17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 457

BepiColombo on its journey across the inner solar system

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Abstract

BepiColombo is an ESA cornerstone mission to Mercury in collaboration with JAXA and controlled from ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany. It was launched on 20th October 2018 as a single composite spacecraft including two scientific orbiters from ESA and JAXA, and a cruise module with electric propulsion. Its 7 years way to Mercury across the inner Solar System includes 9 planetary swing-bys at Earth, Venus, and Mercury before achieving a weak capture by Mercury in December 2025.

This paper presents the mission operation experiences collected during the first four years of cruise. The main flight events are described, with special focus on the second Mercury swing-by at a particularly low altitude (200km) as well as the radio-science campaigns during solar conjunctions involving, for the first time, an ESA ground station. Other cruise routine operations are briefly presented, including the latest updates on the operation of the solar electric propulsion. Finally, an overview of the major in-flight anomalies is given.

Keywords: BepiColombo, Mercury, ESA, Operations, Swing-By, Radio-science

Acronyms/Abbreviations

AOCS	Attitude and Orbit Control System
CAHE	Closest Approach (at Mercury during a swing-by)
CPS	Chemical Propulsion System
DDOR	Delta-Differential One-Way Ranging
EPCM	Electric Propulsion Control Mode
ETB	Engineering Test Bed
FCT	Flight Control Team
FD	Flight Dynamics
FDIR	Failure Detection, Isolation and Recovery
FOP	Flight Operations Plan
FOV	Field of View
HGA	High Gain Antenna
IMU	Inertial Measurement Unit
JAXA	Japan Aerospace Exploration Agency
LEOP	Launch and Early Orbit Phase
MCAM	Monitoring Cameras System
MCS	Mission Control System
MCSA	Mercury Composite Spacecraft Approach
MCSC	Mercury Composite Spacecraft Cruise
MCSO	Mercury Composite Spacecraft Orbit

MEPS	Mercury Electric Propulsion System
MGA	Medium Gain Antenna
MIO	Mercury Magnetospheric Orbiter (new name)
MMO	Mercury Magnetospheric Orbiter
MOI	Mercury Orbit Injection
MOSIF	MMO Sunshade and Interface Structure
MPO	Mercury Planetary Orbiter
MPS	Mission Planning System
MSB	Mercury Swing-by
MTL	Mission Timeline
MTM	Mercury Transfer Module
NECP	Near Earth Commissioning Phase
OGS	Operational Ground Segment
RSE	Radio-Science Experiment
RWU	Reaction Wheel Unit
SCE	Solar Conjunction Experiment
SEP	Solar Electric Propulsion
SEP	Sun-Earth-Probe (angle)
SGS	Science Ground Segment
SOM	Spacecraft Operations Manager
SSMM	Solid-state mass memory
STR	Star Tracker
TCM	Trajectory Correction Manoeuvre
TTC	Telemetry, Tracking and Control (subsystem)
WOL	(Reaction) Wheel Off-Loading

1. Introduction

The BepiColombo mission is a joint project between the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) to study Mercury. It is devoted to the exploration of the planet and its environment, through a global characterization of its interior, surface, exosphere, and magnetosphere [01]. In addition, BepiColombo offers a unique opportunity in fundamental physics, by testing various aspects of the Einstein's theory of general relativity test through a precise determination of multiple parametrized post-Newtonian parameters [02]. The mission has been named after the Italian scientist Giuseppe "Bepi" Colombo, who proposed the concept of a gravity assist manoeuvre with Venus exploited by the Mariner10 spacecraft to visit Venus and Mercury in the 1970s.

The paper is organized as follows. This first section introduces the BepiColombo mission. Section 2 provides an overview of the routine operations during cruise. Sections 3 and 4 focus on the operational approach for the two most important milestones during cruise: swing-bys and solar conjunctions. Section 5 discusses in-flight anomalies. Section 6 concludes.

1.1 The spacecraft

The mission consists of two scientific spacecraft, ESA's Mercury Planetary Orbiter (MPO) and JAXA's Mercury Magnetospheric Orbiter (MMO, later renamed as MIO [03]), launched together as a single composite including a dedicated propulsion module (MTM). Fig. 1 shows an artist's impression of the different modules.

During cruise, the combined stack of MTM, MPO, MMO Sunshade and Interface Structure (MOSIF) and MIO is referred as the Mercury Composite S/C Cruise (MCSC). At Mercury arrival, the MTM will be jettisoned, resulting in the Mercury Composite S/C Approach (MCSA). A set of complex manoeuvres will allow to reach MIO's operational orbit (11640x590 km) and release it. The Mercury Composite S/C Orbit (MCSO), composed by the MPO and MOSIF, will briefly continue until the MOSIF is separated and additional manoeuvres bring the MPO to its own final polar orbit (1500x480 km) to start its scientific mission.

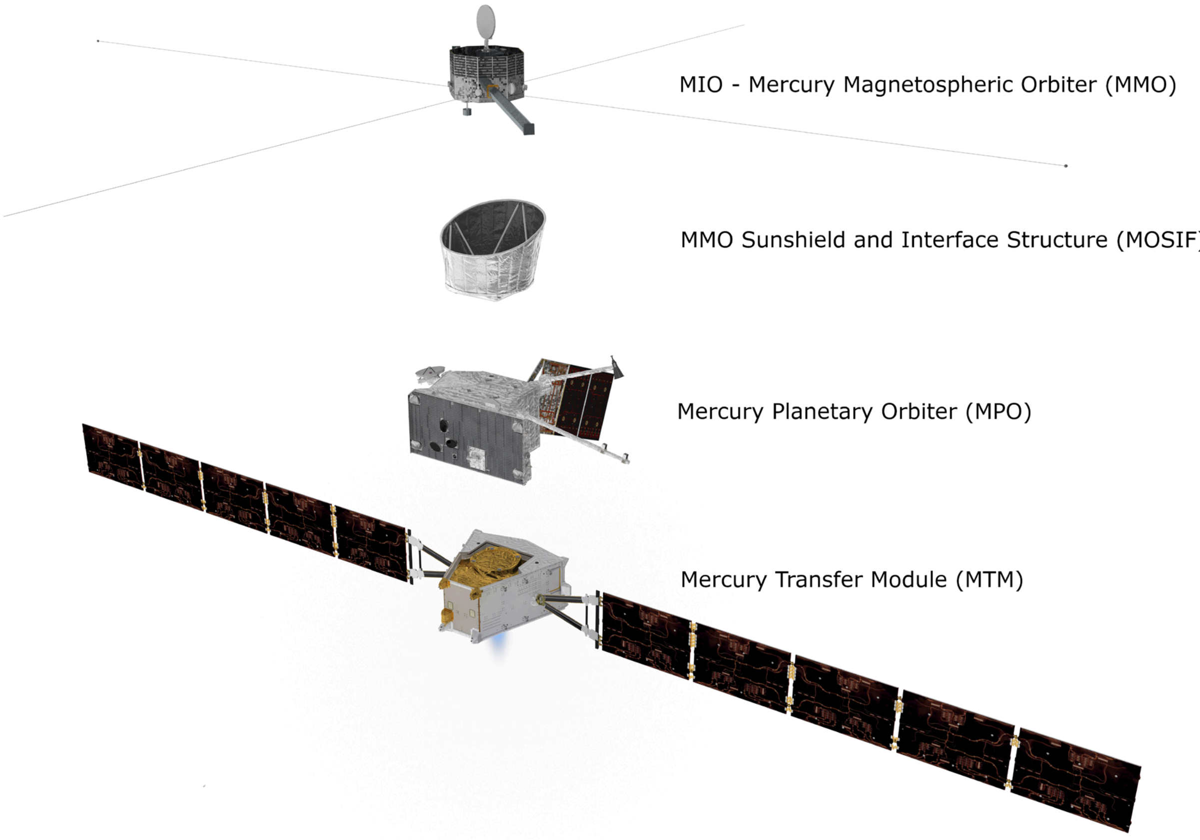

Fig. 1. Artistic view of BepiColombo spacecraft modules. *Credit: ESA/ATG medialab*

MPO and MTM have been developed under ESA contract by an international consortium led by Airbus Defence and Space Germany. MIO has been provided by JAXA and is a passive passenger during cruise, not involved in the control of the composite, which is done centrally within the MPO.

The MPO accommodates 11 scientific instruments and has a box-like shape with a size of 3.9×2.2×1.7 m, and a dry mass of about 1080 kg. An artistic impression with the list of all instruments is shown in Fig. 2. The tremendous heat load at Mercury imposes strong requirements on the spacecraft design, requiring high-temperature multi-layer-insulation and solar array technology. A radiator to dump excess heat into space is mounted on one side of the MPO, which shall not be exposed to Sun or Mercury.

The MPO is a 3-axis stabilised spacecraft. The Attitude and Orbit Control Subsystem (AOCS) employs Star Trackers (STR), Inertial Measurement Units (IMU), fine sun sensors, Reaction Wheels (RWU) and chemical propulsion. AOCS design is impacted by the challenging environment, requiring a tight synchronisation of the attitude guidance along Mercury orbit, special guidance profiles for the MPO solar array (to avoid overheating) and rapid attitude stabilisation in case of contingencies. A separate processing unit, the Failure Control Electronics, is taking over the spacecraft attitude control in case of transient unavailability of the main on-board computer at safe mode entry, when the on-board computer is rebooting. For communications, a X/Ka-band deep space transponder with moveable high and medium gain antennae (HGA/MGA) is used. For more details, see [04].

