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# GNC Operations for the BepiColombo Mission to Mercury: First In-flight Experience

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## Abstract

Launched in October 2018, the ESA/JAXA BepiColombo mission shall arrive at Mercury in late 2025. The modular spacecraft consists of two scientific Mercury orbiters and a cruise module. Challenges for GNC design and operations include electric propulsion usage in cruise, the capability to deal with several S/C configurations, and strict attitude and solar array pointing constraints owing to the harsh thermal environment.

This paper focuses on the return on experience after completion of in-orbit commissioning and the first electric propulsion thrust arc, in view of the mission's specific GNC challenges.

## 1. Introduction

### 1.1 Mission Overview

BepiColombo is an ESA cornerstone mission to Mercury in collaboration with the Japanese Space Agency (JAXA) with the objective to study the planet and its environment, in particular global characterization of Mercury through the investigation of its interior, surface, exosphere and magnetosphere. The mission consists of two scientific spacecraft, ESA's Mercury Planetary Orbiter (MPO) and JAXA's Mercury Magnetospheric Orbiter (MMO), launched together as a single composite including a dedicated propulsion module (MTM). MPO and MTM have been developed under ESA contract by an international consortium led by Airbus Defence and Space Germany. Flight operations are performed by ESA/ESOC.

BepiColombo was launched on 20th Oct 2018 with Ariane-5 from Kourou. Launch is followed by a 7 years cruise phase, including planetary swingbys at Earth, Venus and Mercury, eventually achieving a weak capture by Mercury in December 2025 (Fig. 1). During cruise electric propulsion is provided by the MTM module, which will be jettisoned at Mercury arrival. A series of manoeuvres will deliver the MMO to its operational orbit, and finally the MPO will reach its 1500x480 km polar orbit (2.2h period), with its scientific mission planned to last for one Earth year (1 year extension possible).

See [1] for an in depth overview of the mission.

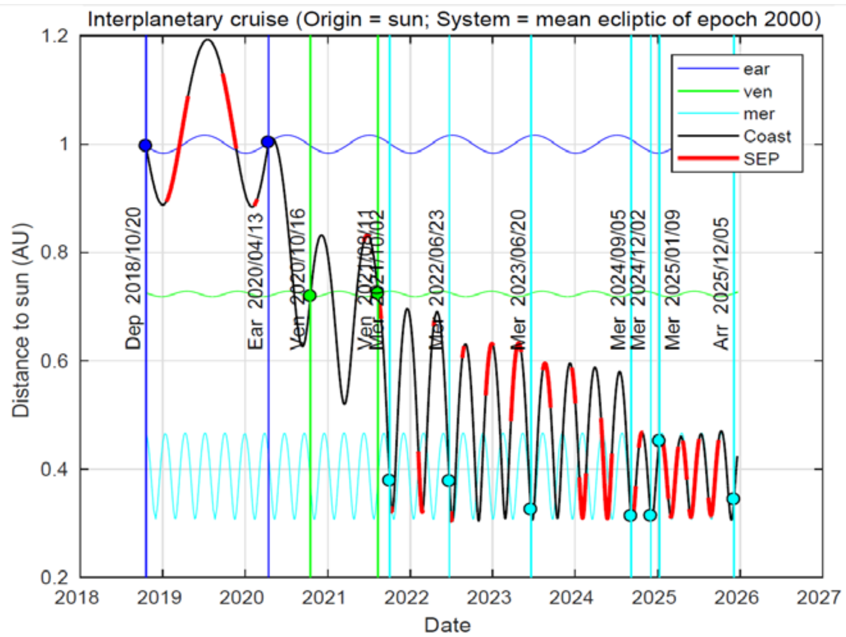


Figure 1: BepiColombo cruise trajectory, showing Sun distance, electric propulsion usage ("SEP"), and planetary flybys (at Earth, Venus, Mercury).

