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BepiColombo: Flight Dynamics Operations during Launch and Early Orbit Phase

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Abstract

BepiColombo was launched on 20 October 2018 to begin its 7 years of interplanetary cruise towards Mercury. The purpose of the paper is to report on the Flight Dynamics activities that have been conducted at ESA's European Space Operations Centre (ESOC) during the Launch and Early Orbit Phase (LEOP). The first three introductory sections give an overview of the BepiColombo mission, the spacecraft design and the baseline cruise trajectory, as far as is relevant for the paper. The remainder of the paper focuses on the LEOP activities. Firstly, the launch, signal acquisition at the ground stations, and the initial spacecraft operations are described. Subsequently, the focus is put onto orbit determination activities, its configuration, the available tracking data and their quality assessment as well as the launcher separation state assessment. Finally, the results of three chemical propulsion test manoeuvres are presented. The paper closes with the current status and outlook of near-term, future operational activities for BepiColombo.

Keywords: BepiColombo, LEOP, Flight Dynamics Operations, Orbit Determination, Mercury

The BepiColombo Mission

BepiColombo is a European Space Agency (ESA) cornerstone mission to Mercury which is being conducted in co-operation with Japan. The Mercury Planetary Orbiter (MPO) is ESA's scientific contribution to the mission. The Japan Aerospace Exploration Agency (JAXA) is providing the other science spacecraft, the Mercury Magnetospheric Orbiter (MMO). For launch and the journey to Mercury, the MPO and MMO are carried as part of the Mercury Composite Spacecraft (MCS). The MCS comprises, in addition to the two orbiters, the Mercury Transfer Module (MTM), which provides solar-electric propulsion and all services not required in Mercury orbit, and the MMO Sunshield and Interface Structure (MOSIF), which provides thermal protection and the mechanical and electrical interfaces for the MMO. ESA built and is controlling the MTM and the MOSIF. Shortly before Mercury Orbit Insertion (MOI), the MTM will be jettisoned from the spacecraft stack. The MPO provides the MMO with the necessary resources and services until it is delivered into its mission orbit, when control is taken over by JAXA. MPO will continue to be controlled by ESA in its scientific orbit. Fig. 1 shows an exploded view of the full MCS stack with all – MTM and MPO - solar arrays deployed.

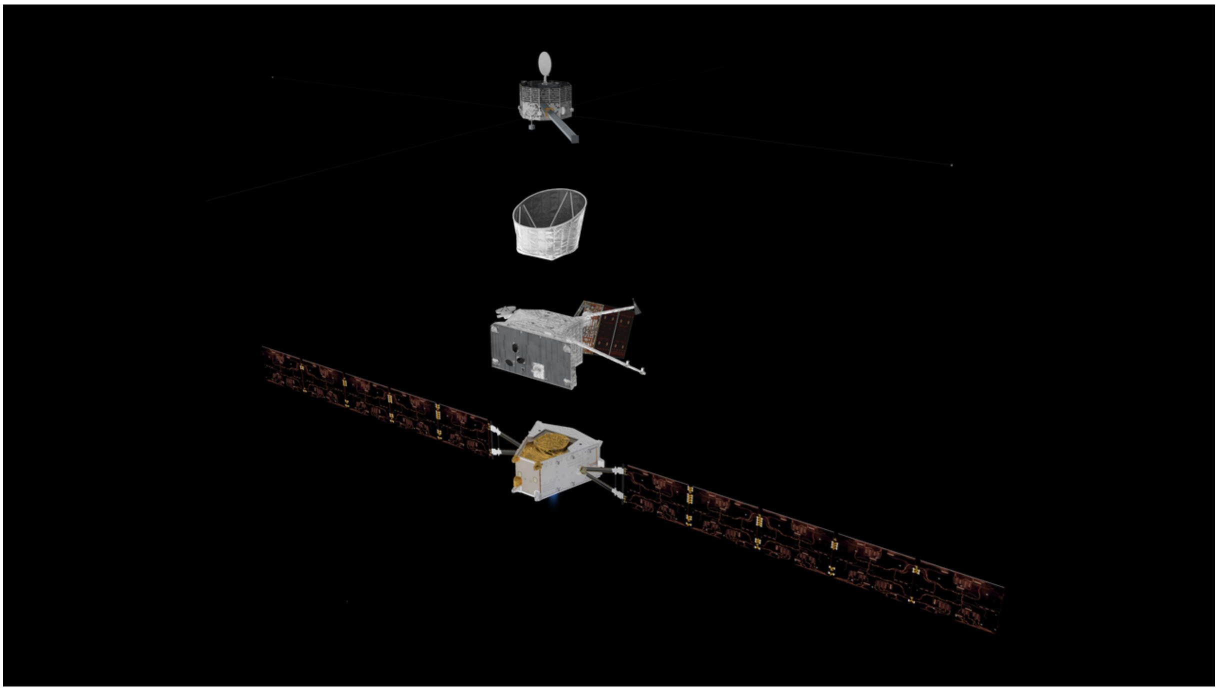

Fig. 1: BepiColombo spacecraft stack in exploded view

The BepiColombo Spacecraft

After the execution of the automatic launcher separation sequence, the BepiColombo spacecraft was in its so-called Mercury Composite Spacecraft Cruise (MCSC) configuration, which will be kept until shortly before MOI. In this configuration, the MTM provides propulsion and power functionalities whereas the MPO is in charge of all avionics and communication functions, while the MMO does not have any active function. The reference frame for the MCSC has its origin at the interface with the launcher close to the bottom of the MTM (see Fig. 1 & 2), the +Z is along the longitudinal axis towards the bottom, +Y is perpendicular to the MTM solar arrays axis on the side where MPO's solar array is located, and +X completes the right-handed coordinate system. For thermal reasons, the Sun's direction in spacecraft frame needs to be strictly controlled throughout the mission. In particular, the Sun is constrained to be in the YZ plane within a limited angular range from the +Y axis. On the –Z side, this range is defined by the MOSIF inclined structure – the Sun is never allowed to shine on MMO - , while on the +Z side it varies depending on the Sun's distance and on the status of the Solar Electric Propulsion System (SEPS). The SEPS comprises 4 SEP Thrusters (SEPT) each with up to 145 mN thrust, that can be fired either singularly or at most two simultaneously, depending on the available power. The SEPTs provide thrust approximately along the –Z direction, but a closed loop control system takes care of tilting them (by up to 16.5°) to minimise the disturbance torque, by aligning the thrust vector with the centre of mass.
Besides the SEPS, the MCSC uses the MTM's Chemical Propulsion System (CPS) for both attitude control in non-wheel controlled modes and for small trajectory correction manoeuvres for fly-by targeting or clean-up purposes. The CPS includes 2x12 MON+MMH 10N thrusters, of which 2x4 provide thrust along +Z and can be used for axial manoeuvres, while the other 2x8 are tilted to provide thrust in the YZ plane. Only the tilted thrusters are used for attitude control, in a force-free configuration (i.e. no parasitic acceleration with nominal alignments), and can also be used for lateral manoeuvres, providing thrust either towards the +Y or the –Y hemisphere in the YZ plane.
The Attitude and Orbit Control System (AOCS) is composed of 3 Star Trackers (STR) on the –Y face of the MPO, 2 Inertial Measurement Units (IMU) in the MPO with 4 gyroscope and 4

accelerometer channels each in a 45 deg pyramid configuration, 4 Fine Sun Sensors (2 on MPO and 2 on MTM) for initial Sun acquisition and safe modes, and 4 Reaction Wheels (RW) - also on the MPO - which provide attitude control actuation for most of the mission.
Communications are via X-band for up- and downlink and via Ka-band for downlink only. 2 Low Gain Antennas (LGAs) are used for near-Earth operations and for emergency, a Medium Gain Antenna (MGA) is mounted on a two degrees-of-freedom boom from MPO‘s –X side for communications during cruise and contingencies, and a High Gain Antenna (HGA) with azimuth and elevation motion is located on MPO's +X side for communications around Mercury, as well as in cruise when necessary. Due to the stringent attitude constraints and the complex MCSC configuration, communications via MGA or HGA during cruise are not always possible in SEP thrust arcs due to blocking effects of the spacecraft itself.