The MTM provides propulsion means for cruise. Apart from a dual mode bi-propellant chemical propulsion system (CPS), it hosts the Mercury Electric Propulsion System (MEPS), with 4 movable Kaufman-type thrusters

capable of producing up to 145mN each, with the possibility to operate up to 2 of them in parallel. Two large solar arrays of more than 20 m2 each can satisfy the high-power demand of the MEPS.

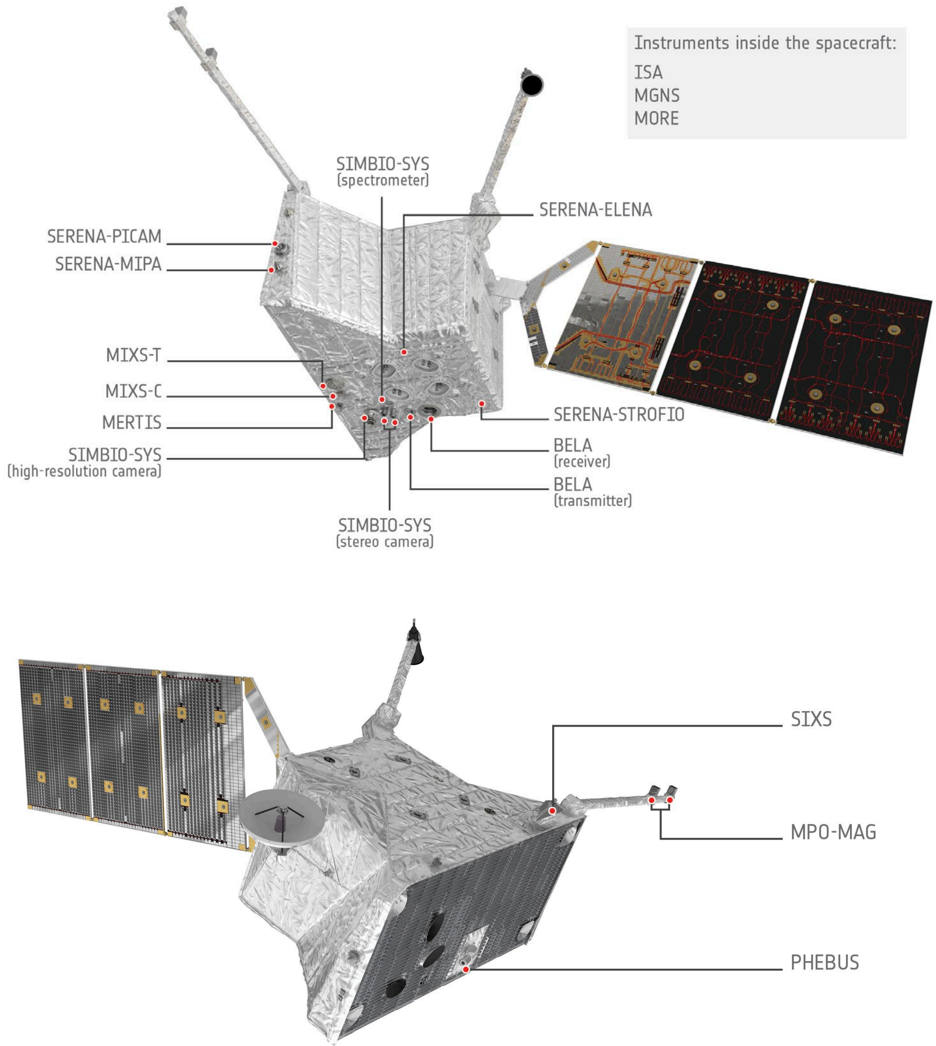

Fig. 2. BepiColombo MPO and its science instruments. *Credit: ESA/ATG medialab*

1.2 Mission profile

BepiColombo was launched on 20th October 2018 from Kourou, French Guiana, on top of an Ariane-5 rocket. The launch is followed by a journey lasting 7 years and 2 months towards Mercury after a direct injection into an Earth-escape trajectory. As illustrated in Fig. 3, a sequence of 9 planetary swing-bys (Earth, 2xVenus, 6xMercury) is required to reduce the high energy level required to reach Mercury.

In addition, a total delta-V of about 2731 m/s needs to be generated during cruise by the spacecraft's electric propulsion system. The current trajectory foresees about 30 "thrust arcs" to adjust the trajectory, lasting from few days up to 2 months. At the time of writing, the spacecraft is on transit between the second and third Mercury swing-by and has completed 14 electric propulsion arcs, some of them divided in multiple subarcs. BepiColombo will eventually achieve a weak stability boundary capture into a highly elliptic orbit around Mercury in December 2025.

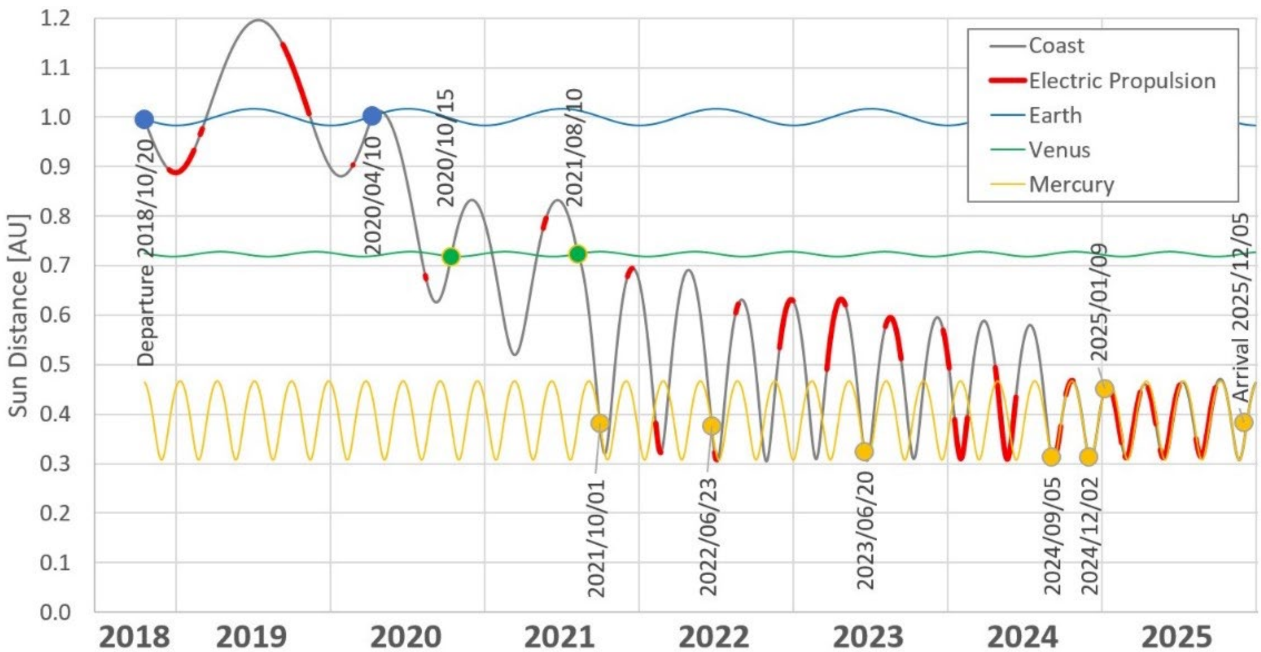

Fig. 3. BepiColombo cruise trajectory. The plot displays the Sun distance, solar electric propulsion arcs ("SEP"), and planetary swing-bys (at Earth, Venus, Mercury)

The mission is split in five distinct phases:

- Launch and Early Orbit Phase (LEOP): first signal acquisition and most critical operations required to get the spacecraft ready to the interplanetary cruise took place between 20th and 22nd October 2018. See [05] and [06] for a detailed explanation of this phase.
- Near Earth Commissioning Phase (NECP): it happened between 23rd October 2018 and 16th December 2018. A detailed checkout of the platform and payloads was performed. Refer to [05] for a summary of the operations performed.
- Interplanetary Cruise Phase: it started on 17th December 2018 with the first solar electric propulsion (SEP) thrust arc and it will end in October 2025 after the successful completion of the last SEP arc. The activities of this phase are the subject of this paper.
- Mercury Approach Phase: this is certainly the most critical part of the mission. It lasts 6 months, from October 2025 until March 2026. At the beginning of this phase, the MTM will be separated. 15 manoeuvres will be performed to secure capture by Mercury and lower the perihelion as part of the Mercury Orbit Injection (MOI) until the final science orbit is reached. On the way down, MIO and MOSIF will be released at their planned orbits. A brief description of this phase is presented in [07].
- Mercury Orbit Phase: following one month of commissioning, science operations start and will last one Earth year, with the possibility to extend the mission an additional year until April 2028. The MPO lacks the capability to perform orbit maintenance manoeuvres. Therefore, the natural orbit decay will bring the MPO into an environment far beyond its thermal envelope limiting the options for further extensions. The unglamorous MPO's thermal death will unfortunately mark the end of the mission.

