NAVIGATION TOOLS AT ESOC MISSION ANALYSIS SECTION

BEPICOLOMBO NAVIGATION ANAYLSIS

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INNOVATING SOLUTIONS

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INTRODUCTION

NAVIGATION IMPORTANCE

Crucial for Interplanetary Missions

Flybys accurate targeting →
- avoid expensive correction manoeuvers
- ensure safe closest approach
- enhance science return

Several tools available at ESOC Mission Analysis Section

INTNAV, LOTNAV, FASTMOPS, others

Goals:

- Assess guidance and navigation costs
- Select baselines and requirements for orbit determination measurements
- Individuate Critical Phases
- Perform sensitivity analyses

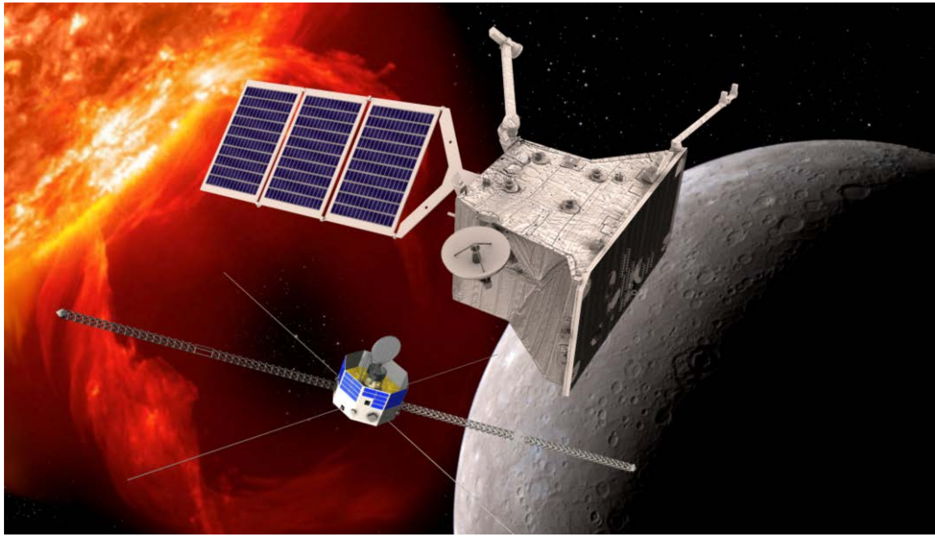
BEPICOLOMBO

ESA/JAXA mission to Mercury

2 spacecrafts → Mercury Planetary Orbiter (MPO)
→ Mercury Magnetospheric Orbiter (MMO)

+

Mercury Transfer Module (MTM)



Hybrid propulsion: low-thrust ion electric + chemical

Multiple Flybys of Earth, Venus and Mercury during the interplanetary transfer

BEPICOLOMBO SETUP

SIMULATION SETUP FOR BEPICOLOMBO

Special Mission Requirements:

- Simulate accurately a low thrust interplanetary orbit with major bodies encounters
- Solve guidance problem for hybrid system (low-thrust and instantaneous manoeuvers)
- Account for uncertainties in propulsion performance
- Simulate the full guidance and navigation process

Ad hoc tools and simulation setup to have realistic reproduction of operation strategy that will be used

- Core tool used is LOTNAV
- MANTRA is used for the trajectory re-optimization

SOFTWARE TOOLS

LOTNAV

LOw Thrust NAVigation tool (LOTNAV)