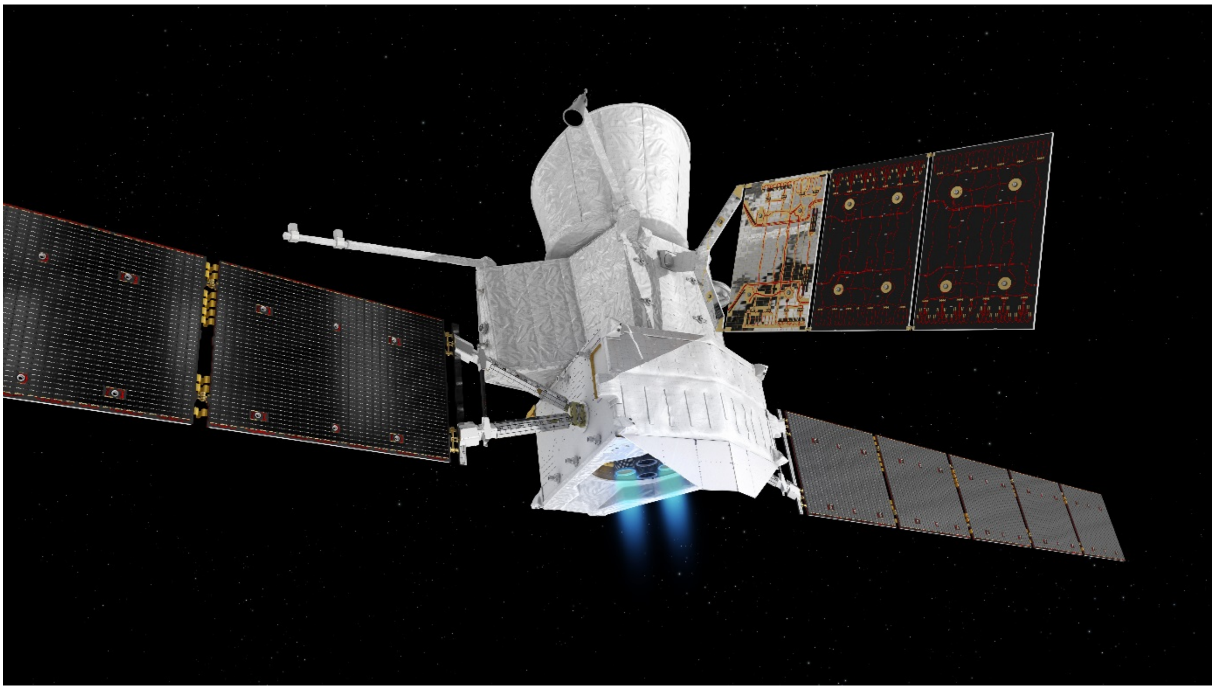

Fig. 2: BepiColombo in MSCC configuration

Baseline Cruise Trajectory

A projection of the BepiColombo baseline trajectory onto the ecliptic plane is shown in Fig. 3. The orbits of the planets are given as well, together with their positions at close encounters. Red lines indicate arcs during which the SEPS is on. The trajectory facilitates the use of the low thrust SEPS and a series of 9 planetary swing-bys in order to reach Mercury with a low relative velocity at the end of 2025 after more than 7 years of cruise. The key dates of the BepiColombo cruise trajectory are listed in Table 1. After launch the spacecraft will spend 1.5 years in a heliocentric orbit which is close to the Earth's orbit. During this period the SEP will be activated twice for about 2 months to achieve the correct phasing for the Earth swing-by on 10 April 2020. The Earth swing-by reduces the heliocentric velocity such that the spacecraft enters a direct ballistic transfer to Venus with a swing-by on 15 October 2020. It will then spend about 1.5 orbital revolutions around the Sun to come back to Venus on 10 August 2021. The second Venus swing-by reduces the spacecraft's heliocentric velocity further such that it reaches Mercury less than 2 months later for the first of a series of 6 Mercury swing-bys. Each Mercury swing by is designed to reduce the spacecraft aphelion down to the orbit of Mercury and by so doing to reduce the velocity relative to Mercury.