1.3 Mission operations

The Operational Ground Segment (OGS) is located at ESOC in Darmstadt, Germany. Flight Operations for all mission phases are conducted there. Once in Mercury, science operations will be performed by the Science Ground Segment (SGS), situated at ESAC in Madrid, Spain.

The OGS follows the typical setup for ESA deep space missions. BepiColombo operations are performed by the Flight Control Team (FCT) in close coordination with the Flight Dynamics (FD) team. The size of the FCT varies across mission phases to adapt to the workload profile. In cruise, it ranges between 4 to 7 engineers, together with a Spacecraft Operations Manager (SOM) and a pool of spacecraft controllers shared with other ESA interplanetary missions. The FD team is a multi-mission team providing support to BepiColombo under the lead of a Flight

Dynamics Manager. FD oversees orbit determination and prediction, command generation (e.g., for attitude and orbit control) and monitoring of the spacecraft status for FD-related items (e.g., star tracker performance). For BepiColombo, there is a particularly close relation between FCT and FD due to the complex AOCS operations and the interdependencies between navigation and electric propulsion activities. In addition, other ground segment multi-mission groups provide support to the mission on the areas of data systems, ground stations, IT infrastructure, product assurance and project control.

Operations are executed with the help of redundant core data systems listed below, completed with auxiliary tools for offline performance monitoring, operations preparation, change control and data visualization:

- A SCOS-2000 based mission control system (MCS), named OPMCS, and currently shared with Solar Orbiter, JUICE, and HERA.
- A SIMSAT-based spacecraft simulator. The simulator is running the platform on-board software on an emulator, and is a key tool for operations preparation, allowing testing with high fidelity. See [08].
- A standalone mission planning system (MPS) described in [09].
- An instance of the Generic File Transfer System and the EGOS Data Dissemination System, developed by ESA, to deliver files and data internally and to external users.

The last element to support mission operations is the Engineering Test Bed (ETB), shown in Fig. 4. The ETB contains flight hardware for all electrical equipment and is used for operations validation when the simulator is not considered representative enough. It has been heavily utilised by Airbus during the development phase and was handed over and installed at ESOC in early 2018.

Fig. 4. BepiColombo Engineering Test Bench at ESOC

2. Flight operations during the cruise phase

BepiColombo cruise operations are governed by three mission events: planetary swing-bys, solar conjunctions and SEP thrust arcs. The first two are key cruise milestones requiring intense planning starting months in advance. They are described in detail in sections 3 and 4. Despite its complexity, electric propulsion is a frequent activity, and it can be seen as an integral part of routine operation and therefore is described in this section.

BepiColombo operations are built on top of the experience of other deep-space missions operated by ESOC, like Rosetta, Mars Express or Venus Express. Refer to [10] for a detailed explanation of the BepiColombo ground segment and the mission operations concept.

2.1 Routine platform activities

During quiet coast phases, the pass frequency is reduced to approximately 10 hours of tracking on average per week (either in one long pass or split in two shorter passes). A large fraction of the commanding is under FD responsibility, and it is related the nominal and contingency spacecraft attitude and MTM solar array guidance, antenna pointing mechanism commanding and reaction wheel momentum management. See [04] for details on the spacecraft guidance. The nominal activities under the FCT responsibility are:

- Pass management and data retrieval from on-board solid-state mass memory (SSMM).
- Antenna (HGA or MGA) and TM downlink bit rate and encoding selection.
- Update of Sun distance driven parameters.
- Regular MEPS pressure checks.
- Management of the TC link recovery function to adapt to pass frequency.

An extensive platform checkout is executed twice a year. The main activity is the mandatory gyro-calibration of the IMUs, requiring a series of slews to update the IMU calibration coefficients when required. During the checkout. All three STRs go through extensive health checks. Finally, the backup deep-space transponder is verified during one pass.

In addition to the routine tasks, there are a wide range of activities required to address contingency situations and investigate and resolve the anomalies raised during cruise. In-flight tests and adaptation of the spacecraft configuration are common. Finally, and in preparation for the Mercury phase, the FCT duties include the characterisation and validation of the spacecraft units and features required for MOI and science operations. One area of particular attention is Ka-band communications. Following ESA's SMART-1 successful demonstration of the technology, BepiColombo is the first ESA's mission using Ka-band operationally. Significant effort is being invested in understating the performance and develop an operational concept to optimise the ka band link exploiting weather statistics and weather forecast. See [11], [12] and [13] for a detailed review of the work done so far.

2.2 Payload operations

The mission was designed assuming that, during cruise, payload operations would be limited to one week of non-interactive payload operations every 6 months, referred to as payload checkouts. In addition, MORE and other instruments are activated for radio-science during selected solar conjunctions as explained in section 4. Still, planetary swing-bys are obviously of great interest to the scientific community for calibration and science purposes and observation requests are implemented on best-effort basis.

A subset of the instruments is also interested in being operated as much as possible during cruise to improve instrument characterisation and readiness for the Mercury phase: BERM (radiation monitor), MPO-MAG (magnetometer), MGNS (gamma-ray and neutron spectrometer), ISA (accelerometer) and SIXS (Solar Intensity X-ray and particle Spectrometer). Their background science operations have been automated with the help of the MPS and are implemented outside electric propulsion periods.

Payload anomalies have been uncovered during near-Earth commissioning and while operating the instruments during checkouts and swing-bys. As the science phase has a short duration, there is a natural interest to address and resolve all these problems before Mercury arrival. Engineering activities, like software updates, and in-flight tests are planned and executed on best effort basis in coordination between the instrument teams and the FCT. The effort invested on these activities is devoted to achieving a high level of readiness before the start of the Mercury commissioning phase and there is a bi-yearly process in place to collect all the requests, group them and implement them in the most efficient way.

2.3 Solar Electric Propulsion

The current trajectory to Mercury requires to operate the MEPS for thousands of hours to obtain the more than 2.5 km/s of required delta-V. Table 1 lists all the SEP thrust arcs performed so far. As electric propulsion is used as well to implement chosen trajectory correction manoeuvres (TCM) around swing-bys, arc duration ranges from one day to over a month. Long arcs are however split in subarcs and interrupted for one or two days for navigation and manoeuvre optimisation reasons. The longest uninterrupted arc so far has lasted 18 days (second sub-arc of SEPS#14). One pass, or two when feasible, are scheduled during the interruption to refill the mission timeline (MTL) with the time-tagged commands for the next subarc. SEP usage will grow in the last 3 years of cruise, as shown in Fig. 3. This will increase the criticality of each thrust arc, as the margin to recover from unplanned outages by shifting the manoeuvres to a later time will be reduced.

Table 1. List of SEP thrust arcs performed in cruise until end of 2022

Name	Duration	Start date	End date	Remarks
SEP1	79 d	17-12-2018	05-03-2019	
SEP2	63 d	12-09-2019	13-11-2019	Single thruster
SEP3	1 d	23-04-2020	23-04-2020	ESB1 TCM+1w / Single thruster
SEP4	3 d	31-07-2020	02-08-2020	
SEP5	3 d	22-10-2020	24-10-2020	VSB1 TCM+1w
SEP6	7 d	11-05-2021	17-05-2021	
SEP6 TU#1	2 d	07-06-2021	08-06-2021	
SEP6 TU#2	1 d	03-07-2021	03-07-2021	
SEP7	1 d	20-08-2021	20-08-2021	VSB2 TCM+1w
SEP8	5 d	31-10-2021	04-11-2021	
SEP9	10 d	02-12-2021	11-12-2021	
SEP10	11 d	15-02-2022	25-02-2022	
SEP11	2 d	08-04-2022	10-04-2022	
SEP12	4 d	01-07-2022	04-07-2022	MSB2 TCM+1w
SEP13	9 d	18-08-2022	27-08-2022	
SEP14	42 d	01-12-2022	11-01-2023	

All manoeuvres performed in dual thruster configuration except the indicated ones

The MEPS is one of the most complex subsystems of BepiColombo. The on-board software running on the on-board computer orchestrates the operation of all the MEPS units (MEPS Control Function) complementing the specific AOCS mode for SEP called Electric Propulsion Control Mode (EPCM). Basic FDIR is implemented in hardware, with the most complex autonomy and FDIR functions implemented in software. For details on the MEPS units and how the subsystem works, please refer to [14] and [15].

BepiColombo EPCM operations is a topic on its own and too extensive to be covered in detail on this paper. An overview of the process and the challenges of EPCM are described in [16]. The FD team is the main responsible of planning each thrust arc, optimising the manoeuvres along the trajectory and implementing most of the EPCM related commanding. The FCT is in charge, in close coordination with FD, of the management of the MEPS subsystem, the balancing of the usage of the four thrusters and the provision of the power-related input files required by FD to command the MTM solar array profiles during EPCM. There are three substantial changes compared with the operational concept presented in [16] and introduced in 2022:

1. As part of the electric propulsion long endurance test (which continued on-ground even beyond the launch of the mission), a non-compliance on the thruster neutraliser was identified. The investigation revealed that a metal flange which supports the neutraliser casing can crack because of repeated on/off operations over thousands of hours of operation. Consequently, the need has arisen to minimise the number of cycles and interrupt long thrust arcs every two or three weeks, instead of weekly.
2. Flight Dynamics has developed a new technique for a Doppler-free navigation approach without interrupting the SEP thrust inspired in the JAXA Hayabusa mission [17]. In this innovative approach, an orbit determination solution is found based on 2-way range plus DDOR from two baselines acquired over a short time interval. The feasibility has been verified in dedicated tests and the formal uncertainties of the solution, even while thrusting, are acceptable for navigation. This approach is an enabler to move away from weekly interruptions to acquire range and Doppler data and therefore to reduce planned thruster interruptions.
3. The MEPS has been not as reliable as anticipated. Due to minor recurrent anomalies, reconfigurations to the backup thruster pair while in EPCM are not uncommon. The weekly monitoring pass strategy is not considered adequate to react fast enough to thrust interruptions. Consequently, a new pattern, with two short monitoring passes and two long uplink passes per week has now been implemented.