Developed by Deimos Space S. L. under ESA contract

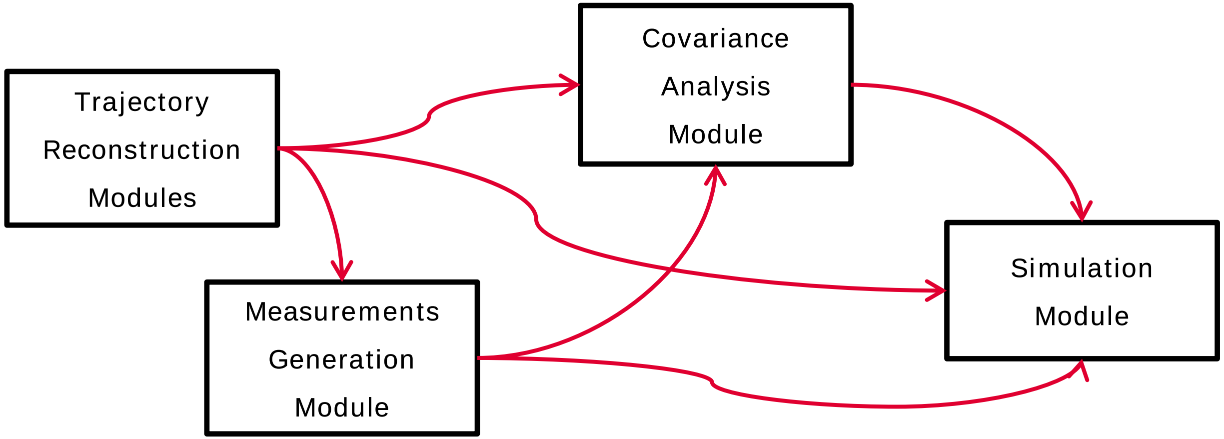
Main Functions:

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

One or more modules per function

LOTNAV: modules

Core modules only (additional and support modules also present)



- Two modules for trajectory reconstruction (increasing level of accuracy)
- Orbit determination measurements simulated according to different schedules
- Measurments processed with batch-sequential Square Root Information Filter (SRIF)
- Simulation module includes the guidance process

MANTRA

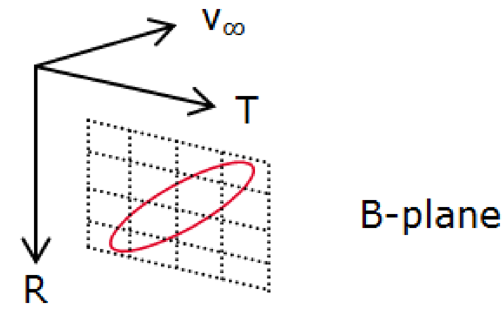
Flight dynamics interplanetary manoeuver optimization software

Key Function: compute during operations the orbit manoeuvers required to reach given orbital targets while satisfying given mission constraints and minimizing a given cost function

Other Functions: mission design and preparation studies (launch window definition or verification, trade-off studies, sensitivity analyses)

Flexibility ↔ different scenarios simulation

Example: low-thrust interplanetary trajectory re-optimization



study how a different B-plane crossing point at a given flyby

affects the optimization of the downstream trajectory

SIMULATION WORK FLOW

SIMULATION WORK FLOW

1. Regeneration of the reference optimized trajectory (LOTNAV internally consistent)
2. full guidance and navigation simulation with LOTNAV (assumptions for the orbit determination and guidance)
3. [Eventual] re-iteration of the guidance and navigation process (different strategies of guidance targeting, measurements schedule)
4. Trajectory re-optimization with MANTRA (given dispersion from step 2/3)
5. [Eventual] re-iteration on step 3/4

Major Assumptions:

- Negligible difference in trajectory after re-optimization (for navigation analysis purposes)
- Clean-up after flyby simulated in LOTNAV not accounted in total budget (re-optimization instead)

