc B16

3.4.5. Contingency Analysis of Arc B18

This is a 24-days braking arc at apocenter with some natural coast buffer still available before next GAM (15 days before next thrust arc, 34 days after this, and 7 additional days before the forced coast arc).

3.4.5.1. Equidistant Coast Arcs

As mentioned before, all the contingency cases can be recovered without relaxing the design constraints.

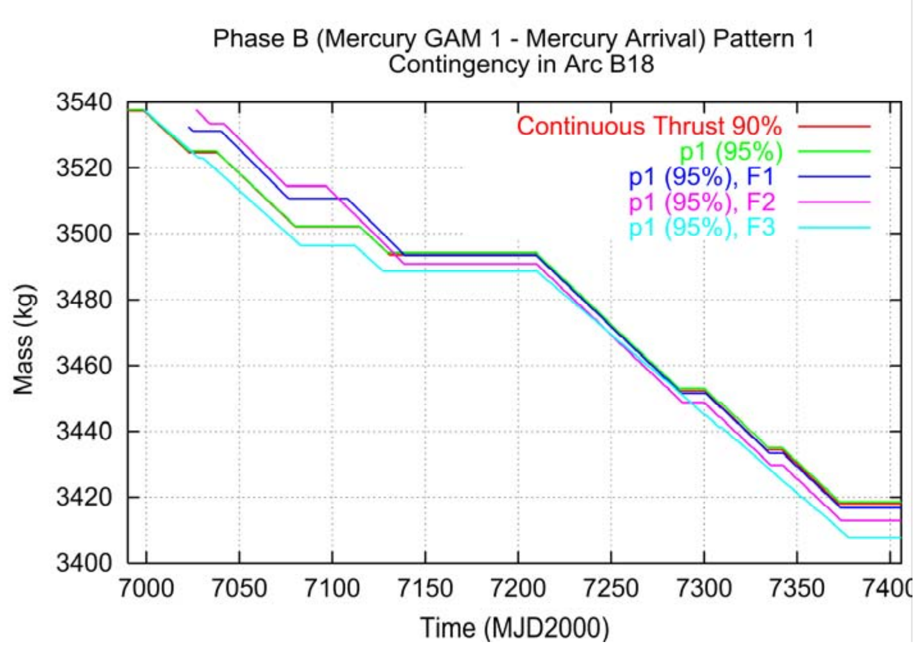

Figure 24: BepiColombo Phase B Mass evolution for different Failure types in Arc B18 with Pattern 1

3.4.5.2. Coast Buffer at the End of the Thrust Arc

All the contingency cases can be recovered without relaxing the design constraints.

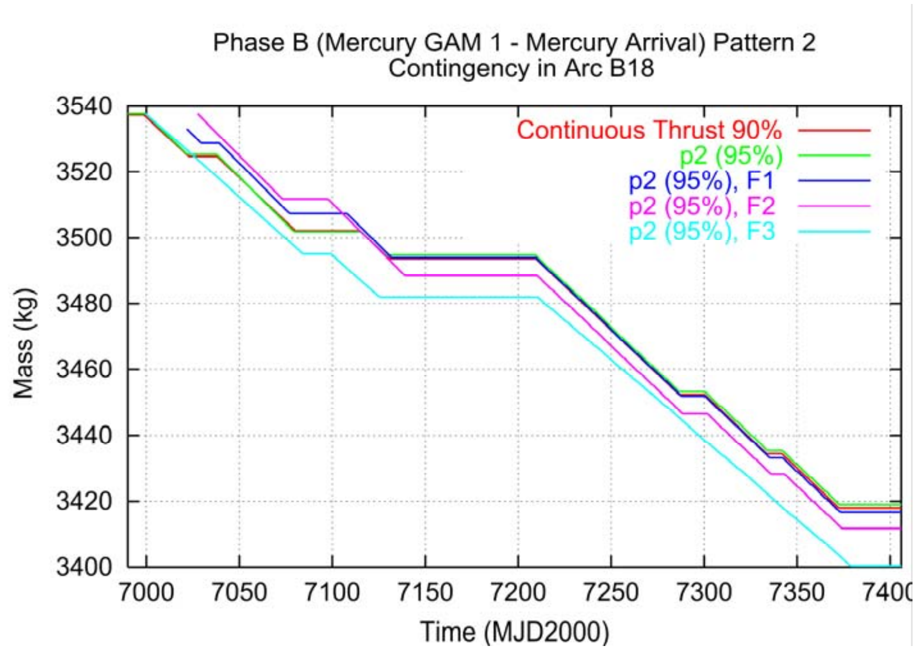

Figure 25: BepiColombo Phase B Mass evolution for different Failure types in Arc B18 with Pattern 2

3.4.5.3. Summary for Contingency Analysis of Arc B18

All the contingency cases can be recovered without relaxing any constraint on the trajectory design. Two patterns have similar behaviour (slight differences can be related to convergence accuracy).

The thrust underperformance failure (F3) is the more demanding case

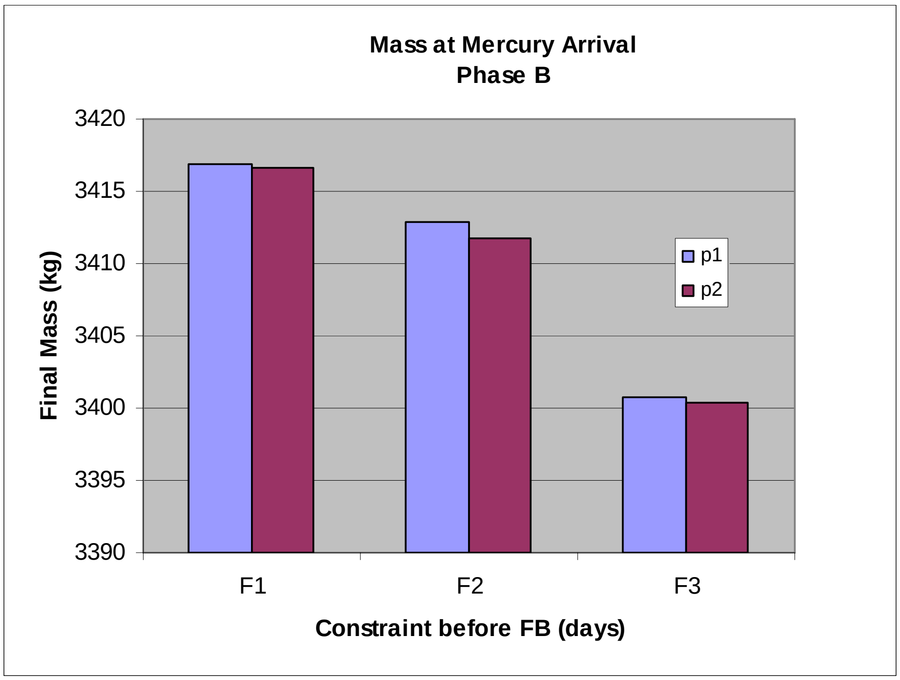

Figure 26: BepiColombo Phase B Final Mass at MOI–40 day for different patterns and failures during Arc B18

3.4.6. Contingency Analysis of Arc B20

This is a 42 days accelerating arc at pericenter. It is followed by 34 days of natural coast arc before next thrust arc.

3.4.6.1. Equidistant Coast Arcs

The relaxation of the constraint before M4 does not provide good results. Several attempts have been tried (reducing the constraint from 30 days down to 10 days as it was done for the case of Arc A13). These cases do not converge. Additional reduction of the constraint down to 5 days has provided a continuous solution with a mass penalty of 49.5 kg. This case has not been reported since it is assumed that such a reduction in the constraint is not affordable from the point of view of the navigation requirements.

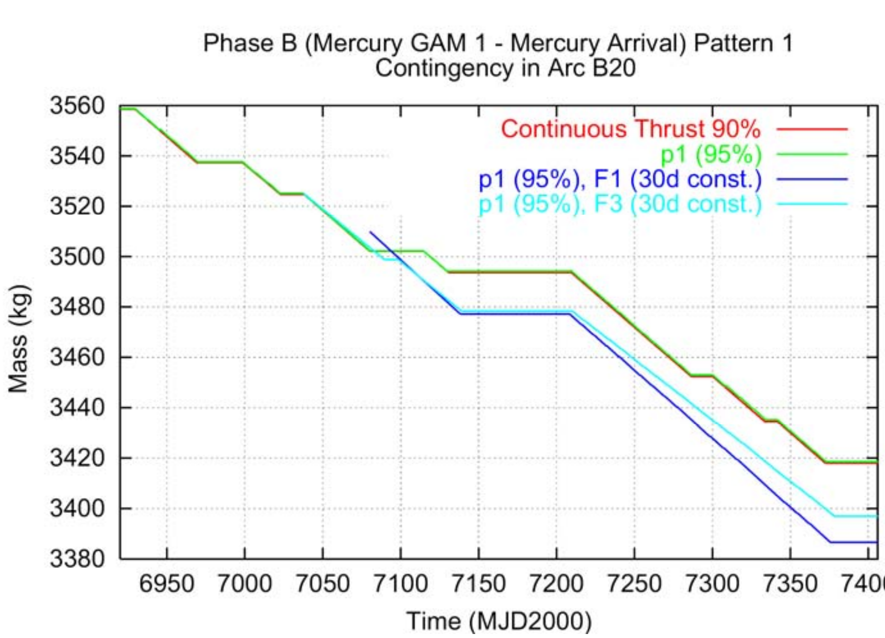

Figure 27: BepiColombo Phase B Mass evolution for different Failure types in Arc B20 with Pattern 1

3.4.6.2. Coast Buffer at the End of the Thrust Arc

Even case of Failure type 2 can be recovered with this patter. The mass penalty is high (over 40 kg).