3. Swing-by operations

Planetary swing-bys are central milestones of the cruise phase. BepiColombo trajectory foresees a total of nine gravity assist manoeuvres to significantly reduce the amount of delta-V to be provided by the MEPS. Table 2 summaries all the BepiColombo swing-bys including the date, the planet, the altitude above the planet surface and the velocity change with respect to the Sun. The data for the first five swing-bys is based on the reconstructed orbit.

Table 2. Main parameters of BepiColombo planetary swing-bys

Date	Planet	Periapsis Altitude	Hel. velocity change	Asympt. Velocity	Semi-deflection angle
10/04/2020	Earth	12993 km	4.5 km/s	4.0 km/s	34.6 deg
15/10/2020	Venus	10722 km	3.7 km/s	8.0 km/s	13.6 deg
10/08/2021	Venus	552 km	7.0 km/s	8.0 km/s	25.8 deg
01/10/2021	Mercury	194 km	2.1 km/s	6.6 km/s	9.2 deg
23/06/2022	Mercury	198 km	2.2 km/s	6.3 km/s	9.9 deg
20/06/2023*	Mercury	200 km	2.8 km/s	3.6 km/s	22.8 deg
05/09/2024*	Mercury	200 km	2.9 km/s	2.8 km/s	31.5 deg
02/12/2024*	Mercury	39960 km	0.4 km/s	2.6 km/s	4.0 deg
09/01/2025*	Mercury	417 km	2.5 km/s	1.8 km/s	44.5 deg

* For future swing-bys, shown data is based on planned trajectory

BepiColombo swing-by navigation approach is built on top of the expertise acquired by FD on previous interplanetary missions, like Rosetta [18]. As part of the navigation campaign, each swing-by includes a coast arc of at least 30 days before, and 7 days after closest approach to ensure an accurate orbit determination. If required, TCMs are executed to precisely control the impact vector.

Thermal and power constraints drive the minimum swing-by altitude. For Mercury, a minimum swing-by altitude of 200 km is targeted except for the last Mercury swing-by. A high altitude of 40000 km is imposed at the fifth Mercury swing-by, so that the trajectory is safe to navigate: there is only half Mercury year before the following swing-by with no chance to correct swing-by dispersion errors with the ion thrusters.

The mission baseline did not foresee science during swing-bys and the field of view (FOV) of several instruments are blocked by the MTM. However, on request of the scientific community, observations for the non-blocked instruments are assessed and implemented on best-effort basis. The Monitoring Cameras System (MCAM), consisting of 3 optical micro-cameras mounted on the MTM, is heavily utilised during swing-bys for outreach purposes. The swing-by pointing timeline always consider the MCAM FOV to ensure good imaging opportunities of the overflown planet.

3.1 Swing-by planning

A swing-by is a major activity that requires laborious planning starting 6 months before the closest approach. The process that has been followed for the first five swing-bys of the mission is common. However, each one has its own specific and unique aspects, linked to the geometry of the swing-by, which require dedicated analysis. As a result, dedicated flight operations procedures are developed for each swing-by. This section describes the steps of the general planning procedure, while section 3.2 takes Mercury swing-by #2 (MSB2) as an example to illustrate how a swing-by is implemented.

The general steps followed for the planning of BepiColombo swing-bys are:

- Closest approach - 6 to 4 months: the project scientist collects from all the instrument teams their intention to operate or not during the swing-by and their wishes and needs around closest approach +- 1 day.
- Closest approach - 4 to 3 months: FD generates a pointing timeline satisfying the spacecraft constraints and addressing instrument wishes on best-effort basis. This is first iterated internally and later with the scientific community. The TCM strategy and deadlines for product generation are agreed between FD and FCT.
- Closest approach – 3 months: FD provides the medium-term products, including the orbit, attitude, and event files. Around this time, the definition of the MCAM strategy starts.

- Closest approach – 2.5 months: the validated swing-by procedures are released and integrated into the Flight Operations Plan (FOP).
- Closest approach – 2 months: the SOM decides the FCT support profile and the on-call support from other teams is agreed.
- Closest approach – 6 weeks: the instrument and MIO teams provide a draft version of commanding products, which are then validated by the FCT.
- Closest approach – 6 to 4 weeks: a simulation campaign is organised to increase the proficiency of the teams on console. The focus is on contingency cases shorty before the swing-by (e.g, safe mode) and on preparing an emergency TCM at closest approach – 6 hours.
- Closest approach – 3 weeks: finalisation of all the commanding products and update of the flight procedures with the feedback from the simulation campaign.
- Closest approach – 2 to 1 weeks: swing-by short-term planning products are delivered by FD and processed in the MPS, and the final commands are loaded on the MTL.
- Closest approach – 1 week: the freeze on ESOC's physical infrastructure and mission specific hardware starts to prevent changes that could negatively affect close approach operations.
- Closest approach – 2 days: FCT briefing meeting takes place shortly before the start of the 24/7 shifts.

3.2 Mercury swing-by 2

The second swing-by of Mercury took place on 23rd June 2022 with closest approach (CAHE) at 09:44:21 UTC. Based on the reconstructed orbit, the minimum periherm distance was 2638.5 km (198.1 km altitude). The spacecraft went through the night side of the planet shortly before CAHE, which resulted in an eclipse of slightly above 18 minutes duration. In addition, Mercury was in the line of sight between the spacecraft and the Earth around the time of CAHE, interrupting the communications. The occultation started shortly before CAHE and lasted about 12 minutes. The swing-by took place close to perihelion, at a Sun distance of 0.37 AU. The Earth distance was 0.96 AU, corresponding to a propagation delay of around 8 minutes.

3.2.1 MSB2 navigation campaign and trajectory correction manoeuvres

The navigation campaign for MSB2 started 6 weeks before the closest approach. The pass schedule was driven by the navigation requirements. TTC pass frequency increased from a weekly pass (standard frequency during quiet cruise phases) up to daily passes for the two weeks before the swing-by. In addition, TTC passes were augmented by dedicated 4h ranging passes from a second station (about 2-4 passes per week). The radiometric data (2-way Doppler and range) acquired from these passes was complemented by a DDOR campaign with 21 DDOR acquisitions of one hour each with four difference baselines with 2 ESA antennas (New Norcia–Cebreros, Malargüe-Cebreros), 2 NASA antennas (Goldstone-Canberra), and for the first time on the mission, a triple baseline combining ESA and NASA assets (Malargüe-Goldstone-Cebreros).

Trajectory correction manoeuvres were planned during the navigation campaign to adjust the trajectory, if required. Three nominal slots were foreseen at 5, 3 and 1 week before CAHE, plus two emergency slots 3 days and 6 hours before CAHE. The decision was driven by a mission rule: a nominal TCM (slots TCM-5w, TCM-3w, TCM-1w) was to be executed if the swing-by periherm altitude was less than 190 km; an emergency TCM (slots TCM-3d, TCM-6h) was to be executed if, based on the latest orbit determination, the subsequent Mercury swing-by could not be reached within the given mission constraints. One week after CAHE, a TCM was planned to correct swing-by dispersion errors. An overview of the navigation campaign is shown in Fig. 5.

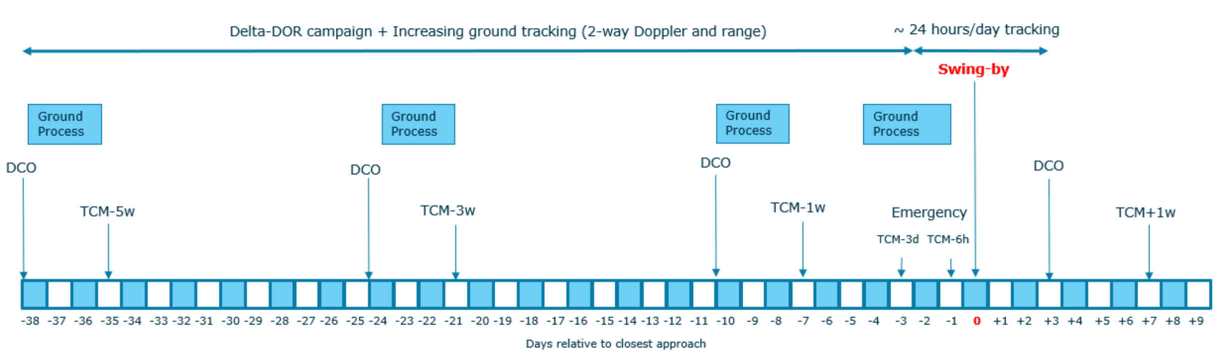

Fig. 5. MSB2 navigation campaign overview. DCO=Data Cut-Off. TCM=Trajectory Correction Manoeuvre.