ASSUMPTIONS

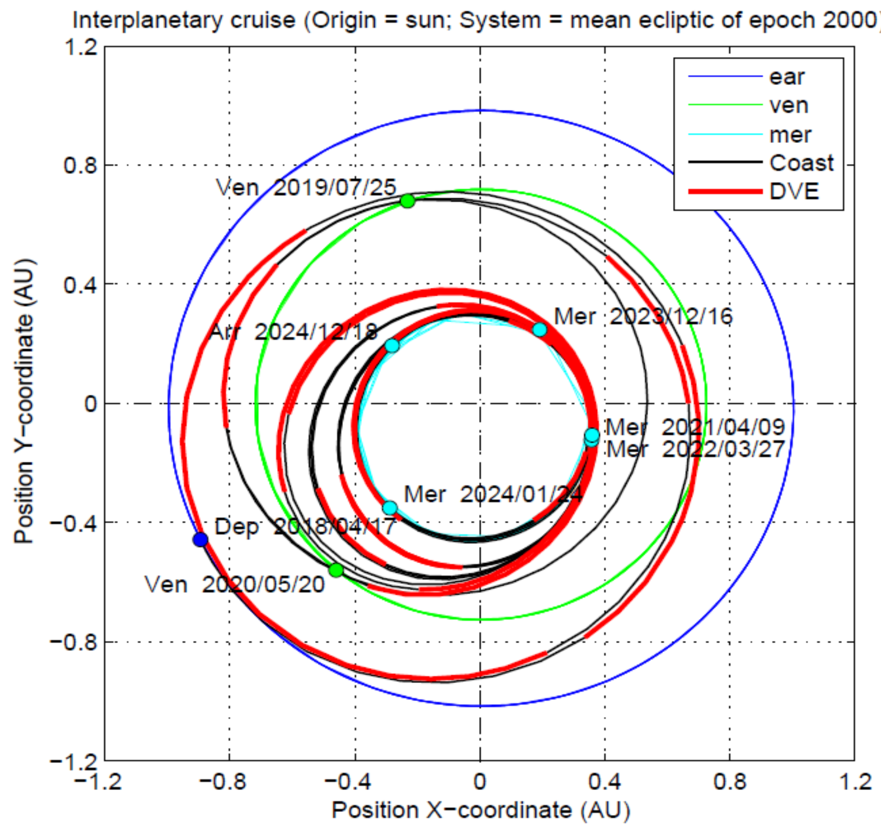
Assumptions: trajectory

Baseline Bepicolombo trajectory

Launch in April 2018

Flybys sequence: dep-V-V-M-M-M-M-arr

Arrival in December 2024



Assumptions: Measurements

OD Measurements types: range, Doppler, ΔDOR

Ground stations: Cebreros (range and Doppler),

Cebreros-New Norcia + possibly Cebreros-Malargüe (ΔDOR)

Ground station availability: one pass per week (interplanetary phases)

one pass per day (last 30 days before each flyby)

minimum elevation of 10° (15° for ΔDOR)

Schedule: range and Doppler sampled every 60 and 10 min

ΔDOR once every four days

Ground station location error: considered bias in all direction, 0.3 m

Measurements errors:

Type	Noise (1σ)	Bias
Range	10 m	2 m
Doppler	0.3 mm/s	--
ΔDOR	0.2 m	--

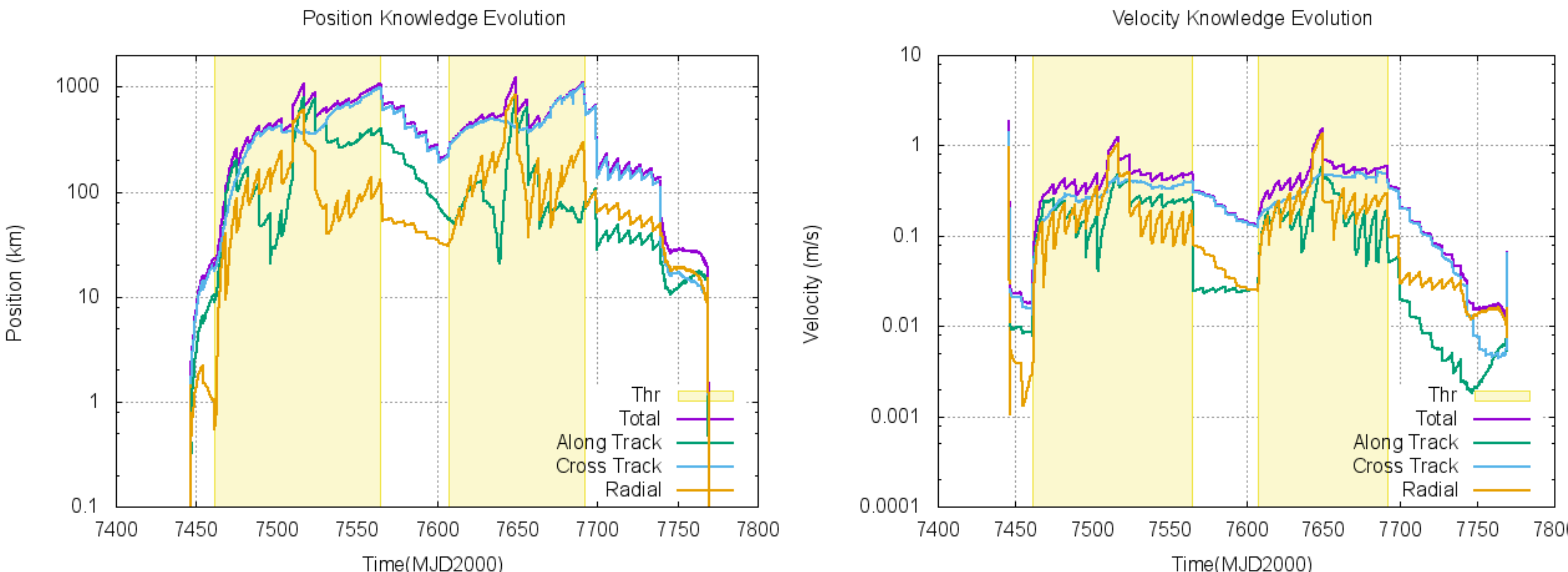
Assumptions: Orbit Determination and Guidance

Initial Knowledge and Dispersion:	from launcher performance data
Spacecraft residual acceleration:	ECRV, 1 σ steady state covariance of 10^{-11} km/s^2, autocorrelation time 1 day
Guidance baseline scheme:	low-thrust guidance whenever possible during thrust arcs
	1 clean-up TCM after each flyby (+5 days, not accounted in budget)
	3 TCMs before each flyby (-20, -10, -2 days)
Low thrust guidance:	delay in guidance upload of 14 days (conservative)
	0.5 days unavailability at beginning and end of each thrust arc
	error in execution as ECRV, 1 σ steady state covariance of 1% in modulus and 0.5° in direction, autocorrelation time 1 day
Chemical guidance manoeuvers:	error in execution as Gaussian, 1 σ of 1% in modulus and 0.5° in direction

Assumptions: low-thrust arcs constraint

Considered in trajectory optimization (MANTRA) but related to navigation:

- 30 days coasting before each flyby imposed ⟶ better spacecraft state knowledge for more precise TCMs