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### 1.2 The BepiColombo Spacecraft

See Fig. 2 and 3 for an artist's view of the spacecraft. The combined stack can have the following configurations:

- Mercury Composite S/C Cruise (MCSC): MTM, MPO, MMO sunshield (MOSIF) and MMO
- Mercury Composite S/C Approach (MCSA): MPO, MOSIF and MMO following separation of the MTM
- Mercury Composite S/C Orbit (MCSO): MPO and MOSIF following release of the MMO

During cruise, the JAXA-provided MMO is a passive passenger, not involved in the control of the composite. This is done centrally within the MPO, while the MTM provides propulsion means.

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. 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 spacecraft, which may not be exposed to Sun or Mercury.

The MPO AOCS performs 3-axis stabilised attitude and orbit control employing star trackers, inertial measurement units, fine Sun sensors, reaction wheels and chemical propulsion. AOCS design is impacted the challenging environment, requiring special guidance profiles for the MPO solar array (to avoid overheating) and rapid S/C attitude stabilisation in case of contingencies. For these cases, the on-board computer contains a separate processing unit, the Failure Control Electronics (FCE), taking over S/C attitude control in case of transient unavailability of the main on-board computer. For deep space communications, the MPO uses a X/Ka-band deep space transponder with moveable high gain and medium gain antennae (HGA and MGA).

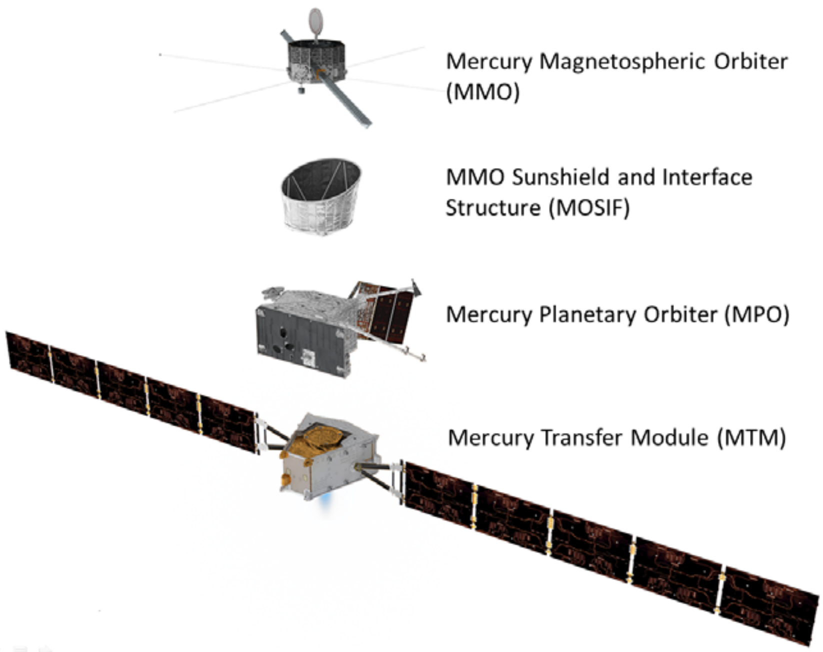


Figure 2: BepiColombo spacecraft in exploded view.

The MTM provides propulsion means for the cruise phase. Apart from dual mode bipropellant chemical propulsion, it features electric propulsion with 4 moveable thrusters based on the Kaufman-type electric bombardment ion motor (max thrust 145 mN). The high power demand by the MTM electric propulsion (up to 11 kW) is satisfied with large solar arrays (area of over 40 $m^2$ in total), using the same high-temperature technology as for the MPO.