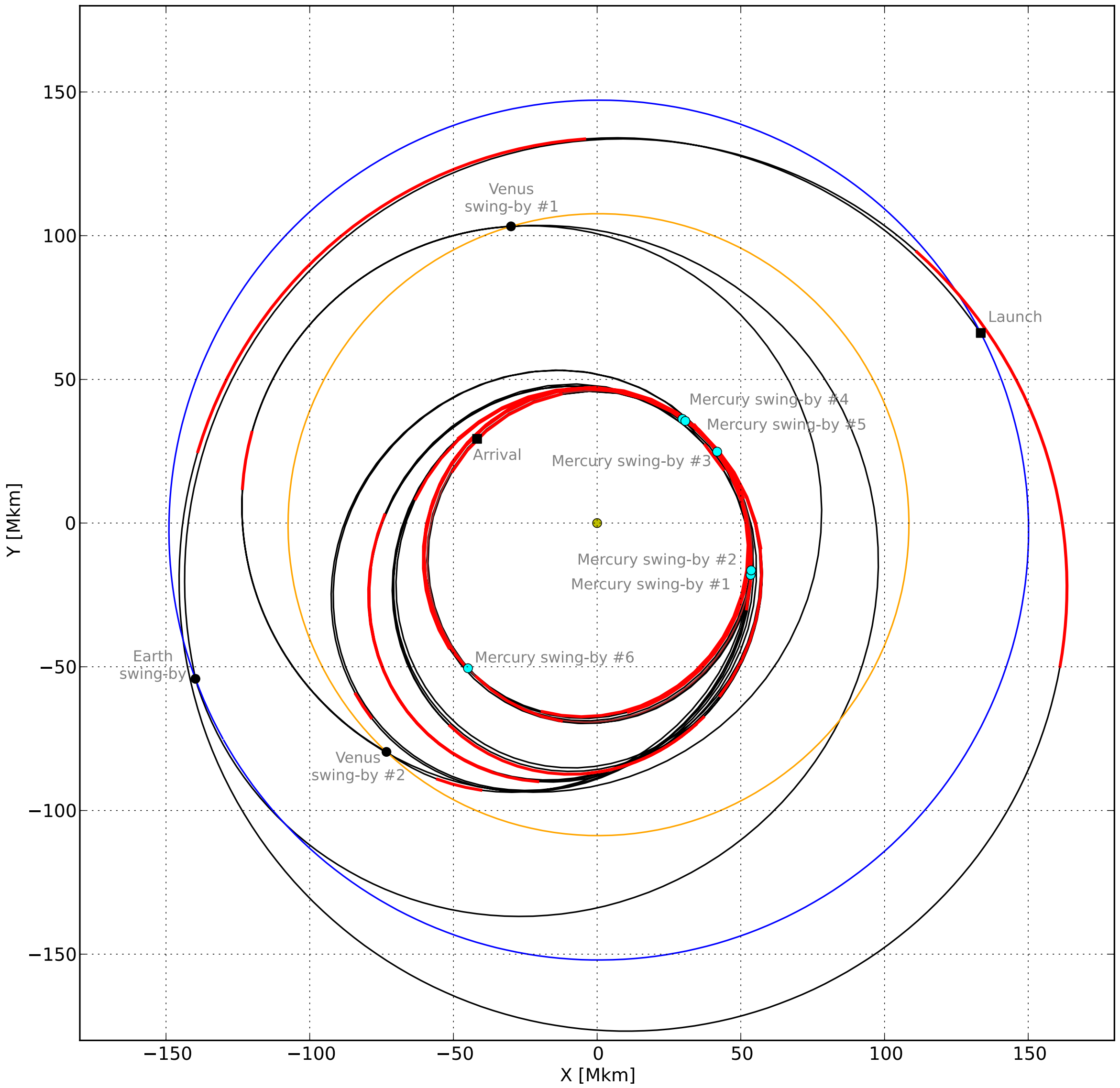

Fig. 3: BepiColombo cruise trajectory projected in the ecliptic plane

Event	From	To
SEP arc #1	17 December 2018	19 February 2019
SEP arc #2	21 September 2019	26 November 2019
Earth swing-by	10 April 2020	
Venus swing-by #1	15 October 2020	
SEP arc #3	20 June 2021	01 July 2021
Venus swing-by #2	10 August 2021	
SEP arc #4	17 August 2021	25 August 2021
Mercury swing-by #1	02 October 2021	
SEP arc #5	09 October 2021	10 October 2021
SEP arc #6	10 December 2021	16 December 2021
SEP arc #6	07 February 2022	25 February 202
Mercury swing-by #2	23 June 2022	
SEP arc #7	30 June 2022	03 July 2022
SEP arc #8	20 August 2022	25 August 2022
SEP arc #9	01 December 2022	03 January 2023
SEP arc #10	22 March 2023	07 May 2023
Mercury swing-by #3	20 June 2023	
SEP arc #11	10 August 2023	14 September 2023
SEP arc #12	17 December 2023	02 January 2024
SEP arc #13	19 January 2024	18 February 2024
SEP arc #14	24 April 2024	12 June 2024
Mercury swing-by #4	05 September 2024	
SEP arc #15	12 September 2024	25 September 2024
SEP arc #16	13 October 2024	25 October 2024
Mercury swing-by #5	02 December 2024	
Mercury swing-by #6	09 January 2025	
SEP arc #17	17 January 2025	17 February 2025
SEP arc #18	26 February 2025	02 April 2025
SEP arc #19	22 April 2025	04 July 2025
SEP arc #20	13 August 2025	27 September 2025
Mercury Arrival	04 December 2025	

Table 1: Timeline of BepiColombo cruise trajectory

Launch

BepiColombo was launched on 20 October 2018 at 01:45:28 UTC with an Ariane 5 ECA launch vehicle from Kourou, French Guiana, designated as Ariane Flight VA245. The ascent phase terminated with a direct injection of the MCS from the rocket upper stage into a hyperbolic escape orbit at separation time 02:12:12 UTC, i.e. 27 minutes after launch. The ultimate requirement for the launcher authority was to launch BepiColombo into an orbit with a specified escape velocity V_∞ = 3.475 km/s of the departing hyperbola within an accuracy of 12 m/s in magnitude and 0.2 deg in direction. As will be seen later, this was achieved with excellent success.

Initial Spacecraft Operations

After on-board detection of separation from the upper stage launch vehicle, an automatic sequence was performed priming the MTM reaction control system and initiate Sun acquisition together with deployment of the MPO and MTM solar arrays while the Attitude and Orbit Control System (AOCS) was temporarily disabled. Finally, Sun re-acquisition with stabilisation in a slow spin around the Sun vector was performed.

At the end of the launcher separation sequence the spacecraft was in a stable attitude with the AOCS enabled, pointing the +Y axis to the Sun and rotating with a period of one revolution per 3 hours with an arbitrary and unknown rotational phase. In this period the three star trackers were switched on sequentially by ground, checked out, and brought into the AOCS loop. Once this had been completed the spacecraft performed an autonomous attitude slew around its +Y axis to set the rotation phase to a pre-launch uploaded on-board guidance. Unfortunately, the set value was almost 180 deg away from the true phase causing a comparatively long slew to catch up with this phase. From then onwards the spacecraft rotational state was fully deterministic which simplified the ground operations considerably since events for LGA swaps and star tracker blinding by the Earth and Moon were predictable and the timeline of activities could be adjusted accordingly.

Thereafter, the reaction wheels were switched on, checked out, and run in for a period of time. After confirmation that all four reaction wheels were healthy, they were brought into the AOCS loop used for attitude control, suspending the period in which the attitude was controlled by thrusters. At this stage the spacecraft was prepared to transition to a normal AOCS mode, in which eventually the rotation around the Sun line could be stopped and transition to a quasi-inertial Sun steering attitude guidance could be achieved.

Unfortunately, after having being in normal mode for a while but before the rotation stop had been initiated by ground commands, the spacecraft went into safe mode at 08:56:55 UTC (i.e. 07:11 hours after lift-off) because of an on-board surveillance which detected a temperature excess in the shaft of one of the reaction wheels. It was soon discovered that the temperature threshold was set too tight for being robust against transients occurring when the shaft heater is switched on and off by the thermal control system. After the on-board monitoring threshold had been set to a more relaxed value, the Flight Control and Flight Dynamics teams were busy to recover from the safe mode, run in the reaction wheels and to transition to normal mode again. Finally, the Flight Dynamics team prepared and uploaded the commands to start stopping the rotation at 15:45 UTC on 20 October 2018, i.e. at 13:30 hours after lift-off and 06:00 hours later than per nominally foreseen timeline. The slew for stopping the rotation completed 02:30 hours later and from then onwards the +Y spacecraft axis was maintained Sun-pointing throughout the remainder of the LEOP.

Ground Station Network and First Acquisition

Fig. 4 shows the ground track of BepiColombo after separation from the launcher upper stage. 24 hours after separation BepiColombo was at an altitude of 363 862 km, i.e. almost at lunar distance. Also shown is the ground station network that was used for tracking, telemetry and telecommand operations during LEOP and their visibility above 10 deg elevation within the first day. Participating stations were the three ESA deep space 35 m antennas in New Norcia, Cebreros and Malargüe, augmented by a 2 m X-band terminal in Malindi (MAL-X, jointly owned by ESA and the Italian space agency) and the ESA 4.5 m antenna 270 m away from the 35 m antenna in New Norcia (and referred to as New Norcia 2 or NNO-2). The latter two were only used for first acquisition support, taking advantage of their smaller aperture diameters and hence larger X-band receiving beamwidths.