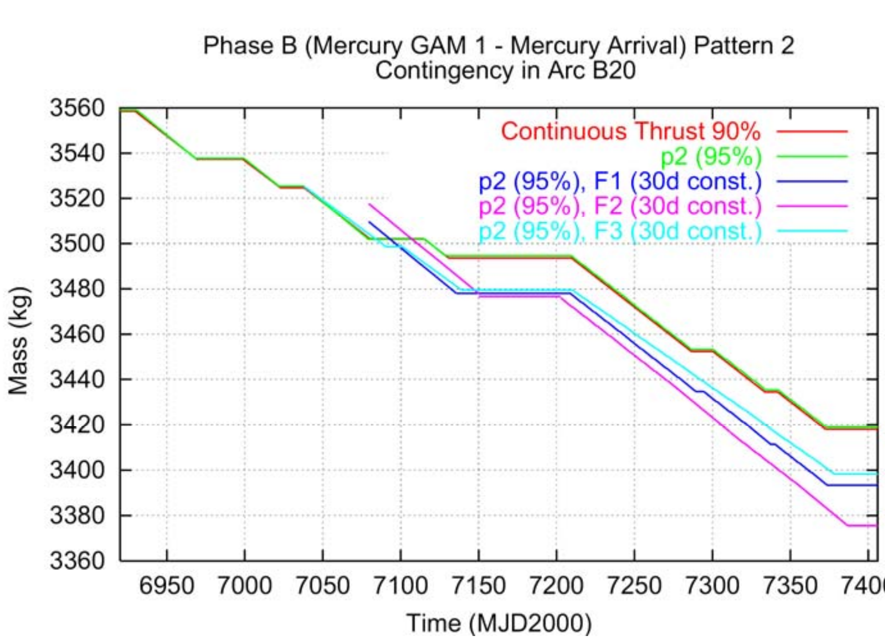

Figure 28: BepiColombo Phase B Mass evolution for different Failure types in Arc B20 with Pattern 2

3.4.6.3. Summary for Contingency Analysis of Arc B20

Pattern 2 shows better performances than Pattern 1, mainly for the failures occurring at the end of the thrust arc (behaviour under F3 is similar for the two cases). This is due to the fact that this arc is getting closer to the nest GAM, and thus the thrust arcs are constraint at theirs ends. Thus, any failure occurring at the end of the thrust will be more demanding.

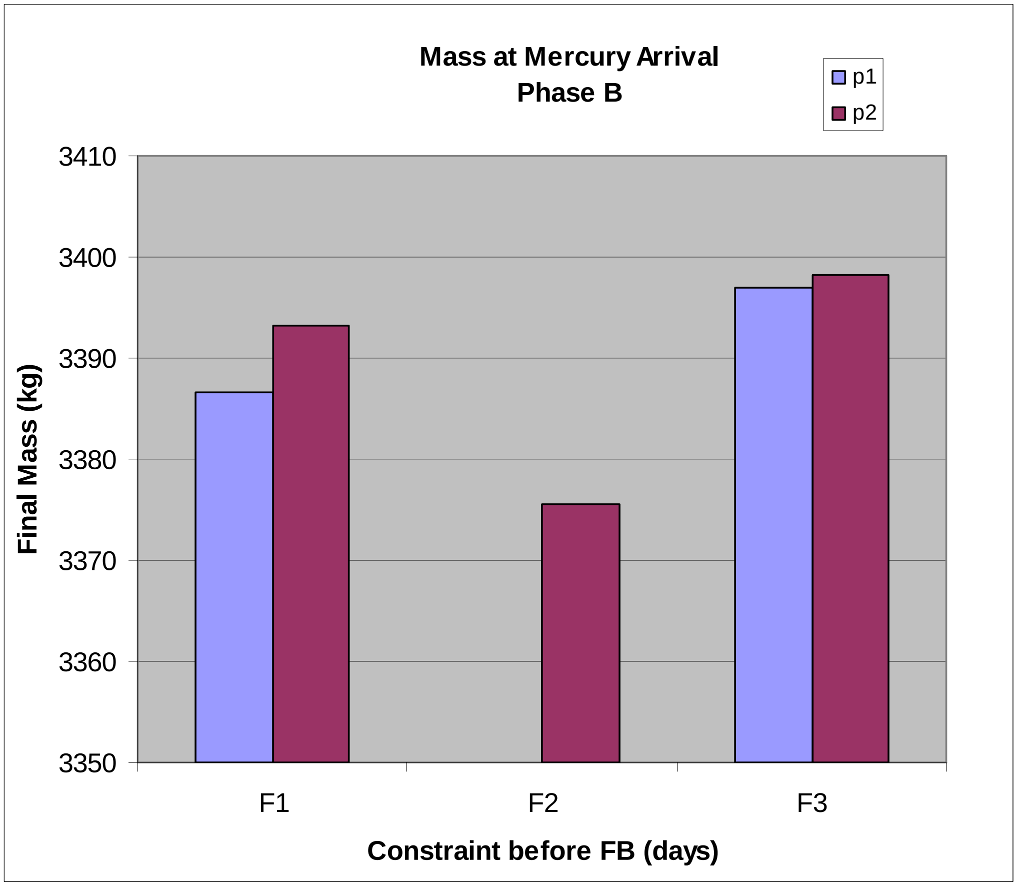

Figure 29: BepiColombo Phase B Final Mass at MOI–40 day for different patterns and failures during Arc B20

3.4.7. Contingency Analysis of Arc B22

The duration of this arc is very short, and thus the assumptions for F1 and F2 have been modified.

For the case of pattern 1, the thrust arc lasts about 15.1 days, and thus, failure F1 occurs 1.1 days after the switch on of the thrust. The outage lasts 14 days and the thrust is on again at 7129.7110 MJD2000. For pattern 2, the thrust arc lasts only 12.7 days, and thus, 14 days of outage covers the full thrust arc and 1.3 days of the following coast arc (buffer arc is then not available for the recovery). In this case, the engine recovers the thrusting capability at 7129.6275 MJD2000.

For the case of failure type 2, in both cases, pattern 1 and 2, the duration of the outage is much larger than the nominal thrust arc. Due to this reason, this failure is not investigated.

3.4.7.1. Thrust outage to occur 14 days before the end of thrust arc and lasting till the end of the arc (F1)

After the application of the contingency, no convergence is achieved for nominal design constraints. Similar analysis to that in Arc A13 is carried on: reduction of 30-days forced coast arc before next GAM. For all those attempts no convergence is achieved, even reducing the constraint before Mercucry GAM3 down to 5 days.

No matter the duration of the coast constraint imposed before Mercury GAM3, the optimiser maintains a coast arc of about 26 days (i.e., when the coast arc constraint is reduced down to 25, 20, 15 or 10 days, the optimiser only reduces this coast arc down to 26 days, and does not impose the constraint of the coast arc). This is the main difference between the resulting data from the analysis of this arc and the analysis of arc 13 in phase A.

The constraints avoiding the appropriate optimisation process are Solar Aspect angle Constraint (both maximum and minimum values). Several attempts (relaxing those constraints) have been tried. Preliminary results with no SAAC are first executed. It seems that the thrust arcs are not enlarged because larger thrust arcs require values of Solar Aspect Angle larger than allowed in order to be effective.

In order to evaluate the impact of thrust outage of different duration, some additional cases are investigated. These cases impose thrust outages at the end of the thrust arc, with duration lasting from one up to 14 days. The purpose of this analysis is to investigate the limit of the convergence for such cases.

3.4.7.1.1. Analysis of thrust outage of different duration

This analysis is executed to investigate the limits in the outage duration for obtaining appropriate trajectories. The analysis is executed for the pattern 1.

The thrust outage is imposed at the end of the nominal thrust arc, all the constraints are maintained as in the nominal trajectory (30 days of coast arc before Mercury GAM3 and SAAC).

The results from this analysis report 9 cases with appropriate continuous trajectories. Thus, the trajectory can be recovered for outages up to 9 days. The optimiser uses the natural coast arc after the initial thrusting period before Mercury GAM3 (this nominal coast arc lasts about 8 days) and increases the thrusting time of thrust arcs after this flyby. The resulting mass penalties for these cases with respect to the nominal trajectory are reported in Table 5. These mass penalties are also provided in Figure 30. The mass penalties are not increasing, as expected, for the first three cases but this is due to the convergence accuracy, and the resulting trajectories are continuous. For the rest of cases, the larger the thrust outage, the larger the mass penalty is.

Larger thrust arc outage may be recovered when reducing the constraint of forced coast arc before the flyby.