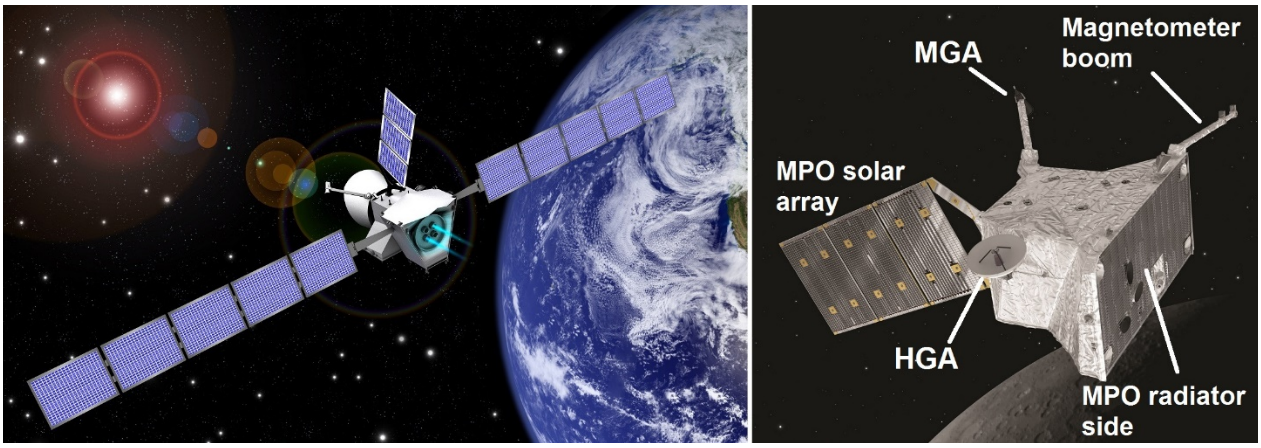


Figure 3: BepiColombo in cruise configuration (left), MPO at Mercury (right).

DOI: 10.13009/EUCASS2019-218



### 1.3 The BepiColombo Mission Operations Centre at ESA/ESOC

Operations of the composite spacecraft and the MPO are conducted at ESA/ESOC, using the typical setup for ESA deep space missions, including a SCOS-2000 based mission control system, a standalone mission planning system, and a SIMSAT-based S/C simulator. The simulator is running the platform on-board software on a processor emulator, and is a key tool for operations preparation, allowing testing with high fidelity.

The Engineering Test Bed (ETB) shown in Fig. 4 was installed at ESOC in early 2018, with the final handover from the S/C manufacturer to ESOC currently ongoing. The ETB contains flight hardware for all electrical equipment and is used for operations validation when the S/C simulator is not considered representative enough.

BepiColombo operations are performed by the Flight Control Team (FCT), consisting of about 10 engineers and controllers at launch. The FCT is interfacing with various multi-mission support groups at ESOC, including Flight Dynamics (FD), ground segment software and hardware support, and ground station operations. FD is in charge of orbit determination and prediction, command generation (e.g. for orbit control manoeuvres) and monitoring of S/C status for FD-related items (e.g. star tracker performance). For deep space missions, there is a particularly close relation between FCT and FD due to the complex navigation and GNC operations activities.

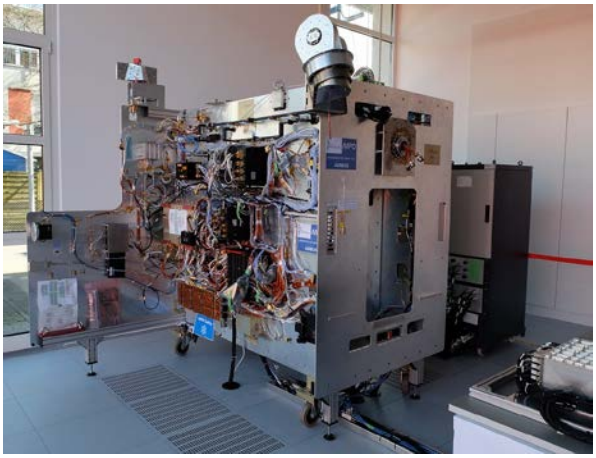

Figure 4: MPO element of the BepiColombo Engineering Test Bed (ETB) at ESOC.

## 2. The Attitude and Orbit Control System (AOCS)

The AOCS is in charge of attitude and orbit control using sensors and actuators for autonomous attitude determination and correction as well as pre-programmed delta-Vs. The AOCS hardware architecture is shown in Fig. 5. The AOCS is built around the On-Board Computer (OBC), the Failure Correction Electronics (FCE) and the Remote Interface Units (RIU). The OBC/FCE is communicating with the following AOCS sensors and actuators either directly via the 1553B interfaces or via the Space Wire interface and the RIUs:

**Sensors:**

- 3 Star Trackers (STR) from Leonardo (formerly Selex ES)
- 4 x 2 Fine Sun Sensors (FSS) from TNO
- 2 Inertial Measurement Units (IMU) from Northrop Grumman (SSIRU - Scalable Space Inertial Reference Unit), where each IMU includes 4 gyroscopic together with 4 accelerometric channels

**Actuators:**

- Reaction Wheel Assembly (RWA) consisting of 4 wheels and 2 electronics, from Bradford Engineering
- Reaction Control System (RCS), where a Chemical Propulsion System (CPS) is available on the MTM (8 x 2 10N tilted thrusters and 4 x 2 10N axial thrusters from EADS-ST) and on the MPO (4 x 2 5N tilted thrusters and 4 x 22N axial thrusters from MOOG-ISP)
- High and Medium Gain Antenna Pointing Mechanisms (HGAPM/MGAPM) with their electronics, from Sener
- 3 Solar Array Drive Mechanisms (SADM) with their electronics, 2 on the MTM from Kongsberg and 1 on the MPO from RUAG
- Solar Electrical Propulsion Subsystem (SEPS) from QinetiQ with 4 gridded ion thrusters (SEPT) mounted on 4 Thruster Pointing Mechanisms (TPM), allowing to use either one or two thrusters at a time [7]

The BepiColombo mission software runs on the OBC processor module (PM). The OBC PM controls the spacecraft under normal circumstances. There is a nominal and a redundant PM within the OBC, with autonomous PM reconfigurations controlled by the OBC reconfiguration module (RM). During an OBC emergency reset, the fully redundant FCE PM takes over attitude and solar array control of the S/C.

DOI: 10.13009/EUCASS2019-218



The SpaceWire router connects the OBC, the FCE and the MTM and MPO RIUs. OBC and FCE are both connected to the MPO/MTM SADEs via the 1553B MIL-BUS, each able to control the MPO and MTM transverse thrusters and solar arrays, as required during normal and emergency operations.

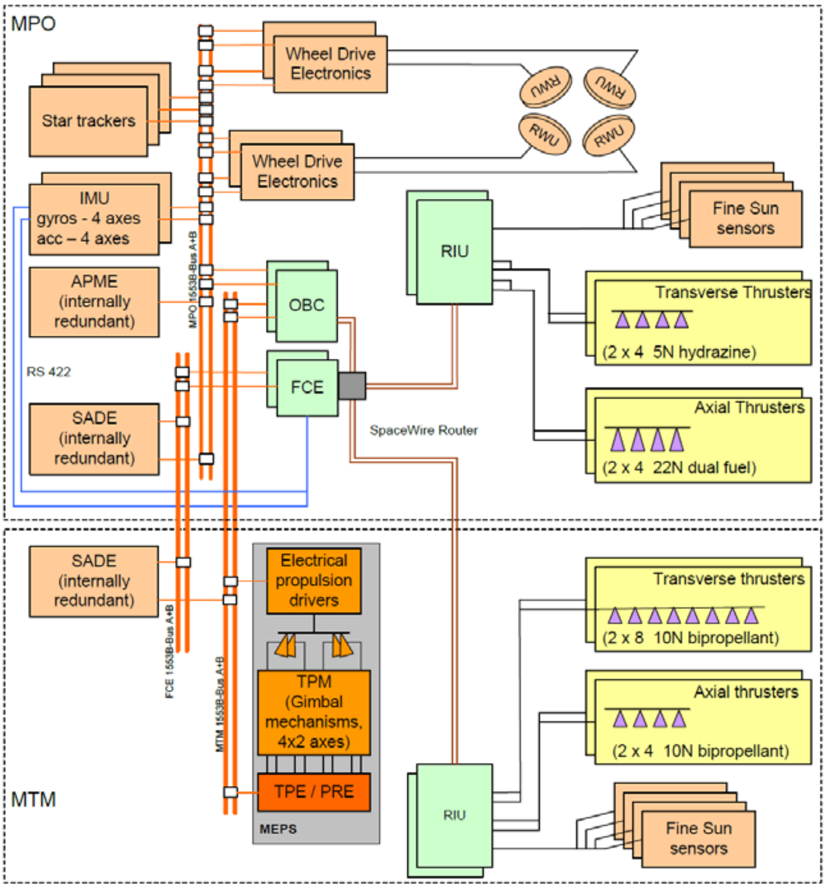

Figure 5: AOCS hardware architecture.