For MSB2, only one TCM was required 5 weeks before CAHE. TCM-5w had a delta-V magnitude of 0.8418 m/s and was executed on 19th May 2022 making use of the MTM CPS axial thrusters. The manoeuvre moved the impact point in the B-plane by 1414 km towards the desired target and put the spacecraft out of the collision course with Mercury (a nominal condition in cruise arisen from the mechanisation errors of the last SEP manoeuvre on 8th April 2022). Despite being executed in thruster pulse count mode, the manoeuvre error was less than 1% and as a result no other pre-CAHE slot had to be used. Despite this early correction, the final impact point was only 3.3 km away from the original target. After the swing-by, an 18.3 m/s manoeuvre was performed using the MEPS in the slot TCM+1w.

3.2.2 Close approach operations

Close approach operations for MSB2 started about 24 hours before CAHE and finished about 12 hours after. During this period, full coverage was provided by the three ESA deep-space antennas with only small gaps due to the non-overlapping ground station visibilities. The full timeline, including the ground station coverage and the different attitude pointings is shown in Table 3. During this period, the FCT worked around the clock in two teams following 12-hours shifts with 1 SOM and 2 engineers on console. On-call support was provided by the ground stations and software support teams for the whole period. FD support was released 20 hours before CAHE, after confirmation that no emergency TCM (TCM-6h) was required.

The science pointing timeline consisted of 4 pointing slots connected by slews:

- COMMS 1: communications attitude used in the approach phase until CAHE - 21 h.
- Biased -X: pointing close to the one that brings MCSC –X axis closest to Mercury and at the same time enables communications through the HGA. It started at CAHE – 18 h and lasted until at CAHE - 6.5 h.
- CA: a purely inertial attitude was kept at close approach from CAHE -3.5h to CAHE + 1.5h. The selected attitude provided HGA coverage, brought the planet disc within the FoV of the three MCAM heads and of several MIO instruments (MIO-LEP, MIO-ENA and MIO-HE) and partly into the FoV of MGNS, allowed PHEBUS observation of the north ecliptic region and minimised simultaneous blinding of 2 or more STR. During this period, attitude remained undisturbed (no WOLs or solar arrays, HGA and MGA movement) as far as allowed by the spacecraft constraints.
- COMMS 2: communications attitude used from CAHE + 4.5h to CAHE + 48h.

Communication for most of the closest approach phase was performed over the HGA at a rate of 130 kbps. During the two slews between COMMS1, Biased -X and CA, communication was only possible over the MGA at a downlink rate of 5.4 kbps.

All the operations before and around CAHE were pre-planned and executed from the MTL. As no emergency manoeuvre was required, the role of FCT was limited to manually handle the antenna and ground stations handover and to monitor the correct execution of the operations. Intervention was only foreseen in case of contingencies. The default cruise configuration setup after CA pointing was prepared in advance but not on-board and was manually executed by the team on console.

The only spacecraft anomaly recorded during MSB2 was the switch-off of the MIXS/SIXS instrument by the on-board FDIR as the unit temperature was above the operational threshold. This was the consequence of an inadequate heater set-point incompatible with the brief temperature peak expected during the swing-by after the eclipse. The problem was quickly understood, the heater settings corrected and MIXS/SIXS was switched on again after confirmation by the instrument team.

Towards the end of MSB2, a major ground station incident occurred. Malargüe RF link was suddenly interrupted due to extreme weather and snow and ice accumulation on the antenna dish. Therefore, not all the science and MCAM images could be retrieved as planned on the same day of the swing-by and had to be dumped again at the next pass the day after.

Table 3. Mercury swing-by #2 close approach timeline

Time to CAHE	Absolute time	Activity	Attitude	NNO	MLG	CEB	Antenna
	17/06/2022 11:11	**MLG 1339 AOS10, decision point eTCM-3d**					
	17/06/2022 19:11	MLG 1339 LOS					
	18/06/2022 10:00	FCT shift for planning					
	18/06/2022 17:00	**eTCM -3d products delivery**					
		MLG 1342 LOS					
	20/06/2022 19:11	Start of STP83					
	20/06/2022 19:30	**MTL breakpoint for eTCM -3d**					
	21/06/2022 00:00	**eTCM -3d**					HGA
	21/06/2022 23:45	MGA visibility starts					
	22/06/2022 00:00	MGA to ET					
	22/06/2022 00:58	NNO 1344 AOS					
	22/06/2022 05:47	NNO 1344 LOS	COMMS 1				
	22/06/2022 09:00	**Decision point for eTCM -6h**					
- 24:00:00	22/06/2022 09:27	Start of pre-heating operations					
	22/06/2022 10:30	Shift A1 starts					
	22/06/2022 10:59	MLG 1344 AOS					
- 21:30:00	22/06/2022 12:14	WOL in preparation for slew					
	22/06/2022 12:36	SSMM Stop dumps					
	22/06/2022 12:39	Swap HGA-> MGA					
- 21:00:00	22/06/2022 12:44	COMMS 1 end, Slew to Biased –X pointing start					
	22/06/2022 14:00	**eTCM -6h products delivery**					MGA
	22/06/2022 15:31	SSMM Stop dumps	SLEW				
	22/06/2022 15:34	Swap MGA -> HGA					
- 18:00:00	22/06/2022 15:44	Slew to Biased –X pointing end, BIASED pointing start					
	22/06/2022 19:00	SSMM Stop dumps					
	22/06/2022 19:11	MLG 1344 LOS					
	22/06/2022 19:30	Shift A1 end/ Shift handover					
- 14:00:00	22/06/2022 19:44	WOL					HGA
	22/06/2022 22:00	B1 starts					
	22/06/2022 22:28	NNO 1345 AOS	BIASED pointing				
- 10:30:00	**22/06/2022 23:14**	**MTL breakpoint for eTCM -6h**					
- 7:00:00	23/06/2022 02:44	WOL in preparation for slew					
	23/06/2022 03:06	SSMM Stop dumps					
	23/06/2022 03:09	Swap HGA -> MGA					
- 6:30:00	23/06/2022 03:14	Biased -X pointing end, Slew to CA pointing start					
- 6:00:00	**23/06/2022 03:44**	**eTCM -6hrs**	SLEW				
	23/06/2022 06:01	SSMM Stop dumps					MGA
	23/06/2022 06:04	Swap MGA -> HGA					
- 3:30:00	23/06/2022 06:14	Slew to CA pointing end, CA start					
- 3:25:00	23/06/2022 06:19	WOL					
- 3:00:00	23/06/2022 06:44	No SA movement or WOL from this point up to CA +1 h					
	23/06/2022 06:52	SSMM Stop dumps					
	23/06/2022 07:03	NNO 1345 LOS					
	23/06/2022 07:23	CEB 1344 AOS					
	23/06/2022 08:30	Shift A2 starts/B1 ends					
- 1:00:00	23/06/2022 08:44	Antennae on hold at least from this time					
- 0:17:20	23/06/2022 09:27	Penumbra start					
		SSMM Stop dumps					
- 0:05:51	23/06/2022 09:38	STR2 Shutters closed					HGA
- 0:02:50	23/06/2022 09:41	Occultation start	CA				
- 0:00:17	23/06/2022 09:44	STR2 and STR3 blinding start					
0:00:00	**23/06/2022 09:44**	**Closest Approach**					
+ 0:00:56	23/06/2022 09:45	Penumbra end					
+ 0:01:08	23/06/2022 09:45	STR1 blinding start					
+ 0:09:19	23/06/2022 09:53	Occultation end					
+ 0:16:08	23/06/2022 10:00	STR1 blinding end					
+ 0:20:44	23/06/2022 10:05	STR3 blinding end					
+ 0:56:38	23/06/2022 10:41	STR2 shutters open					
+ 1:00:00	23/06/2022 10:44	Antennae on hold at least until this time					
+ 1:02:31	23/06/2022 10:46	WOL in preparation for slew					
	23/06/2022 11:09	SSMM Stop dumps					
+ 1:30:00	23/06/2022 11:14	CA end, Slew to COMMS 2 start					
	23/06/2022 12:02	SSMM Stop dumps					
	23/06/2022 12:14	CEB 1345 LOS	SLEW				
	23/06/2022 12:30	MLG 1345 AOS					
+ 3:30:00	23/06/2022 13:14	Slew to COMMS 2 end					
+ 3:30:00	23/06/2022 13:14	COMMS 2 start					
+ 6:00:00	23/06/2022 15:44	WOL					
	23/06/2022 19:01	SSMM Stop dumps					
	23/06/2022 19:12	MLG 1345 LOS					
	23/06/2022 19:17	End of MGA ET / MGA to HOLD					
	23/06/2022 19:30	Shift A2 ends					
	24/06/2022 00:16	NNO 1346AOS					
+ 18:00:00	24/06/2022 03:44	WOL					
	24/06/2022 06:53	SSMM Stop dumps					
	24/06/2022 07:04	NNO 1346 LOS	COMMS 2				
	24/06/2022 11:07	MLG 1346 AOS					
+ 30:00:00	24/06/2022 15:44	WOL					
	24/06/2022 19:02	SSMM Stop dumps					
	24/06/2022 19:13	MLG LOS					
+ 42:00:00	25/06/2022 03:44	WOL					
	25/06/2022 11:11	MLG AOS					
	25/06/2022 19:03	SSMM Stop dumps					
	25/06/2022 19:14	MLG LOS					
+ 58:04:00	25/06/2022 19:48	COMMS 2 end					
+ 58:23:21	25/06/2022 20:07	STR2 blinding end					

3.2.3 Spacecraft configuration and MTM preheating

The spacecraft configuration needs to be adapted before and after a swing-by following the dedicated procedures built based on the spacecraft user manual and the specific aspects of the swing-by. The main changes required are:

- Management of the STR blinding by planet Mercury. For MSB2, it was required in addition to close STR2 shutters to protect the optics.
- Charging the MPO battery 100% before eclipse and back to 40% (cruise charge level) after and the tuning the battery FDIR thresholds.
- Adaptation of safe-mode parameters to reflect the proximity of Mercury in the system init sequence.
- Activation of the backup MTL to guarantee the execution, in case of safe mode, of safety-critical operations related to eclipse and STR2 management.