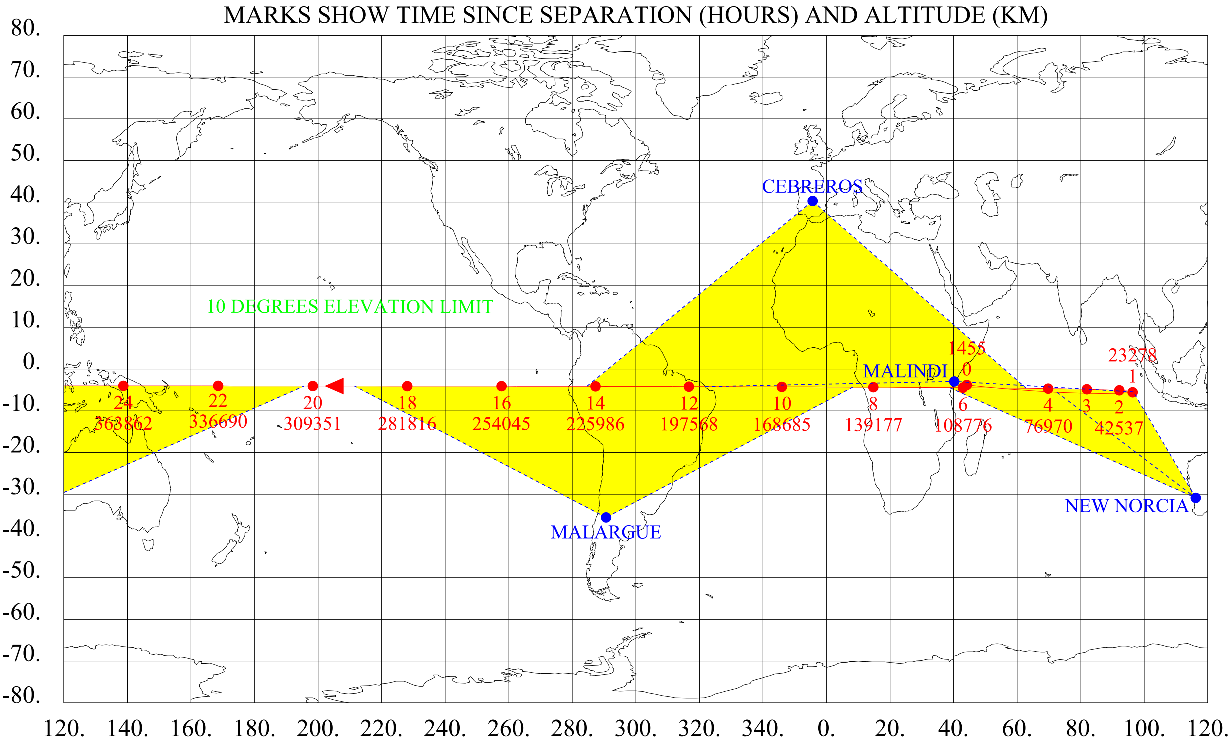

Fig. 4: BepiColombo ground track during first day of mission

Before launch, Arianspace provided covariance matrices on the BepiColombo separation state from which the expected 3-sigma dispersion errors on the plane-of-sky were derived in [1] and are displayed in Fig. 5. The antenna in Malindi has an X-band 3 dB beamwidth of 1.2° whereas that of New Norcia 2 is 0.5°. New Norcia 2 is additionally equipped with a 0.75 m wide beam antenna suitable for first acquisition support close to Earth with a 3 dB beamwidth of 3.3°. With this, no problem was expected at first acquisition when using the wide beam antenna. When using the narrow beam antenna the dispersion drops to below half the beamwidth about 40 minutes after separation (New Norcia had first visibility starting 10 min after separation). In contrast, at Malindi the dispersion drops below half of the 3 dB beamwidth after about 8 minutes from separation.

Malindi acquired the signal straight away after the on-board transmitter has been switched on during the launcher separation sequence and started transmitting. However, it was lost immediately due to an autonomous onboard-reconfiguration of the LGA. New Norcia 2 acquired the downlink signal once the spacecraft rose above the horizon at the expected position in the sky. The uplink was established and once the signal was received on-board the TTC system re-configured autonomously to use that LGA which received the highest signal strength on the uplink. This caused another signal outage of about 4 minutes but once this ended the signal was stable throughout and first acquisition was successfully completed.

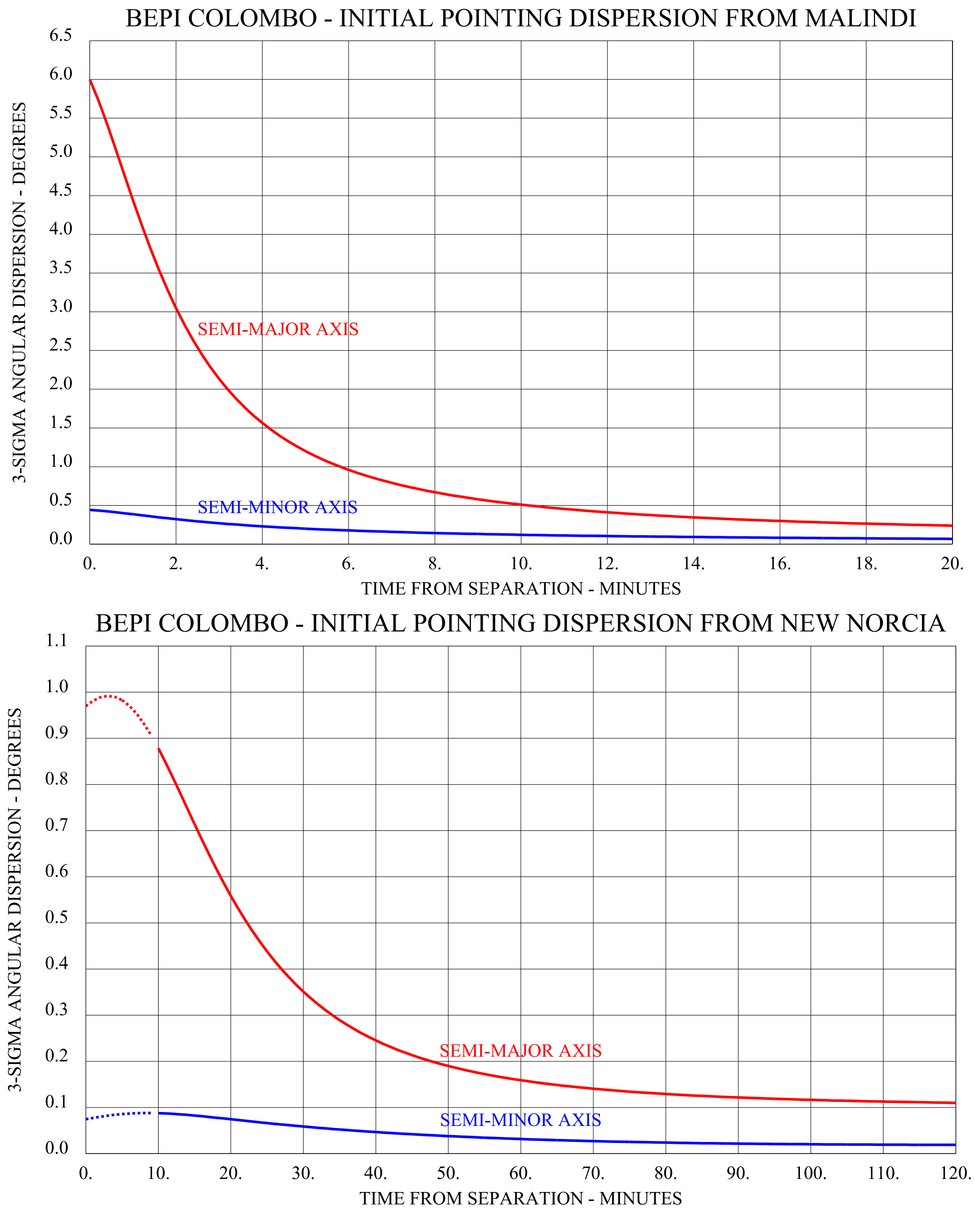

Fig. 5: Initial pointing dispersions from New Norcia (top) and Malindi (bottom)