Introducing the FCE into the design was necessary to prevent unacceptably large depointings during the short outage of attitude control on OBC in case of an emergency reset, safeguarding the S/C attitude at all times in the expected harsh thermal environment. For the same reason, a special approach was chosen for maintaining attitude knowledge and for attitude acquisition in safe and survival mode: attitude information is always maintained and propagated on-board with sufficient accuracy, an attitude acquisition from "lost in space" conditions is never performed (except after separation from the launcher). This is achieved by maintaining the spacecraft attitude information across a PM reset, performed by either the OBC or the FCE. When the FCE takes over attitude control, it keeps propagating the last known attitude by means of gyro measurements coming from the IMU assigned to the FCE, with Sun sensor measurements not used on FCE. This is sufficient for the short time until the OBC regains the control of the spacecraft, retrieving the latest attitude information from the FCE. On the OBC, absolute attitude sensors (star trackers and Sun sensors) compensate for the accumulating gyro measurement errors. During normal operations, the attitude information maintained by the FCE is also regularly updated with STR measurements.

An overview of the AOCS modes and transitions is shown in Fig. 6. The AOCS mode logic includes two safe modes (SASM, SHM) and three normal operational modes (NM, OCM, EPCM). The AOCS also possesses a Standby mode (SBM), which is of no relevance for flight operations.

**Sun Acquisition and Survival Mode (**SASM) is dedicated to initial Sun acquisition after launcher separation and, later, to attitude recovery after OBC resets. Its definition in terms of attitude and solar array guidance as well as ground communication is based on simple and hence most reliable means. The control actuation is exclusively based on thrusters, no wheels are used. The attitude measurement concept is based on rate and incremental attitude measurements from the IMU, Sun position measurements from the Sun sensor and 3-axis attitude measurement from the STRs (if available). In SASM, the spacecraft is brought into a safe Sun pointing attitude with a rotation around the Sun direction, which differs depending on the spacecraft configuration (MCSC, MCSA/O and MPO). Hence each configuration has its specific SASM definition in terms of attitude and solar array guidance as well as MGA strobing.

**Safe and Hold Mode (SHM)** is the AOCS mode where the AOCS waits for ground intervention after an OBC reset. It is more fuel economic than SASM because the attitude is eventually controlled on wheels. The attitude is estimated by the gyro-stellar estimator. Ground communication is maintained by the MGA in Earth tracking mode, but optionally the HGA can also be used. Wheel offloading is managed autonomously by the AOCS. Attitude guidance is defined by Chebyshev polynomials and harmonic series pre-loaded by ground. The MCSA/O/MPO configurations use solar array guidance profiles defined by Chebyshev polynomials in SHM. The MTM SA guidance profile is defined by a sequence of discrete position angles as in SASM.

**Normal Mode (NM)** is the main operational mode, entered from SHM by ground command only. NM uses the same guidance profiles and attitude control equipment as SHM. In SHM, wheel offloading is autonomously performed by the AOCS, whereas it has to be commanded by ground in NM. This is a consequence of the necessity to pre-heat the

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MPO hydrazine thrusters' catalyst bed heaters in the MPO orbit before their usage (which are normally switched off in NM for power reasons). Both the MGA and HGA can be used in Earth tracking mode for communications with ground.

**Orbit Control Mode (OCM)** allows performing delta-Vs by means of the chemical propulsion system (CPS). Both the MPO and MTM modules have their own CPS, comprising an axial and a transverse thruster system. Large delta-V manoeuvres are to be performed by the axial thrusters for fuel efficiency reasons, whereas small delta-V and navigation manoeuvres can be performed by means of the transverse thrusters. Attitude constraints linked to the harsh thermal environment might also prevent ground from using the axial thrusters, in which case the less efficient transverse thrusters are used.