Table 5: Mass penalty and new thrust arc before Mercury GAM3

Thrust outage duration (days)	Final Mass (Kg)	Diff Mass (Kg)	New Thrust Arc duration (days)
1	3417.47	1.11	0.75
2	3417.68	0.90	1.57
3	3417.81	0.77	2.50
4	3417.78	0.80	3.53
5	3417.67	0.91	4.17
6	3417.64	0.94	5.22
7	3417.35	1.23	6.19
8	3416.98	1.60	7.0
9	3415.84	2.74	7.81

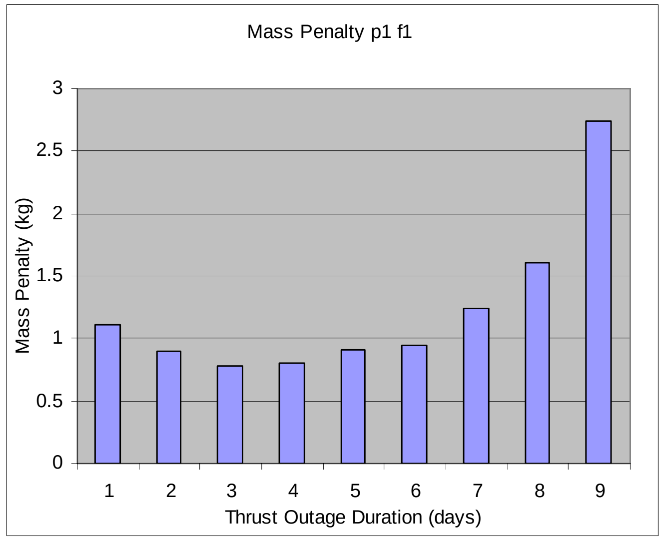

Figure 30: Mass penalty at MOI-40 days for different Failure outages in Arc B22 with Pattern 1

3.4.7.1.2. Cases without Solar Aspect Angle Constraint

The continuous cases obtained when no SAAC is applied are presented in the following. The final mass and mass penalties are not provided, since the comparison with the nominal cases (with SAAC applied) has no sense due to the differences in the assumptions.

3.4.7.1.2.1. Equidistant Coast Arcs

When SAAC are not applied for the rest of the trajectory, converged cases can be obtained for the reduction of forced coast arc down to 20, 15 or 10 days, with common solution for the two less constrained cases (19.7 days of forced coast arc). In the following, the

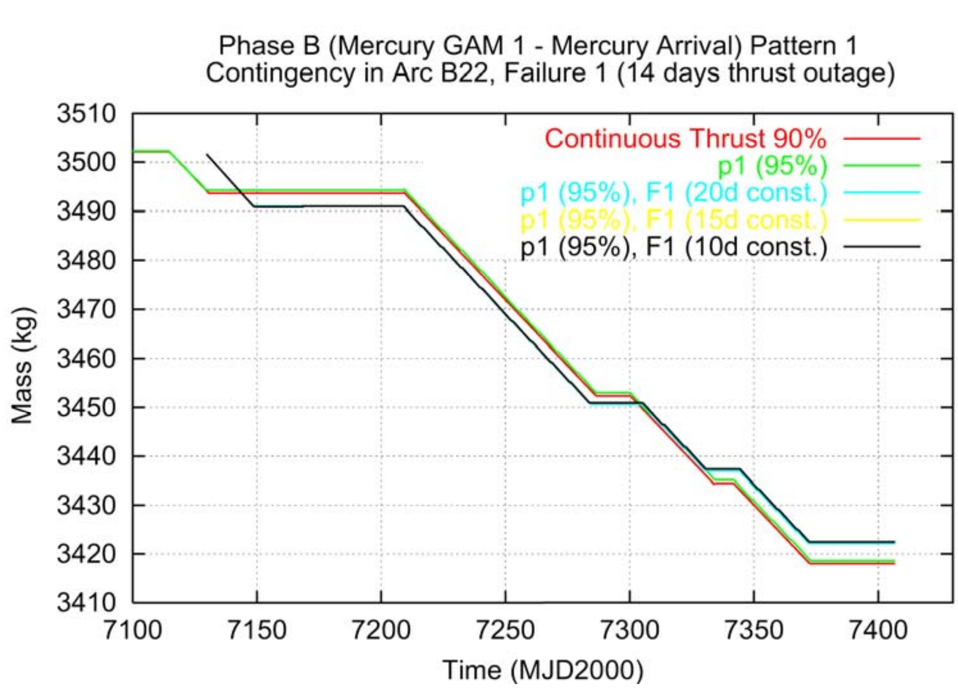

Figure 31: BepiColombo Phase B Mass evolution for different Failure types in Arc B22 with Pattern 1 (without SAAC)

3.4.7.1.2.2. Coast Buffer at the End of the Thrust Arc

When SAAC are not applied for the rest of the trajectory, converged cases can be obtained for the reduction of forced coast arc down to 20, 15 or 10 days, with common solution for the two less constrained cases (19.7 days of forced coast arc).

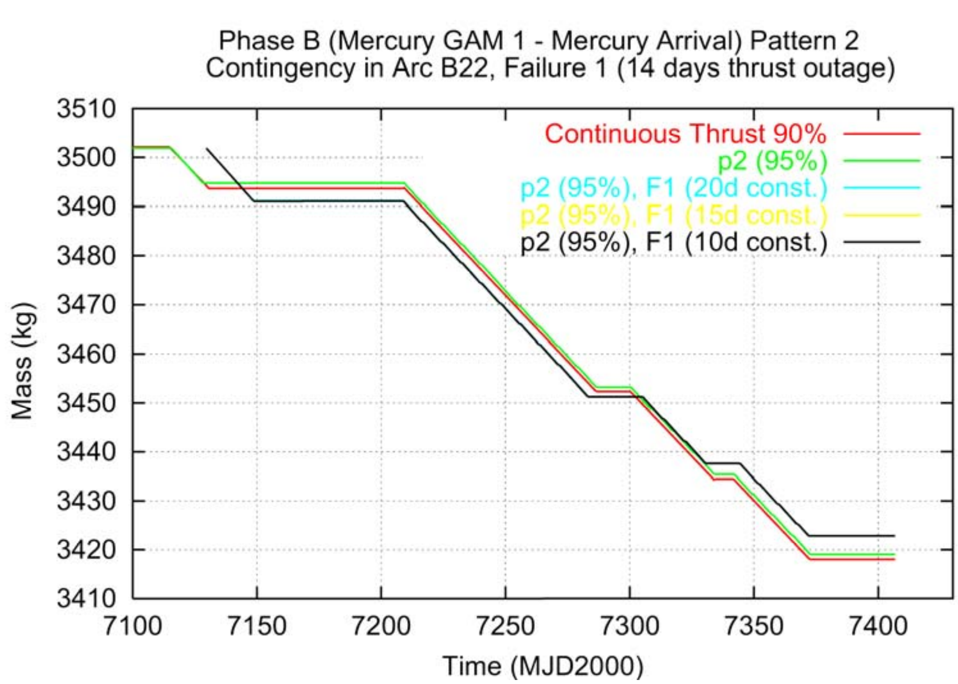

Figure 32: BepiColombo Phase B Mass evolution for different Failure types in Arc B22 with Pattern 2 (without SAAC)

3.4.7.2. Thrust underperformance (F3)

The two patterned trajectories can be recovered when applying a thrust underperformance failure of a 10% for the arc B22 and lasting till the end of the optimised trajectory (MOI-40 days). The mass penalties for these case are 10 and 12.5 kg for pattern 1 and pattern 2 respectively. The reason for the difference between the two cases is not clear. Plots for the comparison of mass and thrust modulus evolution are provided in the following.

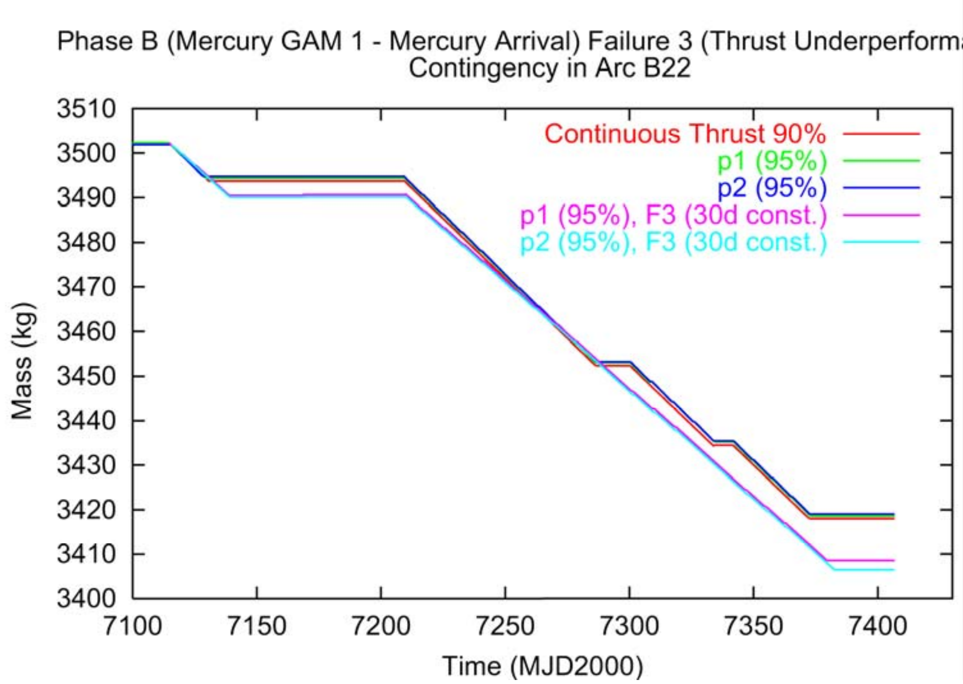

Figure 33: BepiColombo Phase B Mass evolution after a thrust 10% underperformance in Arc 22 for different Patterns

3.5. Summary and conclusions

The assumptions and results of the analysis of BepiColombo Traj_BC_B trajectory regarding contingency cases are reported in this document. The analysis is performed by means of LOTNAV tool. Several modules from this tool are used: Trajectory Reconstruction Utility (TRU), Trajectory Transcription Utility (TTU) and Contingency Analysis Utility (CAU).