Orbit Determination

Orbit Determination: Schedule of activities

Navigation activities for BepiColombo's LEOP followed a standard timeline for direct injection interplanetary missions, with a preliminary orbit assessment at Mission Elapsed Time (MET) 04:00 and a final assessment at MET 12:00. Following consolidated ESOC procedures, the preliminary assessment at MET 04:00 consisted in a first Orbit Determination (OD0) resulting in the assessment of the tracking data quality and in a first estimate of the achieved V_∞ conditions as well as an update of the station predictions before the deep-space station in Cebreros took over, which has neither search nor auto-track capabilities. The final assessment at MET 12:00 involved an OD with Data Cut-Off (DCO) at approximately MET 09:00 followed by an optimization of the full cruise trajectory until MOI. These activities allowed to provide the Flight Operations Director with a reliable separation state assessment (see dedicated section below) and to confirm that BepiColombo was in a suitable escape orbit to follow the reference cruise trajectory and reach MOI within the available propellant budget. Progressive OD activities continued afterwards, with an official OD2 delivered at MET 21:00 and used as input for the preparation of the commands for three test Orbit Control Manoeuvres (OCMs). These were aimed at commissioning both axial (acceleration along +Z) and lateral (+Y and –Y) manoeuvre functionalities, the first executed just before the end of the LEOP and the latter two at the beginning of the subsequent Near Earth Commissioning Phase (NECP). This paper covers until the end of the OD3 activities, finalized at the assessment of the test OCMs (see dedicated section). Table 2 summarizes the early OD activities for BepiColombo.

OD	DCO	Delivery	Purpose
OD0	MET 03:00	MET 04:00	Preliminary Orbit Assessment, station predictions update
OD1	MET 09:00	MET 12:00	Final Orbit Assessment, station predictions update
OD2	MET 18:30	MET 21:00	Test OCMs commanding, station and mission planning products update
OD3	MET ~107 h	MET ~110 h	Test OCMs assessment, station and mission planning products update

Table 2: Early orbit determination activities for BepiColombo.

Orbit Determination: Dynamic Set-up

As for all ESA’s recent interplanetary missions, orbit determination for BepiColombo is carried out using ESOC’s Advanced Modular Facility for Interplanetary Navigation (AMFIN, [2]). With this software package, the spacecraft ephemeris is propagated, given the applied dynamical models, starting from a specified epoch and covering backwards and forward the duration of the observation arc. A linear batch Square Root Information Filter (SRIF) based on Bierman’s formulation [3] is then used to iteratively adjust the estimation parameters, to minimize the root mean square of the normalised measurement residuals (i.e. observed minus computed observable, divided by the observation standard deviation) until convergence is achieved. Within the orbit determination process, the estimated parameters vector is constituted by the spacecraft state vector at the fixed epoch, augmented by a set of other “solve-for” parameters, selected by the user from the set of available dynamic and observation model parameters. Additionally, another set of “consider” parameters can be added to the problem formulation, which are not estimated but whose uncertainties contribute to the formal uncertainties of the “solve-for” parameters.

As is typical for LEOP operations, a very simple dynamic set-up was chosen for the initial OD activities, with the spacecraft heliocentric state vector components at an epoch as the only solve-for parameters. The orbit file generated before launch based on the information from the launcher authority was used to extract the a-priori state at the fixed epoch, which was chosen to be 12 hours after separation. From the moment when the spacecraft introduced the Star Trackers into the attitude control loop and therefore started following the ground-commanded, deterministic attitude profile, Doppler observables were compensated for the known motion of the spacecraft antenna currently being used. Range biases per station per pass were instead only used as consider parameters throughout the LEOP.

The force models for spacecraft dynamics integration included the gravitational accelerations from the Sun, Moon and all solar system planets, perturbative relativistic accelerations from Sun and Earth, a 16x16 spherical harmonics gravity field for the Earth, and a Solar Radiation Pressure (SRP) model based on the surface geometric discretization and optical properties, on spacecraft attitude and articulations angles (both solar arrays and movable antennas). No scaling of the SRP model was introduced during the LEOP, any signature being masked by the dynamics close to Earth or by other non-gravitational accelerations as outgassing and parasitic ΔVs from the attitude control thrusters. Only after strong evidence of outgassing acceleration was available from extended tracking as well as from telemetry data on the external torque, additional outgassing forces were added in the anti-sunward direction (spacecraft -Y). Due to their varying nature, several constant acceleration batches were introduced with different scaling factors as solve-for parameter. This allowed to fit the tracking observables and to characterize the out-gassing activity, which spiked at around 0.5 mm/s/hour when the solar arrays were rotated to be perpendicular to the Sun at MET ~14:00, later decreasing below 0.05 mm/s/hour within 24 hours. Other solve-for parameters introduced during the course of the LEOP, as summarized in Table 3, were an impulsive ΔV synthesizing the parasitic accelerations from thruster actuations during the safe mode event a few hours after launch, and the scaling factors for the test OCMs, whose assessment will be detailed in a later section. It is worth mentioning that, even though the attitude control thrusters for BepiColombo are arranged in a force-free configuration, significant parasitic ΔV in the order of 5 mm/s was first detected through the OD from the safe mode in LEOP, and later confirmed for another safe mode during cruise.

OD	Solve-for parameters
OD0	State vector at fixed epoch (MET 12:00)
OD1	State vector, safe mode impulsive ΔV (spherical 1 mm/s per axis)
OD2	State vector, safe mode, 2x outgassing batches (anti-sun, 1 mm/s/hour const. acc.)
OD3	State vector, safe mode, multiple outgassing batches, scaling factors for all OCMs

Table 3: Solve-for parameters for the OD activities in different phases of the LEOP.

Orbit determination: Tracking data availability

For BepiColombo, orbit determination is based mostly on 2-way X-band Range and Doppler measurements from ESA’s 35-meter Deep Space Antennas (DSA). Additional measurements foreseen for the cruise phase are Delta-DOR as well as Ka-band radiometric tracking, but these are not within the scope of this paper. As already mentioned, ESA’s deep space antennas were complemented for LEOP operations by the smaller dishes MAL-X and NNO-2, for the first acquisition and collection of tracking data over the first few hours of the mission. Both terminals are equipped with a Front End Controller (FEC) that allows auto-track, meaning that the antenna autonomously maintains the direction of the strongest signal by an electronic feedback loop thereby correcting the loaded station predictions that have been derived from a pre-launch trajectory. The angular antenna pointing data while being in auto-track was used for the initial orbit determination together with range and Doppler. All data types were acquired with 1s sampling. For the LEOP, angular data were sampled to 2 s, range data to 1 min and Doppler data integrated over 1 min.
The resulting availability of tracking data over the whole LEOP is summarized in Table 4. Due to the time required by the autonomous on-board sequence for activation of a stable LGA link, angular data recording at MAL-X and NNO-2 was started almost at the same time. A few minutes later, uplink was started from NNO-2, allowing recording of 2-way range data, even though the on-board transponder was not yet set to coherent, preventing acquisition of 2-way Doppler data. About half an hour later, with the spacecraft completing its autonomous separation sequence, communications were lost – as expected – for a few minutes. Given the stability of the signal at the main New Norcia 35-m dish (NNO-1), the Ground Operations Manager took the opportunity to swap the uplink to NNO-1. At re-acquisition of the spacecraft signal, NNO-1 was therefore prime in both uplink and downlink, initially recording only 2-way range data and soon afterwards also 2-way Doppler, as soon as the Flight Control Team

commanded the on-board transponder to coherent mode. Although angular data from both MAL-X and NNO-2 were collected for few more hours, already the OD0 and OD1 assessments were mostly based on range and Doppler from the 35-m DSAs, first solely at New Norcia NNO-1, and then in a repeating pattern with Cebreros and Malargüe for the remainder of the LEOP.