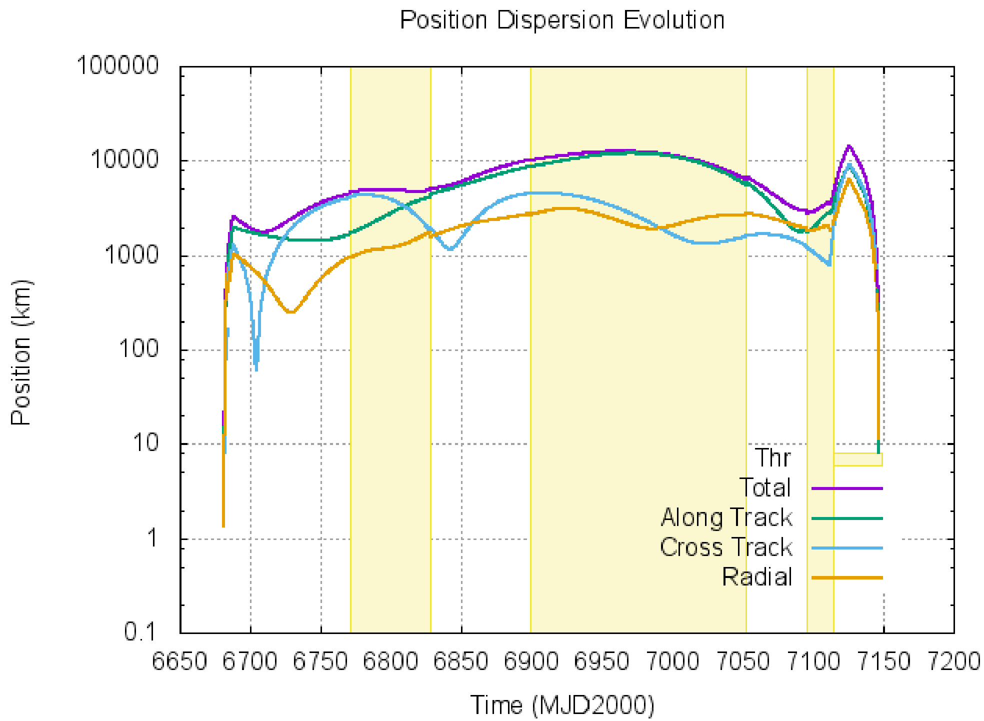


Venus-to-Mercury interplanetary phase

RESULTS

Guidance strategy, example

Earth-to-Venus phase, standard guidance strategy:



low-thrust guidance in all thrust arcs

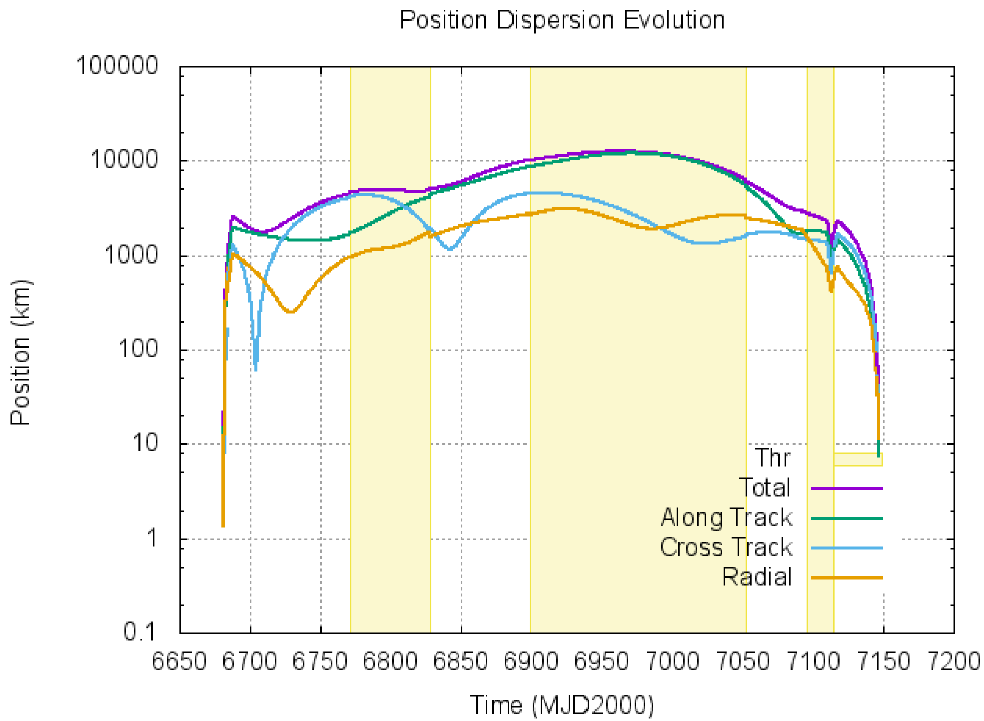
3 TCMs

TCM epoch	TCM magnitude [m/s]
V1-20.9 d	38.900
V1-10.9 d	0.949
V1-2.9 d	0.173

Total > 40 m/s

Guidance strategy, example

Earth-to-Venus phase, modified guidance strategy:



low-thrust guidance in all thrust arcs

3 TCMs + **2 additional**

(1 before and 1 after last low-thrust arc)