The objective of the contingency analysis is the determination of the best way to locate coast arcs within a thrust arcs to act as buffer for the case of contingencies. Two different types of buffers are studied, one distributed along thrust arcs (equidistant coast arcs, P1) and the other locating the entire buffer at the end of thrust arc (P2). The optimum distribution of the buffer depends on the arc of the trajectory under study and the type of simulated failure.

Two types of failures are simulated; thrust outage during the last part of a thrust arc (14 days for the Failure 1 and 28 days for the Failure 2), and a 10% thrust underperformance during the duration of the thrust arc.

The main conclusions from the executed contingency analysis can be summarised in the following:

- The pattern with better failure recovery performances depends on the arc where the failure occurs. In case the arc is located close to a GAM (which constraints the end part of the thrust arc) the pattern 2 presents advantages, since this case locates the entire buffer at the end of the nominal thrust arc.

- For really demanding failures (F2), pattern 2 is sometimes required, specially for very constrained arcs, since pattern 1 does not allow the recovery (Arc A13 and Arc B20).
- Failure type 3 (thrust underperformance) is not really demanding when the arcs are constrained at their ends. But it is really important for some arcs located in the middle of the M2-M3 phase. These arcs are not constrained for thrust outage at the end of the arcs and the importance of the underperformance becomes larger.
- The duration of the coast arc before GAMs is one of the design constraints to be relaxed when the trajectory cannot be recovered after the failure.
- Additionally, the Solar Aspect Angle Constraint should be relaxed for the last arc before third Mercury GAM if convergence trajectories are to be obtained. This SAAC cannot be relaxed, and thus, it is concluded that failure outage in this arc cannot be recovered if the outage is larger than 9 days.

In order to conclude this work, the following table provides a brief summary of the simulated cases.

Table 6: Summary of contingency cases

Arc	Pattern	Failure	Recovery Capability	Mass Penalty (kg)
A13	P1	F1	demanding to recover	Depending on case (coast constraint) Maximum 3.8 kg for 13 days
		F2	no possible recovery	-
		F3	easy to recover	Depending on case (coast constraint) Maximum 6.2 kg for 25 days
	P2	F1	demanding to recover	Depending on case (coast constraint) Maximum 5.1 kg for 20 days 2.9 kg for 13 days
		F2	demanding to recover	10.9 kg for 10 days of coast constraint
		F3	easy to recover	Depending on case (coast constraint) Maximum 7.2 kg for 30 days 3.9 kg for 25 days
B10	P1	F1	easy to recover	-1.0
		F2	easy to recover	3.5
		F3	easy to recover	16.5
	P2	F1	easy to recover	1.6
		F2	easy to recover	4.8
		F3	easy to recover	16.4
B16	P1	F1	easy to recover	12.3
		F2	demanding to recover	43.0
		F3	easy to recover	19.4

Arc	Pattern	Failure	Recovery Capability	Mass Penalty (kg)
	P2	F1	easy to recover	12.8
		F2	demanding to recover	32.0
		F3	easy to recover	6.2
B18	P1	F1	easy to recover	1.7
		F2	easy to recover	5.8
		F3	easy to recover	17.8
	P2	F1	easy to recover	2.4
		F2	easy to recover	7.3
		F3	easy to recover	18.7
B20	P1	F1	demanding to recover	32.0
		F2	no possible recovery	-
		F3	demanding to recover	21.6
	P2	F1	demanding to recover	25.8
		F2	demanding to recover	43.5
		F3	demanding to recover	20.8
B22	P1	F1	no possible recovery	-
		F2	-	-
		F3	no possible recovery	-
	P2	F1	no possible recovery	-
		F2	-	-
		F3	no possible recovery	-

4. NAVIGATION AND GUIDANCE ANALYSIS OF BEPICOLOMBO TRAJECTORY WITH LOTNAV MONTECARLO UTILITY

Several trajectories have been analysed along the study. These trajectories are completely analysed with the traditional approached supported by LOTNAV tool (MonteCarlo execution of different independent navigation cases without re-optimisation). Navigation analysis based on re-optimisation has also been done. In some of the trajectories, the study of the re-optimisation case has been focused on the analysis of the capabilities and testing of the new module whereas for the last trajectory, a complete end-to-end analysis has been executed to allow the comparison with the traditional approach.

Several technical notes are provided with the detailed analysis of the different cases:

- Trajectory based on a DITAN solution with departure in 2014, with four Mercury Gravity Assist Manoeuvres before Mercury Orbit Insertion reported in [RD.12].
- Trajectory based on a MANTRA solution with departure in 2014, with four Mercury Gravity Assist Manoeuvres before Mercury Orbit Insertion reported in [RD.13].
- Trajectory based on a DITAN solution with departure in 2014, with five Mercury Gravity Assist Manoeuvres before Mercury Orbit Insertion reported in [RD.14], and summarised in this document.

A brief summary of the analysis of the last of those trajectories is provided in this executive summary.

4.1. Assumptions for the Navigation and Guidance Analysis

Assumptions for the navigation and guidance analysis can also be found in the reported technical notes and in the final report of this project. They can be summarised in the following:

- Orbit Determination Assumptions
  - Initial Dispersion and Knowledge is obtained from the launcher performance data ([RD.10])
  - Orbit Estimation is updated every 0.5 days.
  - The uncertainty in the influence of the solar radiation pressure is set as an ECRV with a 1-σ steady state covariance of 10%, autocorrelation time of 10 days.
  - An omni-directional residual acceleration is assumed also as ECRV with a 1-σ steady state covariance at 10^{-11} km/s^2, the autocorrelation time is taken at 1 day.
- Measurements assumptions
  - Range and Doppler Measurements are taken from a single ground station located at Cebreros. Range data are sampled at 1 point every 60 minutes and Doppler data at a rate of 1 measurement every 10 minutes
  - The Measurements profile for such tracking measurements:

  - Single Antenna passes every week for interplanetary coast and powered arcs
  - Daily passages 30 days before a flyby, after the GAM (before clean-up manoeuvre).
- Delta-DOR measurements are accounted before GAM when needed (1σ = 0.2 m) (values according to [RD.9]). Minimum elevation angle for those measurements is set to 15º, whereas for stations associated to range and Doppler measurements is set to 10 degrees.
  - Use of Delta-DOR measurements depends on the features of every phase in the trajectories.
- Range measurement uncertainties are assumed at 10 m random and 2 m bias
- Range rate noise is assumed at 0.3 mm/s random and no bias
- Ground station position errors are taken as consider biases with 0.3 m in every coordinate.
  - For he first analysed trajectory, the Ground station position errors are taken as consider biases with 1 m in X and Y coordinates and 2 m in Z coordinate. In the case of Delta-DOR measurements 0.1m at every component are assumed.

❑ Guidance Assumptions for Trim Manoeuvres

- Fixed time guidance algorithm is used
- When coming from a thrust arc, two manoeuvres are scheduled (20 and 10 days before the flyby) some cases require an additional manoeuvre 2 days before the flyby
- When coming from a previous Flyby (no powered arcs within the phase), a clean up manoeuvre is applied 7 days after the FB and two more manoeuvres are scheduled 20 and 10 days before the FB.
- Errors in the execution of trim manoeuvres are assumed to be Gaussian and (1-σ): 1% in modulus and 0.5º in direction

❑ Guidance Assumptions for Low-Thrust Arcs

- Delay of 14 between the measurements processing and control law computation. The first case accounts for a conservative assumption. Measurements are assumed to be acquired every week, thus the updated control law could be uploaded one week after the measurements processing, but it is assumed that some error could occur which made the upload to be delayed till next contact. An additional analysis of the case of 7 days delay is executed for the last studied trajectory.
- The thrust modulus was accounted as ECRV with a 1-σ uncertainty of 1% and an autocorrelation time of 1 day.
- Also the thrust angles were introduced as ECRV's with a 1-σ uncertainty of 0.5 deg and an autocorrelation time of 1 day.

The engine model used for the generation of this trajectory is a translation of the model defined in [RD.15]. This model is heliocentric distance and time dependent.

4.2. Guidance Analysis at each trajectory phase

4.2.1. Phase Earth Departure-Earth GAM

For each phase in the trajectory two relevant parameters for navigation (declination angle and distance to the Earth) are analysed. Declination angle close to zero usually requires the use of ΔDOR measurements since the Doppler does not provide information for the correct estimation of the S/C state vector. This is not the case of the Earth GAM since the fact of being close to the Earth allow a good knowledge of the S/C state vector in spite of the declination angle values. Additionally it also provides the distance to Sun.

ΔDOR measurements can be baselined during the last thirty days of every phase when needed. The angle of the baseline Cebreros-New Norcia and Cebreros-Argentina with respect to a plane defined by the trajectory along-rack and cross-track directions has to be studied to assess the performances of such measurements.

In case mid-course manoeuvres are required to limit the growth of the dispersion along the phase, it is needed to analyse the best time to locate such manoeuvres.

During this phase the nominal scheme for chemical and electric guidance is followed. A clean-up manoeuvre is executed 7 days after launch (Arc A-2.1). Two Trajectory Correction Manoeuvres are executed 20 and 10 days before Earth GAM (Arc A-6.1). Additionally, guidance is executed during the two thrust arcs (Arc A-3.1 and Arc A-5.1). No ΔDOR measurements are required in this phase.