Data Type	Station	Time (UTC)	Notes
Angles	Malindi-X	02:22-03:12	MAL-X angles with known biases up to 0.1 deg
Angles	New Norcia 2	02:22-03:57	NNO-2 angles known to have good quality
Range	New Norcia 2	02:27-02:49	NNO-2 range data never validated pre-flight
Range	New Norcia	02:59-06.33	Uplink moved to NNO-1
Doppler	New Norcia	03:07-06.33	Doppler started after on-board coherency enabled
Range & Doppler	All 35-m antennas	Starting from 10-21T07:00	Almost uninterrupted coverage from Cebreros → Malargüe → New Norcia for the whole LEOP

Table 4: Availability of tracking data during BepiColombo LEOP.

Orbit determination: Tracking data assessment

With many different types of tracking data available over the first few hours of the LEOP, decisions on their weighting represented the biggest challenge during real time operations for OD0/OD1 assessments. Since this was well known in advance, pre-launch tracking tests were executed with the ESA Gaia spacecraft and with several Near-Earth orbiters (ESA's Sentinel 3B and NASA's Aqua and Terra satellites) in order to validate and assess the performance of the tracking systems of MAL-X and NNO-2, which are not routinely used for interplanetary missions. These tests had shown very good quality of NNO-2 angular data, with noise below 40 mdeg and biases below 10 mdeg in both azimuth and elevation, as well as of NNO-2 Doppler data, with noise below 0.1 mm/s when compressed to 60 s. However, as already known from previous missions, reduced quality had to be expected for MAL-X angular data, which suffered from systematic biases up to 0.1° in the configuration expected for the tracking of BepiColombo. And, more importantly, no validation at all had been possible for NNO-2 range data, due to the lack of a spacecraft with X-band up- and down-link capability at a suitable distance from New Norcia (Earth orbiters typically only use X-band for downlink, and Gaia is too distant to allow for 2-way ranging with the small NNO-2 dish).

The lack of validation of NNO-2 range data directly impacted the decisions taken early in the LEOP for the separation state assessment in OD0 and OD1. From the very first angular data coming in from MAL-X and NNO-2, the orbit injection by Ariane 5 seemed well within the 1-sigma uncertainties provided by the launch authority and resulting in pointing dispersions well below the values given in Fig. 5. This was readily confirmed by ranging data from both NNO-2 and NNO-1, as well as from the first 2-way Doppler from NNO-1. However, at this early stage, the different data types appeared to be slightly inconsistent. In particular, all data would fit well when strongly de-weighting or completely discarding NNO-2 range data, whereas including them in the fit with normal weighting would result in some other data type having strong signatures in the first hour or so from separation. Although the strong dynamics in this phase could have been interpreted as the cause for such signatures, it was decided to keep the NNO-2 range strongly de-weighted for the initial OD solutions, in light of the lower confidence placed in such data. In particular, 50 m measurement uncertainty was applied, versus 5 m for the range from the DSAs. Similarly, the Doppler data before antenna articulation compensation could be started was de-weighted to 1.0 mm/s, versus 0.2 mm/s afterwards.

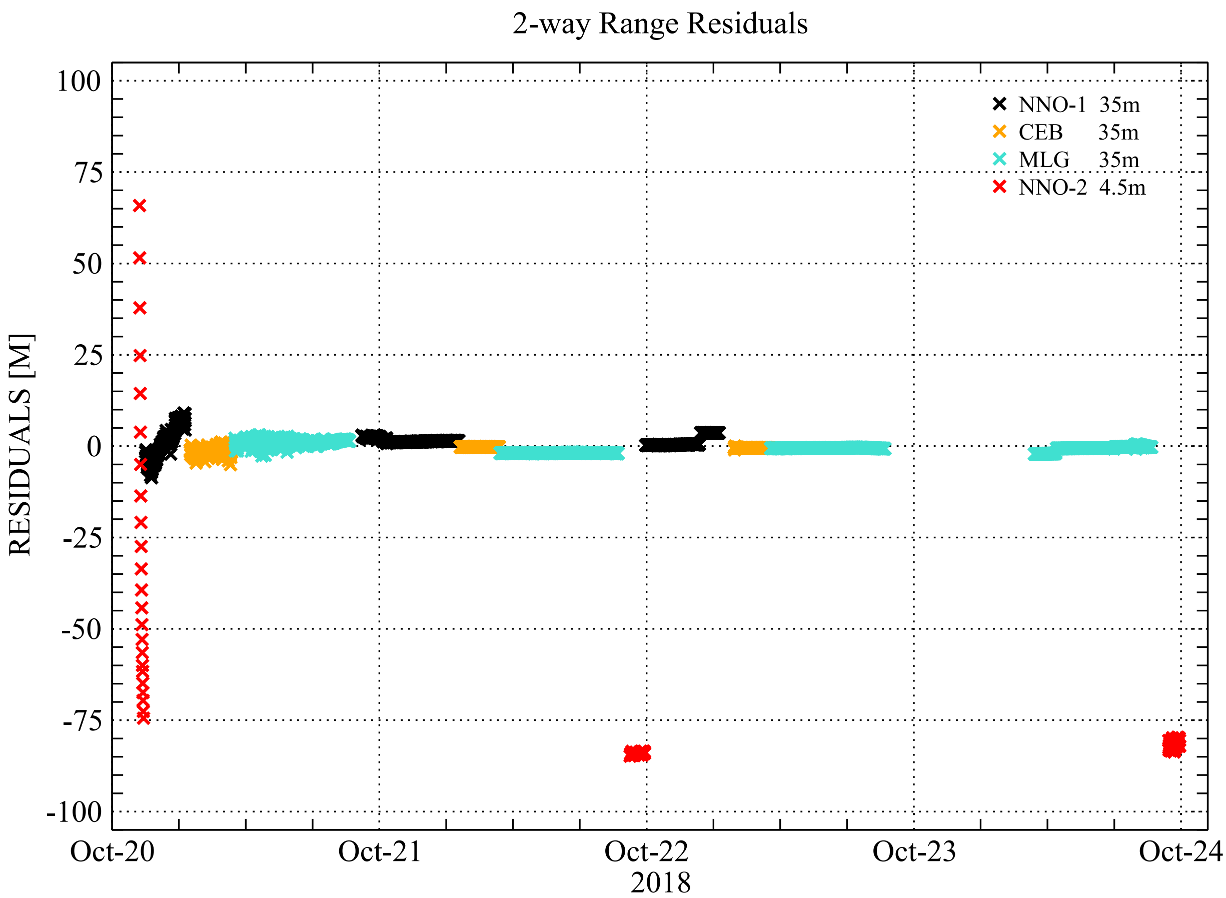

Fig. 6: A-posteriori range residuals from the first 4 days of the BepiColombo mission including NNO-2.

This decision was proven correct a few days later, when additional tracking tests at NNO-2 were run. These showed that 2-way Doppler was of comparable quality to the 35-m DSAs, with low noise and no biases, but that 2-way range was biased by a constant factor of about 80 meters. As shown in Fig. 6, this factor was masked by the spacecraft dynamics close to the Earth, resulting in a parabolic trend over the ~22 minutes of available range data in early LEOP, but was then consistent with the two successive test passes in the following days. The reason for this bias has been traced to an uncalibrated delay in the NNO-2 station cabling as the most likely. These additional tests during the short window of opportunity with BepiColombo being an X-band spacecraft close enough to Earth to allow for ranging with the 4.5 meter NNO-2 antenna have therefore allowed to identify and – once confirmed - to correct an important issue with NNO-2 tracking data, which will prove useful for future missions.