One of the most important aspects of MSB2 was the pre-heating of the MTM. The long eclipse could bring the MTM battery capacity close to its lower limit. To ensure sufficient margin during the eclipse phase, 24 hours before CAHE the MTM is heated to boost the temperature of the spacecraft. Then, 5 minutes before eclipse, reduced heater settings are applied. Finally, 2.5 minutes after eclipse exit, the default heater settings for cruise are restored. Thanks to this operation, heater power consumption of the MTM is practically reduced to zero for most of the eclipse, preserving the MTM battery capacity. This can be seen in the plot of Fig. 6. Average MTM heater consumption decreased from ~1400W to about 40W during eclipse. Furthermore, for the duration of the eclipse, the MPO-MTM power link is disconnected, and each module is powered by its own battery.

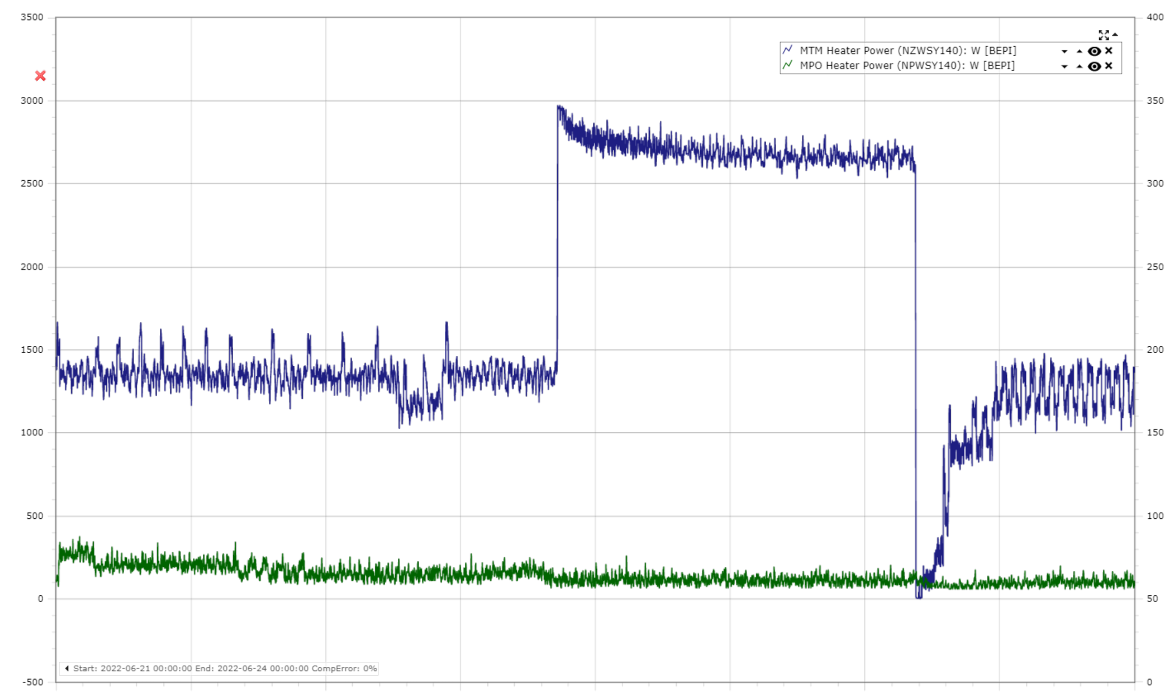

Fig. 6. MTM and MPO heater power consumption

3.2.4 Instrument operations and MCAM imaging campaign

For MSB2, all the MPO instruments not fully blocked by the MTM were operated around closest approach: BERM, ISA, MIXS, MPOMAG, MGNS, PHEBUS, SERENA (MIPA and PICAM) and SIXS. Most of the MIO instruments were also activated. The CA pointing was optimised to satisfy as many of the instrument requests as possible. Data were received at ESA's SGS and at JAXA's MIO control centre and processed offline by the instrument teams.

The MCAM imaging campaign plan was driven by the inputs from the scientific community and from the desire to acquire images that could reach a global audience. These two goals were then combined with the imaging opportunities resulting from the pointing timeline and the technical limitations from the MCAM hardware. A total of 64 images were acquired (the maximum that can be stored by the MCAM HW) across 4 sub-slots:

- MCAM#2 and MCAM#1 imaging [CAHE - 00:02h ; CAHE + 00:04h]
- MCAM#2 and MCAM#3 single setting interleaved imaging [CAHE + 00:05h ; CAHE + 00:10h]
- MCAM#2 and MCAM#3 dual setting interleaved imaging [CAHE + 00:10h ; CAHE + 00:27h]
- MCAM #3 farewell imaging [CAHE + 00:31h ; CAHE + 00:40h]

Different exposure settings were applied to maximise the chances to acquire correctly exposed images. The transfer of the images, from the MCAM to the mass memory first and later to ground, is a lengthy process. Best suitable images for public outreach were prioritised and they were available on-ground only two hours after CAHE. One of the first images officially released is shown in Fig. 7. All MSB2 images are available in ESA's Planetary Science Archive [19].

Fig. 7. MCAM2 image acquired during MSB2. *Credit: ESA*

4. Solar conjunctions and radio science

Frequent solar conjunctions are an inherent feature of the inner Solar System high pace. In the case of BepiColombo, superior solar conjunctions are defined as Sun-Earth-Probe (SEP) angles below 5 degrees and inferior solar conjunctions as SEP angles below 0.35 degrees. Table 4 lists all solar conjunctions foreseen during the cruise phase. Inferior conjunctions are not shown, as these periods are noticeably short and with limited impact on spacecraft operations.

Table 4. List of superior solar conjunctions in cruise

	Duration (days)	Start Date	End Date	Min. SEP angle (deg)	Electric Propulsion	Radio Science	Prime station
SC 1	16 d	11/03/2021	26/03/2021	1.2	No	Yes	MLG
SC 2	14 d	29/01/2022	11/02/2022	2.0	No	Yes	MLG
SC 3	10 d	10/07/2022	19/07/2022	1.6	No	Yes	DSS-25
SC 4	15 d	28/01/2023	11/02/2023	2.2	No	Yes	MLG
SC 5	9 d	26/06/2023	04/07/2023	1.0	No	TBD	MLG
SC 6	32 d	30/11/2023	31/12/2023	1.3	Partial	Yes	MLG
SC 7	9 d	17/05/2024	25/05/2024	0.3	Yes	No	-
SC 8	14 d	24/09/2024	07/10/2024	0.8	Partial	No	-
SC 9	12 d	01/02/2025	12/02/2025	2.0	Yes	No	-

In cruise, the average solar conjunction duration is 14 days with a minimum of 9 days and a maximum of 32 days. The first six solar conjunctions are free of electric propulsion so that they can be used for radio-science for 15 days centred on the minimum SEP angle.

The test of Einstein's Theory of General Relativity is a prime science objective of the BepiColombo mission. The MORE radio tracking system, one of BepiColombo instruments, allows to establish precise ranging and Doppler measurements on Ka-Band, thus providing an accurate measurement of the relativistic time delay and frequency shift experienced by a radio signal during solar conjunctions [20]. The final objective is to place new limits to the accuracy of the General Relativity as a theory of gravity in the weak-field limit. Three radio-science campaigns, normally referred as solar conjunction experiments (SCE) or radio-science experiments (RSE), have been successfully completed, while three more are planned in 2023. The conjunctions in 2024 and 2025 unfortunately cannot be exploited for radio-science as they conflict with solar electric propulsion periods.

4.1 Radio Science Experiment 2 (RSE2)

To illustrate the operations performed for a radio-science experiment, the second conjunction of the mission is taken as an example. This radio-science campaign, named RSE2, lasted 2 weeks centred around the minimum SEP angle, from 29th January 2022 to 12th February 2022.

The period with a SEP angle below 3 degrees went from 2nd February 2022 to 7th February 2022, with a minimum value of 2.0 degrees on 5th February 2022. The Sun distance evolved during the campaign from 0.5 AU to 0.37 AU, and the Earth distance from 1.48 AU to 1.34 AU. A visual representation of the RSE2 geometry is shown in Fig. 8.