TCM epoch	TCM magnitude
V1 – 54.7 d	3.130
V1 – 29.4 d	11.129
V1 - 20.9 d	0.852
V1 - 10.9 d	0.080
V1 - 2.9 d	0.156

Total < 16 m/s

Guidance strategy, targeting

Targeting parameters:

- Spacecraft state at given epoch
- B-plane parameters at flyby epoch

Targeting epoch:

- Strongly affects the total navigation cost
- Optimum choice related to trajectory dynamics and not trivial

Example: Earth-to-Venus-1 interplanetary phase, targeting epoch influence

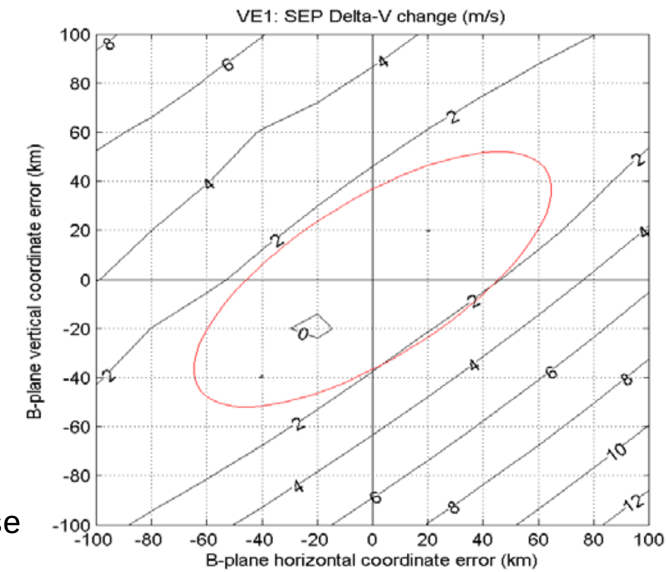
Targeted parameters time (epoch [MJD2000])	First TCM before M2 [m/s]
SOI entrance (7145.8)	14.287
End of last thrust arc (7114.1)	11.129

Dispersion at B-plane

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

- Always acceptable levels of dispersion
- No need of second ΔDOR baseline to reduce the knowledge error

- Very cheap re-optimization in most cases can be used instead of reducing dispersion via direct clean-up



Venus-1 case

Mercury-3-to-Mercury-4 re-optimization

Very short interplanetary phase: 37 days

↓

Low-thrust arcs cannot be introduced (30 days constraint)

↓

Re-optimization cannot correct for the dispersion accumulated

↓

Clean-up manoeuver is <u>only option</u>*

Clean up at M3 + 5.04 days selected as baseline: 3 sigma cost = 9.557 m/s

*Normally discarded since low-thrust re-optimization is much less expensive (in mass terms)

Total Navigation Cost

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

Total low-thrust ΔV = 158.021 m/s

Total chemical ΔV = 58.959 m/s

Close to pre-allocated value if all losses taken into account

All values are at 3 σ confidence

CONCLUSIONS

Conclusions

General remarks:

- Current software setup is considered reliable and coherent

BepiColombo navigation analysis:

- Selected measurement schedule is sufficient
- Most of the interplanetary arcs required additional TCM to lower the overall cost
- Critical phases individuated (Dep-to-V1, M3-to-M4)
- Total chemical ΔV is close to limit but still acceptable

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THANK YOU