4.2.2. Phase Earth GAM-Venus GAM1

This phase contains a short thrust arc used for low-thrust guidance. For such a purpose the delay between measurements processing and guidance execution is reduced down to 7 days instead of the nominal 14. After those guidance activities, chemical manoeuvres are executed before the GAM. In order to select the conditions for such chemical guidance (number of manoeuvres and measurements processed) the declination angle and distance to the Earth are analysed together with the angle of the baselines with respect to the trajectory. One ΔDOR baseline shall be entered 30 days before the Venus flyby in order to diminish the clean-up manoeuvre. It is also interesting to include an additional TCM 2 days before the flyby in order to increase such reduction in clean-up manoeuvre.

4.2.3. Phase Venus GAM1-Venus GAM2

This phase is almost a pure ballistic phase (only a 0.9 d thrust arc is included w within the phase) of a full revolution about the Sun and thus, the baseline scheme for guidance includes a clean-up manoeuvre after the first Venus GAM and two additional TCMs 20 and 10 days before Venus GAM2. An additional manoeuvre 2 days before the GAM is needed to reduce the dispersion at pericentre. Additionally, ΔDOR measurements are needed (null declination close to the V2 GAM). Two baselines are selected for such approaching phase. Figure 34: Angle defined by the baseline directions 212.887 with respect to the trajectory during the 30 days approaching to second Venus GAM. Three manoeuvres before the flyby are executed and ΔDOR measurements from two baselines are processed.

4.2.4. Phase Venus GAM2-Mercury GAM1

It has been mentioned in former section, that a clean-up manoeuvre after second Venus GAM is required. Theoretically, this TCM should not be included in the guidance scheme, since this phase contains powered arcs. But the first of these arcs is about 165 days after the beginning of the phase and it only lasts 15 days. Following powered arc comes after other 99 days. In case no clean-up manoeuvre is included, the dispersion grows largely and cannot be controlled afterwards. One baseline for ΔDOR is entered.

4.2.5. Phase Mercury GAM1-Mercury GAM2

This phase contains two powered arcs suitable for guidance activities. The two thrust arcs are short but they allow a reduction of dispersion, although an additional manoeuvre is needed before the baselined at 40 days before the GAM. A manoeuvre has been located at 6680 MJD2000, where the required ΔV is small and the dispersion has not grown a lot after the last guided thrust arc.

4.2.6. Phase Mercury GAM2-Mercury GAM3

This phase is a multi-revolution arc composed by eight powered arcs with coast arcs in between. Last thrust arc in the phase is very short, and it does not allow for an effective guidance. If no guidance activity is done from the previous thrust arc up to the TCMs before the arrival, the dispersion grows a lot and it requires very large manoeuvre to be executed before the arrival (with additional required clean-up manoeuvre). Thus, it is decided to enter a TCM between the two last thrust arcs. The manoeuvre at that arc costs 8.182 m/s. In the case this extra manoeuvre is delayed after the last thrust arc, it grows up at about 40 m/s.

Approximation to Mercury GAM3 requires the use of Delta-DOR, From the analysis showed in former table, the use of Cebreros- Argentina allows to reduce the knowledge uncertainty and so the dispersion at flyby, with an important reduction of the post-flyby manoeuvre.

4.2.7. Phase Mercury GAM3-Mercury GAM4

This is a pure ballistic phase, where the guidance can only be executed through chemical manoeuvres. A clean-up manoeuvre is applied right after the third Mercury fly-by, and additional manoeuvres 20 and 10 days before the fourth Mercury GAM are executed. No ΔDOR baselines are considered in this phase.

4.2.8. Phase Mercury GAM4-Mercury GAM5

This is a pure ballistic phase, where the guidance can only be executed through chemical manoeuvres. A clean-up manoeuvre is applied right after the fourth Mercury fly-by, and additional manoeuvres 20 and 10 days before the fifth Mercury GAM are executed. Two ΔDOR baselines are considered when approaching Mercury GAM5.

4.2.9. Phase Mercury GAM5-Mercury Orbit Insertion –40 days

Four thrusting periods are included in this phase. No special considerations are required on this phase.

4.3. Total Fuel Consumption for Navigation Activities

This section reports a summary of formerly presented data. Results for navigation requirements are obtained for 99.7% of the associated χ^2 distribution with three degrees of freedom for the trim manoeuvres. Similarly, data for the navigation requirements during powered arcs are provided in terms of the 3-σ value of the related normal distribution.

Table 7 provides the Start time of the low-thrust arc or time when the TCM is executed in the first column (MJD2000). Then, information on the type of event is provided:

- In case of TCM the associated planet (E-Earth; V-Venus; M-Mercury) and the time to (or past) event are provided (E-20: 20 days before the Earth flyby; V1+7: 7 days after the V1 flyby).
- For low-thrust arcs, the duration of the arcs is provided in days, together with the arc number within the trajectory profile.

Third column provides the nominal ΔV during low thrust arcs whereas fourth column provides the navigation ΔV required for the guidance during Low thrust arcs. Column number five reports the required ΔV for the TCM and column number six summarises all the ΔV required for navigation purposes, no matter it is related to Low thrust arcs or TCMs.

Additionally, Figure 35 shows the fuel consumption for all guidance activities. The total fuel consumption for all the guidance tasks is 316.44 m/s, 117.824 m/s corresponding to trim manoeuvres and 198.62 m/s for the guidance during the low thrust arcs. This last value corresponds to a 4.4 % of the total fuel consumption (4492.34 m/s) during the nominal low thrust arcs, below the 5% limit kept for navigation issues when designing the trajectory.

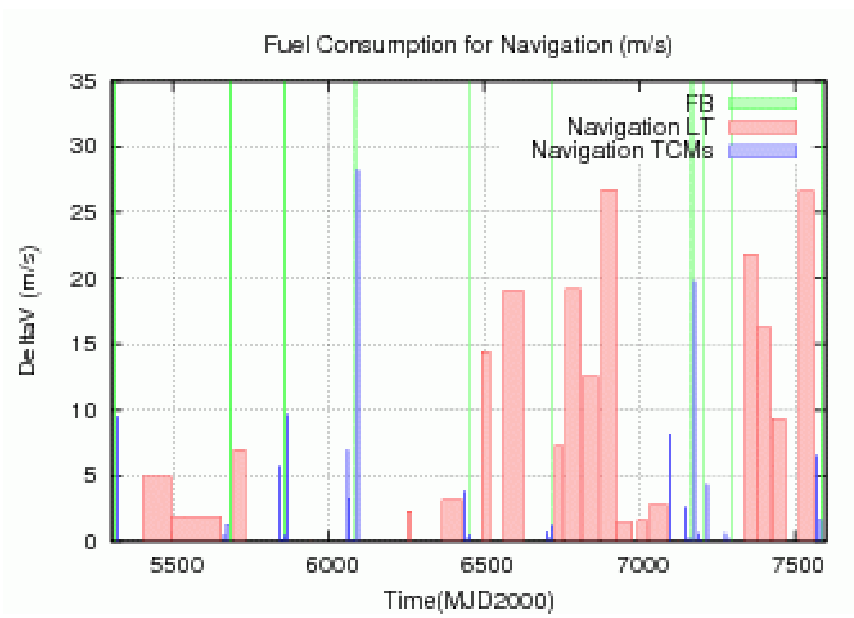

Figure 35: Total Fuel Consumption for Navigation Activities for BepiColombo Traj_BC_3 trajectory

Table 7: Fuel Consumption for TCMs and navigation during low-thrust arcs (99.7%) for BepiColombo Traj_BC_3 trajectory

Start Time MJD2000	Event/Arc (duration, days)	ΔV (m/s)	Navigation LT (m/s)	Navigation TCMs (m/s)	ΔV nav (m/s)
5318.8	Ed + 7 d			9.50	9.50
5401.89	A 3 (92.06)	330.87	4.97		4.97
5493.95	A 5 (160.03)	350.72	1.88		1.88
5673.9	E - 20 d			1.32	1.32
5663.9	E – 10 d			0.54	0.54
5695.63	A 10 (34.96)	95.33	6.99		6.99
5840	V1 - 20 d			5.74	5.74
5850	V1 - 10 d			0.19	0.19
5858	V1 - 2 d			0.48	0.48
5867.01	V1 + 7 d			9.62	9.62
5944.7	A 15(0.98)	2.39	0.00		0.00
6064.66	V2 –20 d			3.30	3.30
6074.66	V2 – 10 d			0.10	0.10
6082.66	V2 – 2 d			0.15	0.15
6091.17	V2 + 7 d			28.18	28.18
6250.91	A 20 (15.1)	73.49	2.34		2.34
6364.96	A 22 (61.98)	306.59	3.22		3.22
6436.94	M1 – 20 d			3.78	3.78
6446.94	M1 – 10 d			0.22	0.22
6454.94	M1 - 2 d			0.52	0.52
6491.78	A-27 (24.04)	138.81	14.45		14.45
6562.64	A-29 (62.96)	371.25	19.07		19.07
6680.92	M2 - 40 d			6.96	6.96
6700.92	M2 – 20 d			0.69	0.69
6710.92	M2 – 10 d			0.28	0.28
6718.92	M2 – 2 d			1.24	1.24
6728.35	B-1 (24.48)	132.58	7.28		7.28
6761.46	B-3 (48.35)	296.96	19.15		19.15
6815.51	B-5 (49.92)	279.97	12.58		12.58
6877.50	B-7 (46.7)	291.03	26.72		26.72
6924.55	B-9 (53.8)	302.44	1.45		1.45
6993.32	B-11 (31.65)	197.24	1.65		1.65
7031.90	B-13 (57.62)	324.24	2.81		2.81
7099.03	M3 – 66 d			8.18	8.18
7121.66	B-15 (7.32)	45.88	0.00		0.00