The quality of the angular data acquired at NNO-2 and MAL-X can be seen in Fig. 7, which displays the post-fit residuals in topocentric elevation and azimuth. The azimuth residuals are multiplied by the cosine of the elevation in order to obtain a Euclidian metric. The data were sampled every 2 seconds. The difference in bias and noise is clearly visible. The MAL-X residuals statistics give a mean of 92 mdeg and 74 mdeg with a standard deviation of 107 mdeg and 143 mdeg in azimuth and elevation respectively. The NNO-2 residuals statistics give a mean of 7 mdeg and -5 mdeg with a standard deviation of 5 mdeg and 7 mdeg in azimuth and elevation respectively.

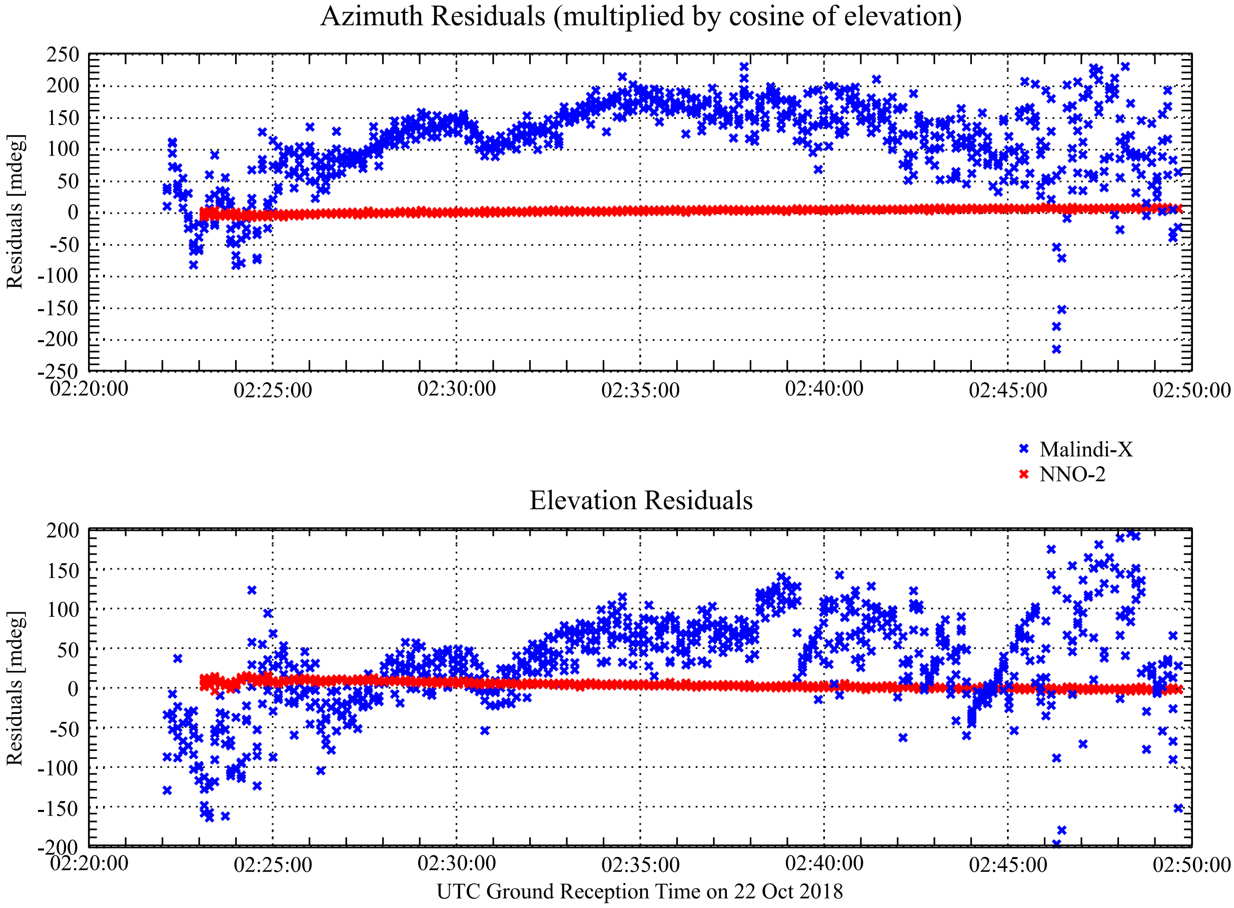

Fig. 7: A-posteriori angular residuals from the first hour of the BepiColombo mission

Separation State Assessment

Tables 5 to 7 give a detailed comparison of the BepiColombo separation state relative to the Earth Mean Equator and Equinox at epoch J2000 (EME2000) between the predicted state provided by Arianespace before launch and the determined state by ESOC in OD1, i.e. 12 hours after launch. As detailed in Table 7, the off-set in the targeted V_∞ was only 0.1 m/s in magnitude and 2 mdeg in direction which is well within the required (3σ) injection accuracy of 12 m/s and 0.2 deg.

Separation epoch = 2018-10-20 02:12:15.51 UTC				
Cartesian w.r.t. EME2000	Arianespace State	Arianespace 1σ uncertainty	ESOC/ESA State	Difference (ESOC – Arianespace)
X (km)	-1486	52	-1497	-12
Y (km)	7671	12	7673	2
Z (km)	-466	6	-467	-1
V_x (km/s)	-10.377	0.007	-10.376	0.001
V_y (km/s)	2.269	0.032	2.262	-0.007
V_z (km/s)	-1.042	0.003	-1.042	< 0.001

Table 5: Separation state comparison

Osculating at separation epoch = 2018-10-20 02:12:15.51 UTC				
Keplerian w.r.t. EME2000	Arianespace State	Arianespace 1σ Uncertainty	ESOC/ESA State	Difference (ESOC – Arianespace)
Semi-major axis (km)	-33006	72	-33005	1
Eccentricity	1.20258	0.0004	1.20258	< 0.00001
Inclination (deg)	5.75	0.01	5.75	< 0.01
R.A. of asc.node (deg)	244.6	0.25	244.6	< 0.1
Arg. of perigee (deg)	173.6	0.25	173.6	< 0.1
True anomaly (deg)	42.9	0.36	42.9	< 0.1

Table 6: Separation elements comparison

Osculating at separation epoch = 2018-10-20 02:12:15.51 UTC				
V_∞ w.r.t. EME2000	Arianespace State	Arianespace 1σ Uncertainty	ESOC/ESA State	Difference (ESOC – Arianespace)
Magnitude (m/s)	3475.1	3.8	3475.2	0. 1
Right Ascension (deg)	204.638	0.04	204.639	0.001
Declination (deg)	-3.704	0.02	-3.702	0.002

Table 7: V_∞ comparison

Test Manoeuvres

As described in the introduction, BepiColombo in its MCSC configuration is capable of performing OCMs with thrust either in the +Z direction (i.e. ΔV towards –Z) with the axial 10N thrusters or in the +Y / -Y hemispheres on the YZ plane with the tilted 10N thrusters. These lateral burns use a different thrust modulator with respect to the axial ones, are not exactly along +Y or–Y, and vary in direction throughout the mission, in order to align the thrust vector with the centre of mass to provide minimum parasitic torque. Overall, the availability of these three types of OCMs allows to satisfy the requirements on all trajectory correction manoeuvres for fly-by targeting or clean-up, within the thermal constraints on the attitude pointing.

In order to commission all OCM functionalities, three test burns were foreseen, one for the axial thrusters on the last day of the LEOP and the remaining two for the lateral thrusters on the next day, already part of the NECP. The test burns were designed to have a fixed ΔV of 33 cm/s each, with a direction as close as possible to the Earth direction, compatible with the attitude constraints. Table 8 reports the resulting geometric configuration for the 3 OCMs, as computed within the commanding session based on OD2. Due to different modulators, the expected durations for +Z,-Y,+Y manoeuvres were respectively of 229.5, 124.9 and 129.0 s.