The radio science campaign was conducted from ESA’s ground station in Malargüe, Argentina. This is currently the only 32 m deep-space antenna on ESTRACK (ESA’s ground station network) with radio-science capabilities. Daily 8-hours passes were scheduled at a fix time and above an elevation of 15 degrees. Malargüe was complemented with four overlapping passes from NASA’s Deep Space Network terminal DSS-25 at the beginning and at the end of the campaign. DSS-25 shadow-tracked BepiColombo and, one hour before the end of the Malargüe pass, the roles were inverted, and the uplink was handed-over to the NASA terminal while ESA’s station shadow tracked.

For radio science, BepiColombo offers the unique capability of multi-frequency links. Two links are provided by the TTC subsystem: X up/X down (the standard link used for commanding and regular telemetry) and X up/Ka down (for science telemetry downlink). MORE Ka Band Translator (KAT) provides the third one: Ka up/Ka down. Ka downlink frequencies are different between X/Ka and Ka/Ka links, as each Ka downlink signal is generated by a different unit (deep-space transponder, MORE) and coherent with a different uplink.

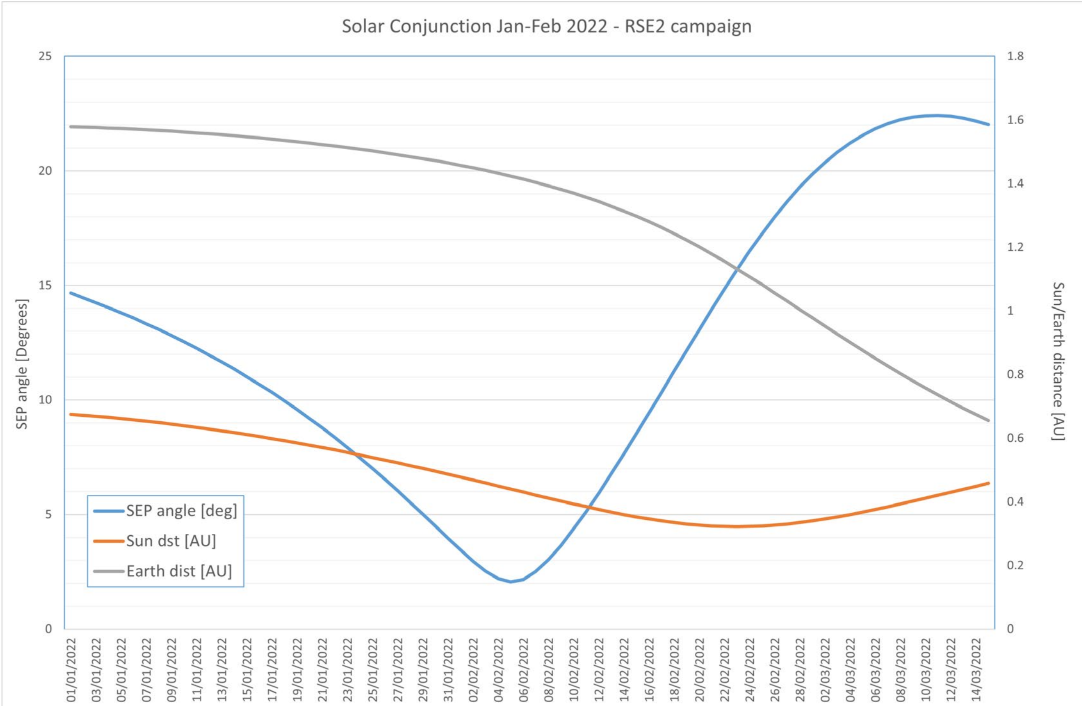

Fig. 8. RSE2 geometry

4.2 Solar conjunction operations

As the angular distance between the spacecraft and the Sun decreases, the TM/TC links are degraded by solar scintillation. The spacecraft configuration and the operations need to be adjusted to maximise the link stability and to deal with the potential communication outages. The changes to each subsystem are detailed in the next subsections.

4.2.1 TTC configuration and ground station setup

Preparations for each solar conjunction start with a link budget study. The analysis allows to assess the impact of the solar scintillations on the X-band link and to decide the most optimum configuration for each daily pass. In the case of conjunctions with a radio science campaign, the analysis also needs to cover Ka-band.

On the spacecraft side, the strategy is to reduce the downlink bitrate and increase the ranging modulation index, at the expenses of reducing the TM modulation index. In the case of RSE2, the safe mode TM rate (255 bps) was adopted around the lowest SEP angle, which severely limited the visibility of the spacecraft status. In extreme cases, TM modulation needs to be switched-off; this was the case for RSE1. The same principle is applied to the uplink: in the worst days of the conjunction, an uplink rate of 7.8 bps is set and there is no guarantee that the commanding link will work.

On the ground side, the uplink power is increased for the worst days of the conjunction (up to 20 kW EIRP) and the PLL bandwidth is adjusted as required. The ground station operations for radio science are complex and require the adaptation of multiple station parameters. They are discussed in detail in [21], including a summary of the station performance during RSE2.

It is well known that Ka-band is less affected by solar scintillations than the X-band [22]. This has been experienced directly during RSE2. While downlink of engineering data over the X-band was limited to 255 bps around the lowest SEP angle, science data could be downlinked at 43 kbps over Ka-band for the whole conjunction. If the uplink is stable enough, it may be possible to exploit this during the science phase to increase the amount of data received during conjunctions.

4.2.2 AOCS configuration

As in all gravity experiments, non-gravitational accelerations acting on the spacecraft are a major concern. MORE instrument team has requested to avoid reaction wheel off-loading (WOL) during RSEs, as the thrusters are used to desaturate the wheels and would introduce parasitic delta-V, severely degrading science performance. The spacecraft has not been designed to satisfy such requirement. However, the FD team at ESOC have envisioned a clever momentum management strategy that has successfully achieved a full campaign without WOL during RSE1 and RSE2.

To avoid WOL, a regular attitude flip cycle is executed daily. For RSE2, the spacecraft was in an inertial attitude, with the HGA tracking the Earth for 8 hours a day (during the MLG pass), followed by 180 degrees slew around the Sun axis lasting 4 hours, followed by 8 hours inertial in a non-communication attitude, followed by 4 hours slew to go back to the start of the cycle. On top of the perfectly symmetric cycle, the two MTM solar array wings were commanded applying 1.3 degrees offset between them (windmill angle) to partially offset the forces imposed by the solar radiation pressure. As a result, the momentum of all four RWU always remained below the threshold that would have triggered an autonomous WOL.

This strategy has unfortunately not been entirely successful for RSE3. The third solar conjunction occurred during perihelion, at a close Sun distance (between 0.31 AU and 0.42 AU). Consequently, the disturbance torques induced by solar radiation pressure were higher than in RSE2, which resulted in three WOLs being executed autonomously by the spacecraft. The same problem is expected to occur again during RSE5, as the perihelion is in the middle of the conjunction. As this will significantly degrade the scientific value of the campaign, whether to perform or not RSE5 as originally intended is currently under discussion.

4.2.3 Data handling configuration

During solar conjunctions, the time-out of the TC link monitor function (which reconfigures the TTC subsystem, and later triggers a safe mode, if no command is received before the time-out) needs to be first increased to the worst-case link interruption duration and then gradually reduced as the solar conjunction progresses. In addition, the TM generation rate on the real-time channel needs to be adjusted to be compatible with the X-band downlink bitrate.

For RSE3, there was a TM and TC outage of more than 10 days, since the whole campaign was performed with DSS-25 as the prime station and the passes were exclusively radio-science passes (no TTC). As a result, on-board storage had to be re-arranged to avoid overflooding the engineering packet store dedicated to housekeeping TM.

4.2.4 Instrument configuration

MORE is active during the whole RSE period. On each day, a self-calibration of the instrument is scheduled a few minutes before the start of the ground station pass. In addition, the Italian Spring Accelerometer (ISA) is operated continuously to measure non-gravitational accelerations to support MORE data processing.

For RSE4, SERENA PICAM instrument will be operated as well, as it provides additional data that could be useful to estimate the solar wind and better model and remove from the MORE data the effect of the associated non-gravitational forces.

Operation of other payloads not related to the campaign is limited by the available on-board storage and downlink data volume during and after the campaign. For RSE2, MPO-MAG, MGNS and BERM were operated in parallel.

5. In-flight anomalies

In total, 245 anomaly reports have been raised so far. As shown in Fig. 9, they are equally distributed between the platform subsystems and the instruments and MIO. About 75% of them are either closed (anomaly has been fully mitigated), rejected (not accepted as a spacecraft anomaly), testing (problem is not fully solved or understood, but no further action is required, and impact in case of re-occurrence is accepted) or resolved (solution is available but not applied). The other 25% are anomalies which are still open and for which investigations are ongoing and actions are in place to resolve or mitigate them.

A large fraction of the platform anomalies is related to minor problems at subsystem level and are resolved with simple configuration changes or procedure updates. There is however a small subset of anomalies with a wider system impact, which are complex to tackle and require detailed analysis and system changes, including the patching or deployment of new on-board software versions. Work is in progress with the extensive involvement of Industry and ESA experts to mitigate them before Mercury arrival.