Start Time MJD2000	Event/Arc (duration, days)	ΔV (m/s)	Navigation LT (m/s)	Navigation TCMs (m/s)	ΔV nav (m/s)
7147.66	M3-20 d			2.59	2.59
7157.66	M3-10 d			0.19	0.19
7165.66	M3-2 d			0.22	0.22
7175.54	M3+7 d			19.73	19.73
7188.94	M4-20 d			0.63	0.63
7198.94	M4-10 d			0.16	0.16
7215.87	M4+7 d			4.33	4.33
7275.30	M5-20 d			0.61	0.61
7285.30	M5-10 d			0.20	0.20
7337.88	B-27 (40.7)	215.68	21.84		21.84
7378.61	B-29 (43.1)	243.45	16.30		16.30
7425.82	B-31 (44.5)	241.18	9.28		9.28
7513.75	B-33 (47)	252.23	26.64		26.64
7570.27	MOI-60 d			6.49	6.49
7580.27	MOI-50 d			1.68	1.68
TOTAL		4492.34	198.62	117.82	316.44

4.3.1. Summary and conclusions

The total fuel consumption for all the guidance tasks is 316.44 m/s, 117.824 m/s corresponding to trim manoeuvres and 198.62 m/s for the guidance during the low thrust arcs. This last value corresponds to a 4.4 % of the total fuel consumption (4492.34 m/s) during the nominal low thrust arcs, below the 5% limit kept for navigation issues when designing the trajectory.

The case with a delay of 7 days between measurements processing and guidance activities in powered arcs show a saving in ΔV of a 16.5% during the second part of the trajectory. From 145.7 m/s when the delay is 14 days to 121.66 m/s when the delay is 7 days. The impact on the TCM requirements is not noticeable.

When comparing the navigation requirements of this trajectory to that reported in in [RD.13] (similar to the one presented here but with only four Mercury Gravity Assist Manoeuvres), it is shown that for the former trajectory, 141.9 m/s were required for the guidance activities during powered arcs of the last part of the trajectory, and 54.3 m/s for the TCMs. Thus, the modified trajectory shows similar requirement for thrust arcs (145.7 m/s) and much lower fuel requirements (45.01 m/s) for TCMs.

5. NAVIGATION AND GUIDANCE ANALYSIS OF THE DAWN TRAJECTORY WITH LOTNAV MONTECARLO UTILITY

An analysis of the Dawn trajectory was conducted to show the performances of such mission. This mission is characterised by very long thrust arcs. Only the summary of the resulting data is provided. Detailed information is provided in the Final Report of the project.

5.1. Description of the Trajectory

The trajectory has been split in two parts, part one from Earth departure up to Vesta (MJD= 2825.9 to 4169), and part 2 from departure from Vesta to the end of the mission (MJD= 4580 to 5525) .

5.2. Guidance activities during part A of the trajectory: Earth-Mars-Vesta

Information on the guidance activities of Dawn mission has not been found on public references, the only data found is related to the first TCM implemented during the mission. This TCM takes place on 20th of November of 2008. This TCM made the scheduled following TCM not needed.

For that TCM, electric propulsion was used. The spacecraft pointed a thruster in the required direction. While typical thrusting during the mission has lasted for almost 7 days at a time (followed by short coast arcs of 7 to 8 hours), in this case only a short burn was necessary (about two hours). This manoeuvre changed the spacecraft speed by a bit more than 60 cm per second.

For the simulated case, a TCM is established close to that date. In case this TCM is not included, the following TCM 20 days before the flyby was about 20 m/s, showing the effectiveness of a correction manoeuvre at that time (as it was the case in the real trajectory).

The amount of ΔV computed in the simulated trajectory is not comparable to that in the real trajectory. It has to be accounted that the results provided from the simulations correspond to the 3σ value and the real ΔV correspond to one case. Additionally, difference may exist on the orbit determination capabilities, although the knowledge obtained for the real trajectory is not known.

5.3. Guidance activities during part B of the trajectory: Earth-Vesta-Ceres

Since this phase has not yet started in the real Dawn trajectory, and thus no information on the real TCM is available (nor on the planned manoeuvres), we have simulated the navigation approach with similar assumptions than those used for the analysis of BepiColombo trajectory.

Since the last thrust arc lasts until the arrival to Ceres, no TCMs have been included. The last 30 days of this last thrust arc are simulated with daily measurements to improve the knowledge before the arrival.

5.4. Total Low-Thrust and TCMs Fuel Consumption

Table 8 provides the one and the three-σ of the normal distribution for fuel consumption associated to the Monte Carlo execution for every arc. LOTNAV provides the fuel consumption in terms of mass (kg). The nominal fuel consumption for each arc is provided in column five and the arc duration is given in column six. The percentage of the nominal mass consumption represented by the 3-σ for guidance purposes is provided in column 4. It must be noted that this percentage gives a value that may compare different arcs, since the fuel consumption (column number three) is dependent on the arc duration. Two last columns provide the nominal and guidance ΔV in m/s.

Table 9 summaries data on the required TCMs for guidance purposes. The fuel consumption for the trim manoeuvres is provided for different values of the relevant percentiles. The 99.7% percentile will be used for the summary of the total fuel consumption (in order to compare data with Low Thrust arcs, whereas required fuel consumption for guidance is provided in terms of 3-σ of the normal distribution).

Table 8: Navigation requirement during Low-Thrust arcs of Dawn trajectory

Arc	Navigation sigma (kg)	Navigation 3sigma (kg)	Fuel Consumption %	Fuel consumption (kg)	Arc Duration (days)	mass init (kg)	mass end (kg)	deltaV (m/s)	DeltaV nav (m/s)
A -3_1	0.02	0.07	0.26	26.32	0.00	1201.26	1174.93	911.97	2.35
A -3_2	0.03	0.08	0.20	40.00	0.00	1174.93	1134.93	1425.68	2.83
A -8_1	0.05	0.16	0.54	30.01	0.00	1135.03	1105.02	1102.90	5.98
A -8_2	0.08	0.23	0.81	28.00	0.00	1105.02	1077.02	1056.39	8.53
A -9_1	0.10	0.30	0.63	47.02	0	1077.02	1030.00	1837.32	11.63
A -9_2	0.15	0.46	1.09	42.35	0.00	1030.00	987.65	1728.21	18.81
B -1_1	0.02	0.05	0.17	29.00	0.00	985.00	956.00	1230.01	2.08
B -1_2	0.08	0.25	0.88	28.13	0.00	956.00	927.87	1229.12	10.77
B -3_1	0.09	0.26	1.29	19.87	0.00	927.87	908.00	891.18	11.50
B -3_2	0.07	0.20	1.36	15.00	0.00	908.00	893.00	685.63	9.33
B -3_3	0.05	0.15	3.20	4.67	0.00	893.00	888.33	215.62	6.91
TOTAL	0.73	2.20	0.71	310.37	kg			**12314.04**	**90.71**

Table 9: Correction manoeuvres for the Dawn trajectory

date	TCM (m/s)	90th P	91th P	92th P	93th P	94th P	95th P	96th P	97th P	98th P	99th P	99.5th P	99.7th P	99.9th P
2830.50	Ed+7	2.539	2.579	2.638	2.696	2.752	2.826	2.915	3.018	3.167	3.401	3.620	3.772	4.085
3244.95	M- 86	2.222	2.257	2.309	2.359	2.408	2.473	2.551	2.641	2.771	2.976	3.167	3.301	3.574
3310.78	M-20	0.704	0.715	0.731	0.747	0.763	0.783	0.808	0.837	0.878	0.943	1.003	1.046	1.132
3320.78	M-10	0.081	0.082	0.084	0.086	0.087	0.090	0.092	0.096	0.101	0.108	0.115	0.120	0.130
3327.78	M-3	0.067	0.068	0.070	0.071	0.073	0.075	0.077	0.080	0.084	0.090	0.096	0.100	0.108
3341.96	M+10	18.306	18.594	19.018	19.433	19.839	20.369	21.011	21.757	22.831	24.516	26.093	27.191	29.445
	TOTAL	23.919	24.295	24.850	25.392	25.922	26.616	27.454	28.429	29.832	32.034	34.094	35.530	38.474

5.5. Summary of Fly-By Performance

Table 10 provides data on the dispersion ellipse (3-σ) in the B-plane and pericentre plane. The 3-σ dispersion ellipsoids at B-plane and pericentre plane for the flyby at Mars in Figure 36.