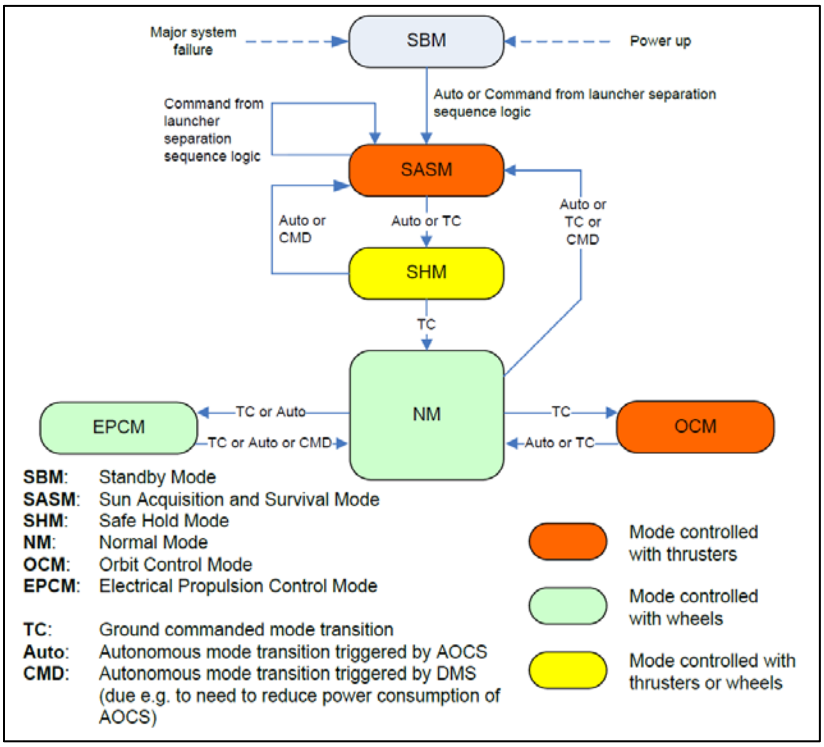


Figure 6: AOCS modes overview.

**Electric Propulsion Control Mode (EPCM)** is dedicated to performing delta-V manoeuvres using the Solar Electric Propulsion System (SEPS). The attitude control equipment used in EPCM is the same as in NM. The wheels are however continuously offloaded by means of the SEP engines, as long as two SEP engines are in use. If only one SEP engine is used (e.g. when insufficient electrical power is available at larger Sun distances), an offloading of the wheel momentum is not possible along the SEP thrust axis and chemical thrusters are used for this purpose. The EPCM design incorporates the autonomous reorientation of the spacecraft and MTM solar array such as to provide the SEP thrust in the required inertial direction, and to provide the necessary electrical power for the SEP engines. The reorientation slew between the NM and EPCM attitude guidance profiles is computed autonomously on-board based on target profiles defined by ground, respecting the strict Sun pointing constraints.

While all above AOCS modes are implemented on the OBC, the FCE AOCS (running on the FCE processor module) only implements a subset of SASM phases to establish correct Sun pointing, controlling the S/C attitude during a period of about 7 min before handing back control to the OBC.

For what concerns Failure Detection, Isolation and Recovery (FDIR), the AOCS employs a layered FDIR concept with sets of local, functional and global surveillances, aiming at isolating a failure rapidly with the least reconfiguration overhead.

## 3. Overview of GNC Operations Preparation and Execution

Prior to launch, GNC operations preparation by ESA/ESOC ran in parallel to the complex AIT campaign to prepare the composite for launch. Key milestones were the testing slots with the flight model and the engineering model (about 30 days in total), used to validate AOCS procedures and operational products provided by Flight Dynamics:

- System Validation Tests (SVT) with the flight model, located at ESA/ESTEC for several years, prior to its shipment to the launch site in April 2018
- Integrated Ground Space Tests (IGST) with the engineering test bed (ETB) located at Airbus Friedrichshafen premises. In March 2018 the ETB was transferred to ESA/ESOC, to serve as highly representative test bed throughout the mission (ref. Fig. 4).

See also [4] for an in depth overview of early GNC operations preparations in 2014 and 2015.