Test OCM	Thrust Dir.	Sun Dir.	Earth Dir.	G/S Angle
Axial +Z	(0.00,0.00,+1.00)	(0.00,0.71,+0.70)	(0.02,-0.61,-0.79)	37.24 deg (NNO)
Transv. –Y	(0.00,-0.94,+0.35)	(0.00,0.99,-0.14)	(0.06,-0.96,+0.28)	175.26 deg (MLG)
Transv. +Y	(0.00,+0.90,+0.43)	(0.00,0.96,+0.29)	(0.00,-0.90,-0.43)	0.21 deg (MLG)

Table 8: Directions of thrust, Sun and Earth in spacecraft frame and angle between ΔV *vector and ground station direction for the 3 test OCMs*

Within the OD3 activities, the performance of all three test burns was calibrated, computing the Doppler residuals based on orbits propagated with the predicted acceleration profiles (a so-called "pass-through"). From these residuals, the average acceleration after stabilisation of the thrust could be computed by linear fit, as well as the final integrated ΔV at the burn cut-off, under the assumption that the actual thrust direction matched sufficiently well the predictions. AOCS telemetry showed average attitude control errors below 0.1 deg for –Z and –Y OCMs, and below 0.2 deg for the +Y OCM, reasonably fitting the assumption. Results for this magnitude only calibration are reported in Table 9, and an example of Doppler residuals from the pass-through for the +Z axial OCM is shown in Fig. 8.

Test OCM	True duration	Acc. Error	Total ΔV
Axial +Z	241.5 s (+5.2%)	-7.0%	329.9 mm/s (-0.02%)
Transv. –Y	127.4 s (+2.0%)	-2.5%	329.8 mm/s (-0.05%)
Transv. +Y	140.0 s (+8.5%)	-4.9%	342.5 mm/s (+3.78%)

Table 9: Performance assessment for the 3 test OCMs based on OD calibrations

Two main anomalies were found. First, the ground models seemed to overestimate the thrust level provided by the 10N thrusters, especially for the axial thrusters. This was analysed by the thruster suppliers and simply led to the re-calibration of the ground models. Second, and most importantly, the +Y burn was not properly stopped by the accelerometers being in closed loop manoeuvre control, resulting in a large over-performance in total ΔV of almost 4%. According to AOCS telemetry however, the accelerometers correctly stopped thrust when reaching the desired 33 cm/s of ΔV (as computed onboard), indicating a significant inaccuracy in the accelerometer measurements for this specific burn. While not mission critical, this is much larger than expected for this type of accelerometer and as of now not yet understood. Overall, the test OCMs were successful and the required functionalities for the targeting and clean-up of planetary fly-bys were demonstrated, although close attention will have to be paid in future transverse manoeuvres to the accelerometer performances.

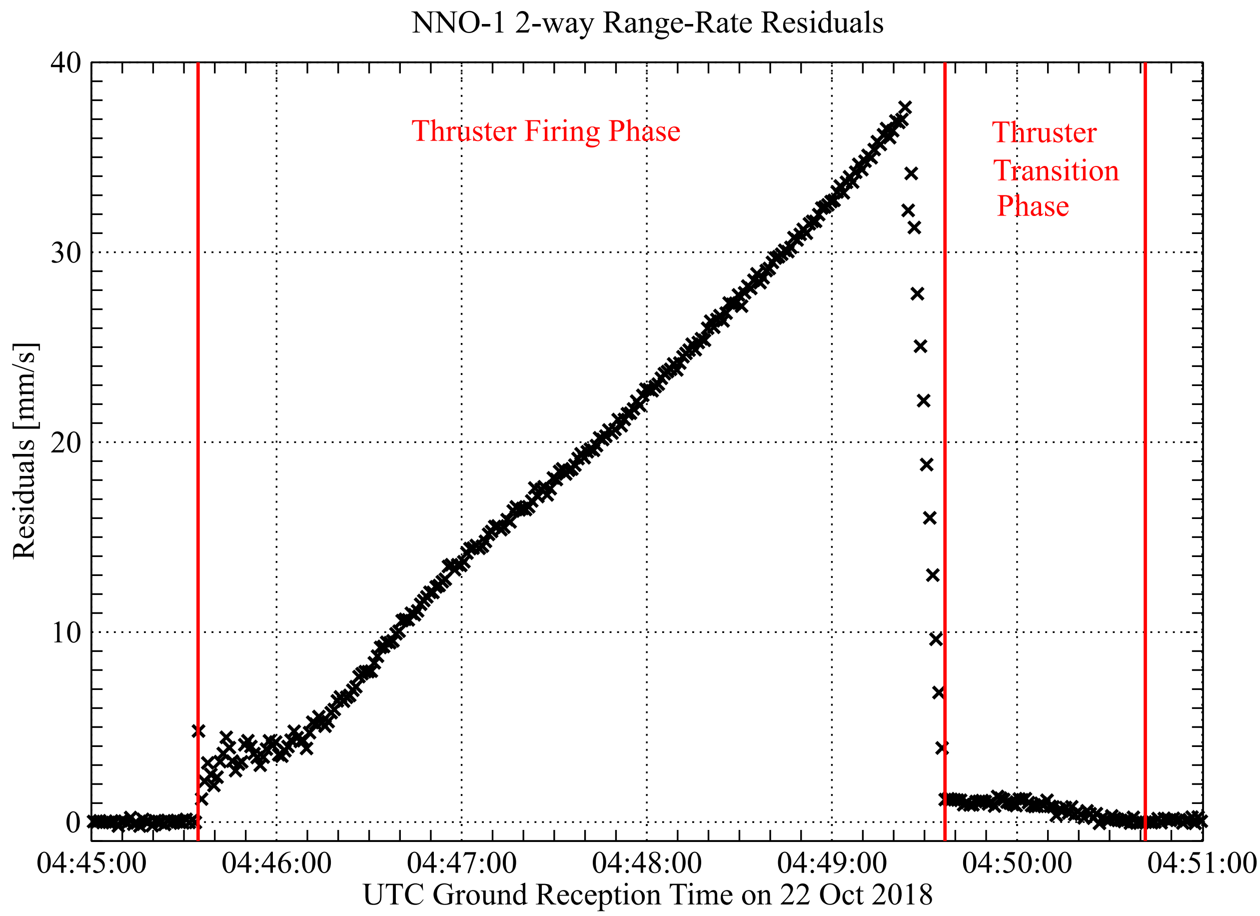

Fig. 8: A-priori Doppler residuals (count time of 1s) for the axial test OCM, pass-through against orbit with predicted manoeuvre acceleration profile.

Conclusion and Outlook

The Launch and Early Orbit Phase (LEOP) of BepiColombo can be considered as successful. Despite one transition to safe mode on the first mission day, which could be recovered quickly, all foreseen activities could be completed within the allocated 3 days of LEOP.

Immediately after the end of LEOP the Near Earth Commissioning Phase (NECP) started with commissioning activities for the spacecraft platform and some of the payloads. The NECP lasted about 2 months and ended on 14 December 2017. Highest priority was thereby put on the activation and check out of the MTM Solar Electric Propulsion System (MEPS) since this was the most time consuming activity (about 2 weeks in total) and the system has to be ready to start the first electric propulsion manoeuvre on 17 December 2018 (cf. Table 4).

At the time of writing, the MEPS has been fully and successfully commissioned and the Flight Dynamics Team is preparing the commands to start the first three weeks of SEP arc #1. The team is looking forward for a successful first manoeuvre using solar electric propulsion and to continue the 7 year journey towards Mercury. This will be reported on in a future paper.

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