Table 10: Dispersion Ellipse in Mars B-plane and Pericenter-plane for Dawn trajectory

	B-plane	Pericenter Plane
X-coord. of ellipse centre (km)	-4321.887	-2173.643
Y-coord. of ellipse centre (km)	-5601.696	-3235.554
Semi-major axis of the ellipse (3σ,km)	101.263	58.832
Semi-minor axis of the ellipse (3σ,km)	38.861	26.527
Angle of the semi-major axis (deg)	-66.913	-82.648

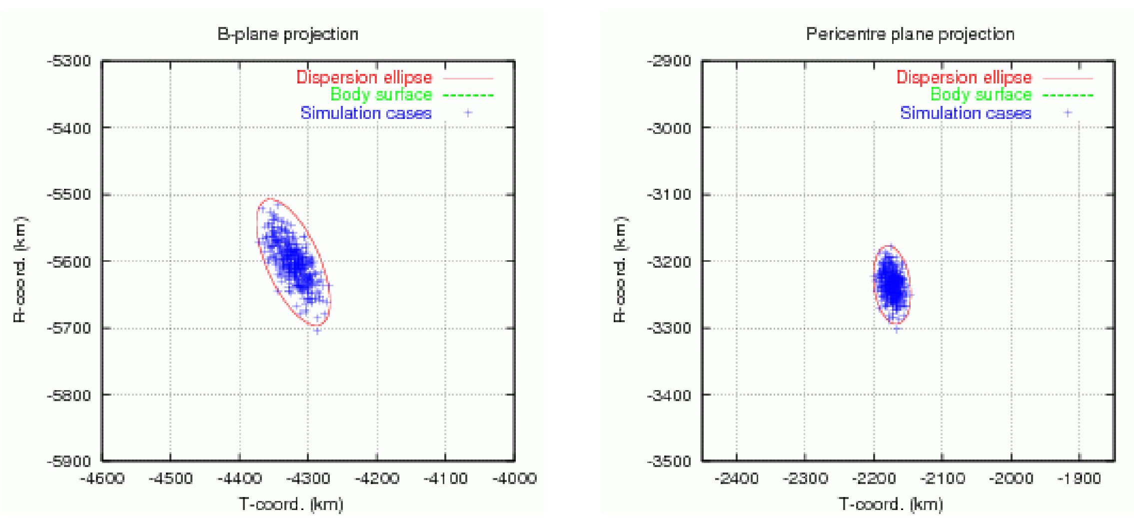

Figure 36: Dispersion at Mars GAM at the B-plane (left plot) and Pericentre plane (right plot)

6. NAVIGATION AND GUIDANCE ANALYSIS OF THE BEPICOLOMBO TRAJECTORY WITH RE-OPTIMISATION

The project was devoted to the analysis of operational navigation concepts and, among others, the most promising one is the re-optimisation of the trajectory when processing data from the navigation activities. For such analysis, it is required to mix the re-optimisation activities (used for the design of the trajectory) with the knowledge and dispersion information. This is a hard task which requires a complete evaluation of the quality of the analysed trajectory. Explanations on that analysis are provided in the Final Report of the project.

This section only reports the main findings on the navigation and guidance analysis with the re-optimisation process for a segment of a BepiColombo trajectory.

The trajectory of application to the analyses presented in this document is the one computed in the Spring of 2008 and fully documented in our [RD.12] which also includes the navigation and guidance analyses for this trajectory as performed with the use of LOTNAV's *Monte Carlo Utility* aka *Simulation Utility*. That document includes all the relevant information which are not reproduced here

Segment 1 relates to the trajectory segment from Earth departure to the Earth swingby one year after. Table 11 provides a summary of the trajectory, navigation and guidance conditions for each of the sub-arcs in this trajectory segment. In the table, the central body is identified by its first letter (S for Sun, E for Earth), the sub-arc type by whether is of coast (C) or thrust (T) and whether (Y) or not (N) there are trajectory correction (TC) events defined in a given sub-arc. Lines corresponding to thrust arcs are slightly shaded.

In particular, we have within this segment 7 arcs and 10 sub-arcs. Arcs 3 and 5 are of thrust, whereas the rest are of coast. Scan time for measurements is 10 min for all sub-arcs and mapping time unit is half a day, which results in the number of mapping times provided in the third column starting from the right. TCMs are defined 6 days after the start of sub-arc 2.1, and respectively 20 and 10 days prior to the end of sub-arc 6.2. Low-thrust re-optimisation processes are performed at the start of each of the thrust arcs. This means that this segment of the whole trajectory is re-optimised at 5 different times in the execution of the RGU for each simulation..

Figure 37 provides the results of computing the target position unitary kilometre delta-V cost and the target matching delta-V residual. The boundaries between the arcs are also provided as dashed vertical lines. In the first plot the discontinuity present at 5565 MJD2000 is due to the start of the first arc (arc #5) in the backward propagated part of the segment, which has slightly different state vector than before, due to the optimisation mid-point residuals. Regarding the second plot, it provides the delta-V required to compensate the segment's mid-point residual, which is observed to peak at around 5478 MJD2000 with about 22 m/s. Correction burns around this area shall be avoided. From arc #5 the values go to zero because in those places the trajectory was obtained by backward propagation from the target state.

Comparing to the case presented in [RD.12] following comments are provided:

- Orbit determination conditions are the same
- TCMs are performed at same instants
- Low-thrust guidance is performed differently between MCU and RGU in the following:

- With the MCU the thrust law was recomputed weekly in each of the thrust arcs by means of LQC and targeting to the end of the arc or the end of the next arc. Some intervals of time at the end of each thrust arc were left without guidance and two weeks were assumed to elapse between OD and updated guidance solution upload to S/C
- With the RGU the thrust laws are going to be recomputed once at the start of each of the thrust arcs by means of trajectory re-optimisation from those instants down to next Earth encounter

The Monte Carlo with re-optimisation consisted of 200 simulations with a maximum limit of 100 iterations in the re-optimisation process whenever this is called. The computation required 142 hours, thus 43 min per simulation.

Table 11: Summary of trajectory and navigation conditions of application to segment 1

Arc	Sub-arc	Start date (MJD2000)	Central body	Sub-arc type	Sub-arc duration (day)	Mapping time unit (day)	Num. of mapping times	TCs	TCs performed at MT
A1	1.1	5327.441	E	C	2.559	0.5	7	N	-
A2	2.1	5330.000	S	C	18.390	0.5	38	Y	7
-	2.2	5348.390	S	C	30.000	0.5	61	N	-
A3	3.1	5378.390	S	T	41.318	0.5	84	Y	1
A4	4.1	5419.708	S	C	115.642	0.5	233	N	-
-	4.2	5535.350	S	C	30.000	0.5	61	N	-
A5	5.1	5565.350	S	T	40.247	0.5	82	Y	1
A6	6.1	5605.597	S	C	54.794	0.5	111	N	-
-	6.2	5660.391	S	C	30.000	0.5	61	Y	21, 41
A7	7.1	5690.391	E	C	2.364	0.5	6	N	-

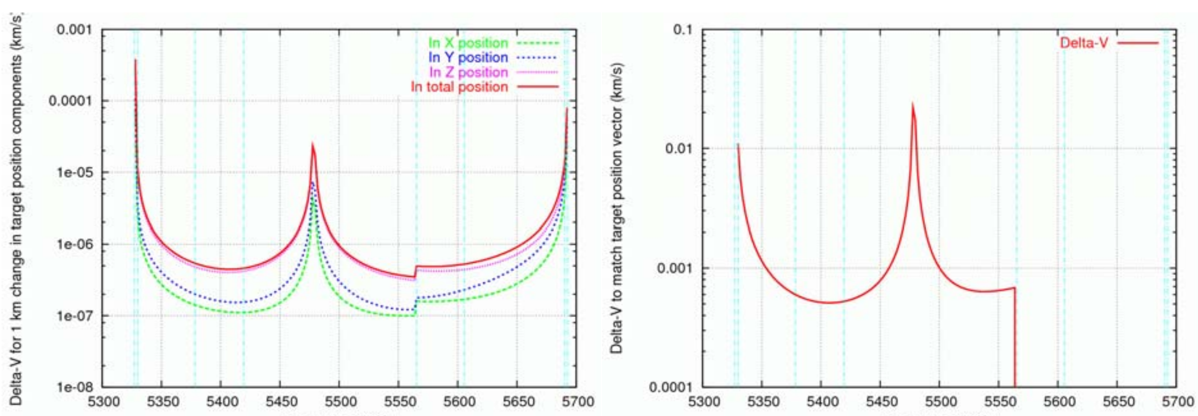

Figure 37: Segment 1: Target position unitary kilometre delta-V cost (left) and target matching residual delta-V (right)

Figure 38 provides the obtained evolution of the 1-sigma position and velocity knowledge as derived after the statistical analysis of the obtained results. These plots are to be compared to the ones provided in figure 10 of **Error! Reference source not found.**, where a great similarity can be found between the traditional MC results and the re-optimisation results. The effect of the error in the implementation of the low-thrust during arcs #3 and #5 over the knowledge in velocity is quite clear, with a lesser impact over the position uncertainty.

Figure 39 provides the obtained evolution of the 1-sigma position and velocity dispersion as derived after the statistical analysis of the obtained results. These plots are to be compared to the ones provided in figure 9 of **Error! Reference source not found.**. The similarity here fails to occur, having the case after re-optimisation larger average dispersions during the transfer although achieving final values very comparable to the ones obtained in the traditional MC.

The larger dispersion from the beginning is due to the fact that the re-optimisation process is not giving any relevance to the initial TCM, as the re-optimisation of the ulterior thrust arcs is preferred by the optimiser to compensate the launch dispersions. In fact, this can be observed in Table 12 where the original 11.39 m/s TCM is almost zero for the re-optimisation case. This means a saving of 14.3 kg of propellant. Looking to the low-thrust consumption, this is slightly larger, as expected by the larger needs to mitigate the non-compensated launcher dispersion. However the increase is not very large, which translates in a slight increase in fuel mass of less than 0.4 kg. The final TCMs result smaller for the re-optimisation case resulting in a further mass saving of 1.37 kg.