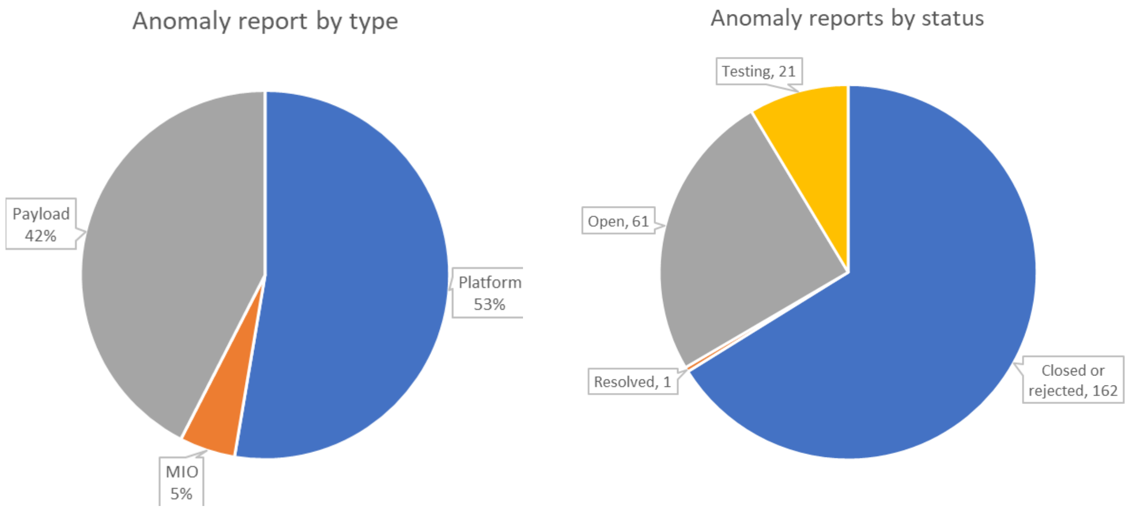

Fig. 9. BepiColombo in-flight anomalies statistics

Most of the payload anomalies are linked to unexpected behaviours, which could be explained by errors in the flight procedures or in the instrument operations. These are tackled by procedures or user manual updates or, in some cases, with an update of the instrument software. Few major instrument anomalies have been identified so far, but none of them is currently a concern for the scientific phase of the mission. The instrument teams are working on instrument software and operational changes to mitigate them or expect the impact to be small and to not compromise the science objectives.

BepiColombo average of 5 spacecraft anomalies per month is noticeably higher than other missions operated at ESOC. There are multiple explanations to this observation:

- The technical complexity of the system and the large number of units and instruments. Most of them are specific and new developments for the BepiColombo mission.
- The high pace of the inner Solar System, with frequent swing-bys and solar conjunctions. The number of anomalies raised highly correlate with these critical periods, as well as with SEP thrust arcs.
- The harsh thermal environment is behind many of the anomalies raised since Venus Swing-by 2, when the spacecraft Sun distance regularly goes as low as 0.3 AU.

BepiColombo has experienced 5 safe modes so far. The first 3 occurred in the early mission phases (1 in LEOP, 2 during commissioning of MEPS and first thrust arc) and were related to FDIR threshold too tight and mismatches in the interpretation of the spacecraft constraints. The other two emergency resets have occurred in the course of 2022. In both cases, the root cause was quickly identified, and the spacecraft was timely recovered to nominal mode with limited impact on the mission.

The fourth safe mode happened on 4th January 2022. The emergency reset was triggered on reaction to a hardware overspeed flag raised by one of the reaction wheels. The spacecraft isolated the RWU and achieved a stable attitude on 3 wheels configuration. High frequency diagnostic data acquired shorty before the safe mode entry could be recovered. The speed of all reaction wheels was in the expected range. It has been concluded that the problem has been triggered by a glitch on the RWU electronics, possible induced by radiation, and causing the overspeed error flag to be latched on the RWU hardware. The satellite was initially recovered in nominal mode on a 3 wheels configuration. Then, the faulty RWU was tested keeping the attitude control on 3 wheels with the suspected one running in speed mode. The test was run first at low speed and for very short duration and later at the same speed level as at the time of the emergency reset. As no anomalous behaviour was observed, the Anomaly Review Board declared the RWU healthy. The transition back to a 4 wheels configuration was implemented on 26th January, just in time for the start of the RSE2, which required the 4 RWU to be active to achieve a WOL-free campaign (see 4.2.2).

The fifth safe mode of the mission occurred on 6th December 2022, for the first time in the middle of a SEP arc with the spacecraft in EPCM and thrusting. It was also the first time that BepiColombo has experienced in flight a hardware safe mode, with no software involved on the detection. This last-chance safety net mechanism was never expected to trigger in flight, as any equipment failure shall be detected and handled by the on-board software first. The reason for the emergency rest was the high temperature detected on one of the two MTM radiators. This alarm is based on a majority-voted triple thermistor, and it is intended to protect the spacecraft in case the Sun starts illuminating the radiator. The three alarm thermistors reported a large increase in temperature of tenths of degrees, but it was not consistent with the stable temperature of all the other thermistors inside the MTM. The temperature levels dropped immediately after the safe mode entry. It was found that the increase was in steps and strongly correlated with the MTM solar array movement. Further analysis has confirmed that an unexpected reflection of the Sun on the solar array yoke (which is covered by optical solar reflectors for thermal reasons) illuminated the thermistors triplet. This was linked to a particular geometry and position of the solar array flown for the first time of the mission during SEP15 arc. The design has accounted for potential MTM solar array reflections on the array and the yoke, but the impact on the alarm thermistors was unfortunately not realised. The Anomaly Review Board agreed to perform the remaining of the thrust arc with the specific hardware alarm disabled. There is little margin to adjust the solar array position or the spacecraft attitude during EPCM, as they are dictated by the electric propulsion needs. While there is the risk of burning the thermistors, this alarm is not considered a critical surveillance for cruise. On the other hand, skipping the thrust arc completely would have implied missing the next flyby and Mercury arrival in 2025. The spacecraft was commanded back in EPCM on 15th December 2022. Fortunately, the required EPCM and solar array geometry had evolved, and no Sun was casted on the alarm thermistors for the remaining of the thrust arc. The 9-days outage have induced a minor delta-V penalty but is fully recoverable before MSB3.

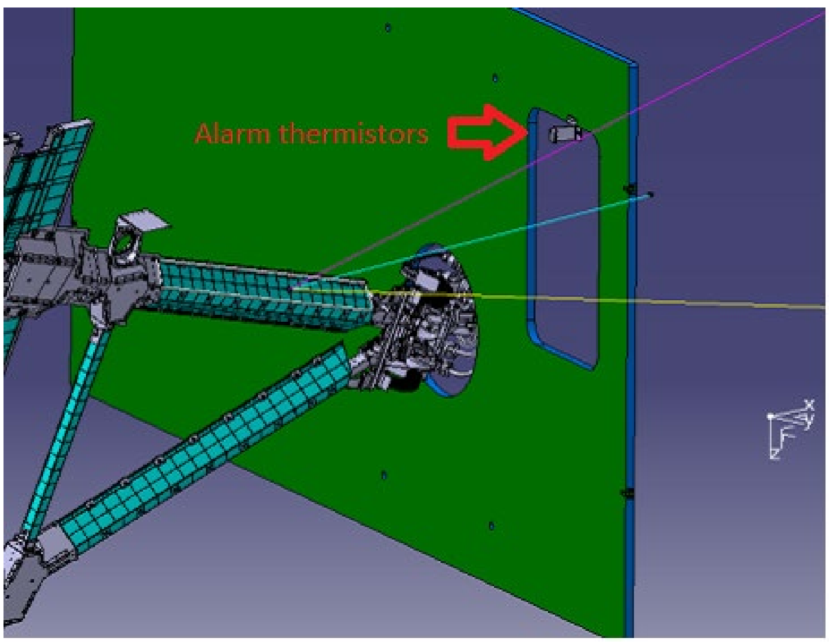

Fig. 10. Sun incident light (yellow) reflecting on MTM solar array yoke (purple). *Credit: AIRBUS*

6. Conclusions and outlook

In this paper, an overview of the BepiColombo mission operations during the cruise phase has been presented. Despite the technical complexity and the anomalies found along the way, the spacecraft remains in good condition and continues its planned way to Mercury. The rapid succession of swing-bys, solar conjunctions and SEP thrust arc are driving the operations during this phase. The high intensity pace of the BepiColombo cruise is not comparable with previous ESA deep-space missions, stressing the challenge of flying a spacecraft in the inner solar system.

Swing-bys and solar conjunctions are two of the main milestones during cruise and their planning and execution have been presented on this paper, taking MSB2 and RSE2 as an example. European end-to-end radio-science making use of Malargüe ground station is a first for an ESA mission.

In the short term, the next steps are the preparations for the next Mercury gravity assist manoeuvre (MSB3) and the next solar conjunction campaign (RSE5). They will be followed by an intense phase in 2024 and early 2025, with 3 swing-bys in less than 6 months. The cruise phase will end in October 2025 with the arrival to the vicinity of Mercury and the MTM separation, marking the transition to the MOI phase.

The main challenge now is to focus on the development activities for the Mercury approach and routine phase, while flying the spacecraft in parallel and taking care of all the cruise milestones. This dual nature of BepiColombo, which is at the same a mission in development and in operations, will make the years ahead the most challenging ones of the mission.

Acknowledgments
The authors would like to thank to all the members of the FCT, FD and all the other teams involved in the operations of the BepiColombo spacecraft, as well as the experts on Industry and ESTEC providing their support and expertise. This paper is the outcome of their work and their commitment to the success of this complex mission.

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