Table 13 provides the obtained values for the dispersion ellipse at the next encounter, resulting in very similar ellipses in both cases in what regards the semi-major axis (0.3 km difference) and angle (11.5º difference). The difference in semi-minor axis is about double. No explicit explanation has been found yet for this difference, although it has been seen that the evolution of the dispersion among the two cases is relatively different, which might lead to this situation.

Additionally to the previous, Figure 40 provides the statistical cumulative distribution of arc start epoch, arc end epoch and arc duration for arcs #3 (left) and #5 (right) with respect to their respective mean values. As it can be observed, the variations in the timely parameters of the two thrust arcs in this segment are smaller than 3 days. The resulting numerical statistics for those variables are provided in Table 14.

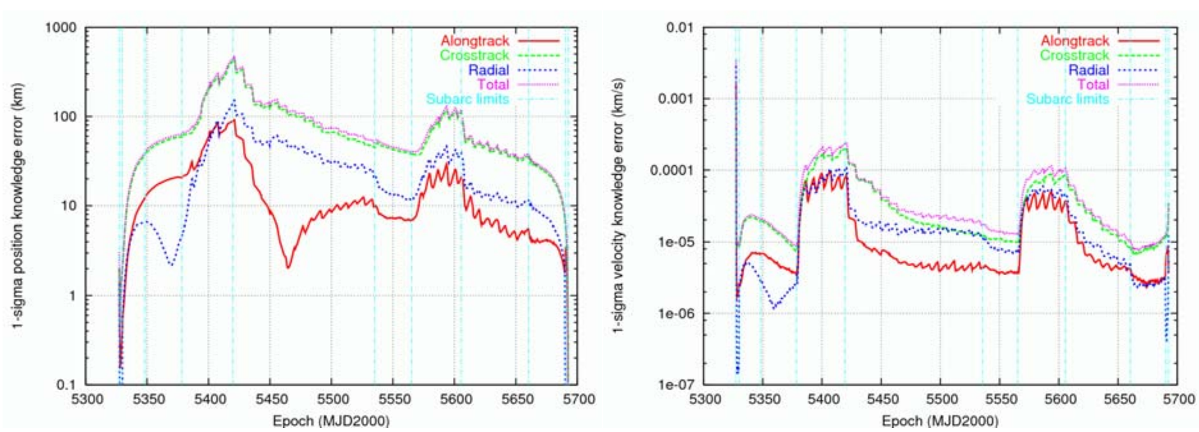

Figure 38: Segment 1: 1-sigma position and velocity knowledge evolution

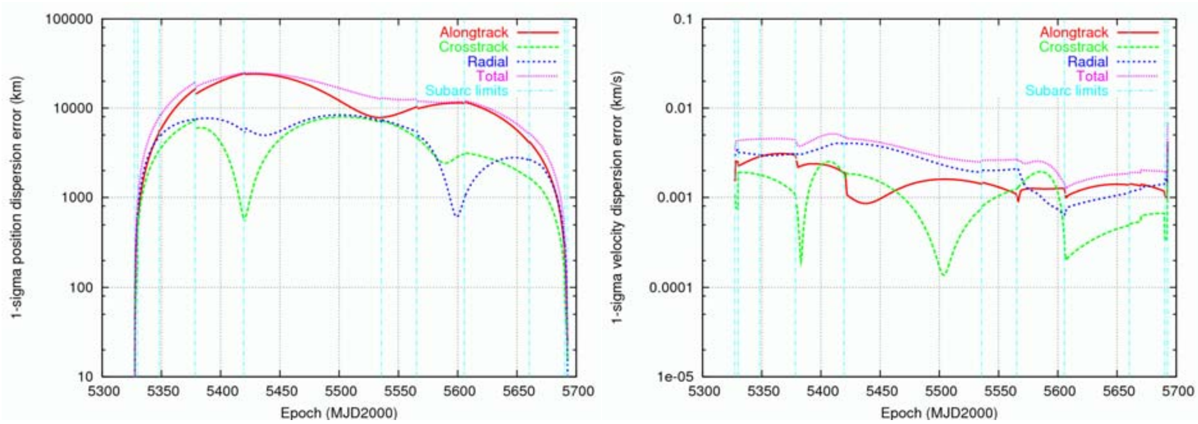

Figure 39: Segment 1: 1-sigma position and velocity dispersion evolution

Table 12: Segment 1: Resulting delta-V and fuel mass navigation budget (99.7% percentile)

TC sub-arc & MP	Correction type	Delta-V budget (m/s)		Mass budget (kg)		
		Traditional	Re-optimisat.	Traditional	Re-optimisat.	Difference
A2.1-7 / Ed+5	TCM	11.39	0.02	14.30	0.03	14.27
A3.1-1	LT	3.17	5.78	0.27	0.48	14.05
A5.1-1	LT	5.74	7.20	0.48	0.60	13.93
A6.2-21 / E-20	TCM	3.48	2.41	4.35	3.02	15.27
A6.2-41 / E-10	TCM	0.11	0.08	0.14	0.10	15.31

Table 13: Segment 1: Resulting B-plane dispersion ellipse at Earth GAM1

Parameter	Traditional analysis	Re-optimisation analysis
T-coord. of ellipse centre (km)	23225.157	23223.214
R-coord. of ellipse centre (km)	-13149.434	-13147.868
Semi-major axis (3-sigma) (km)	78.481	78.196
Semi-minor axis (3-sigma) (km)	14.753	32.807
Angle of the semi-major axis (deg)	-88.461	80.048

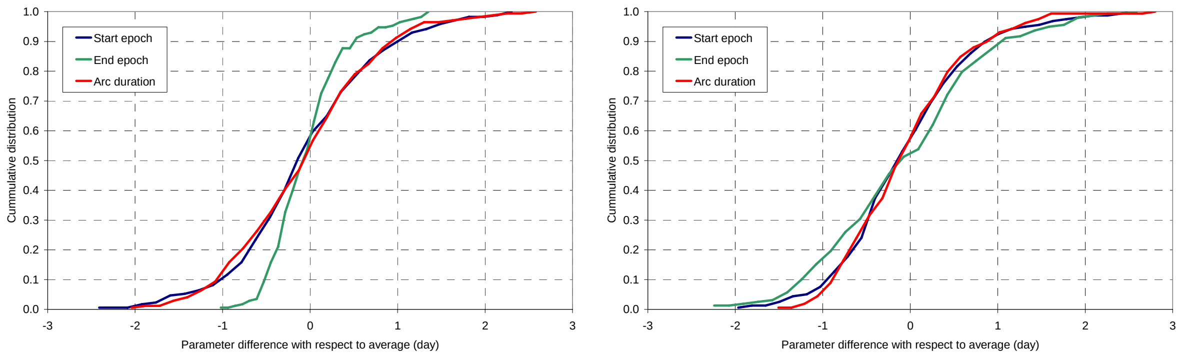

Figure 40: Segment 1: Statistical cumulative distribution of arc start epoch, arc end epoch and arc duration for arcs #3 (left) and #5 (right) with respect to their respective average values

Table 14: Segment 1: Statistics of the timely definition for arcs #3 and #5

Arc	Derived data	Nominal	Minimum	Maximum	Mean	Sigma
3	Start epoch (MJD2000)	5378.3899	5377.5119	5382.3890	5380.0040	0.8314
	End time (MJD2000)	5419.7081	5420.1204	5422.5758	5421.1813	0.4361
	Duration (day)	41.3182	39.0576	43.8350	41.1773	0.8065
5	Start time (MJD2000)	5565.3497	5564.4678	5569.1574	5566.5115	0.7737
	End time (MJD2000)	5605.5969	5604.7353	5609.7296	5607.0582	0.9193
	Duration (day)	40.2472	38.9662	43.4213	40.5468	0.6881

7. SUMMARY AND CONCLUSIONS

The work done during this activity has allowed the evaluation of operational constraints and their impact on the trajectory design.

In particular, two main aspects have been analysed:

- Location of time buffer to allow recovery under different contingency cases and thus, defining an operationally safe trajectory
- Operational Navigation Concepts based on Re-Optimisation of the trajectory and its comparison with traditional analysis at mission analysis phases based on MonteCarlo executions of guidance activities (with variations of thrust modulus and insertion of TCMs).

Regarding the contingency analysis, it can be concluded that the pattern with better failure recovery performances depends on the arc where the failure occurs. In case the arc is located close to a GAM (which constraints the end part of the thrust arc) the trajectory with pattern with the entire buffer at the end of the nominal thrust arc is more robust. A thrust underperformance of a 10%¨of the thrust modulus is not really demanding except for arcs located in the middle of M2-M3 phase. Demanding failures may require second pattern for duty cycle, whereas the evenly distributed coast arcs cannot solve those contingency cases. The duration of the coast arc before GAM needs to be relaxed in some cases if the trajectory cannot be recovered after failure. Solar Aspect Angle constraints should be relaxed in some cases, although that is not possible and thus, the recovery is not possible for some failure outages.

In regards to the Navigation and Guidance analysis, a complete analysis of several trajectories (BepiColombo and Dawn) was done, providing the required fuel for the guidance activities. Additionally, a comparison of the results from traditional analysis with the re-optimisation analysis is done. This comparison shows a similar behaviour in the evolution of knowledge and dispersion along the trajectory, except for some particular cases derived from the different means for reduction of dispersion. In the case of re-optimisation analysis, the re-definition of thust arcs is preferred to the application of TCM, and thus the fuel consumption and dispersion evolution is different. In particular for the Earth to Earth phase of the analysed trajectory, 14.3 kg in the TCM to compensate launch dispersion are saved, whereas a slightly larger low-thrust consumption is found.

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