**Launch and Early Orbit Phase (LEOP):** BepiColombo was launched into an Earth escape orbit on 20$^{th}$ Oct 2018 with Ariane-5 from Kourou. The first 2.5 days of the mission were conducted with 24/7 ground station coverage and the ESA/Industry combined mission control team working in shifts around the clock. An overview of LEOP activities is shown in Fig. 7. The LEOP timeline was driven by key GNC activities:

DOI: 10.13009/EUCASS2019-218



- Autonomous Sun acquisition after separation, with AOCS stopping in SASM-SAPP3
- First switch ON and checkout of star trackers and reaction wheels by ground
- AOCS mode transitions from SASM-SAPP3 to SHM and eventually to NM under ground control
- Deployment of MGA and HGA
- Orbit control test manoeuvre on MTM axial thrusters (0.33 m/s deltaV)

See [6] for more information on GNC operations during LEOP.

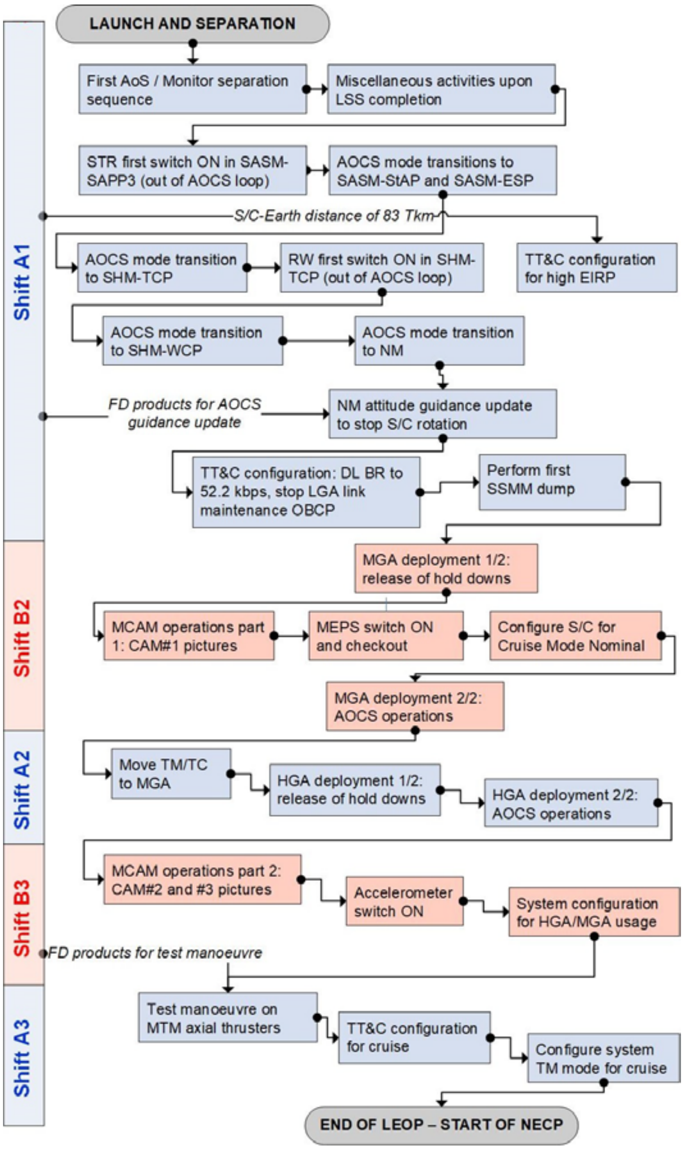

Figure 7: LEOP overview.

**Near Earth Commissioning Phase (NECP):** NECP operations following end of LEOP took place from 22nd Oct to 16th Dec 2018 and were supported by daily station contacts (10-12h duration), 7 days a week. The aim of this phase was to perform a full checkout of the spacecraft (platform and payload) with on-site support of the S/C manufacturer and the scientific instrument teams. The following GNC commissioning operations took place, confirming good health of the AOCS subsystem:

- Orbit control test manoeuvre on MTM transverse thrusters
- Commissioning firings of MTM CPS B-side thrusters out of the AOCS control loop to verify health of the redundant thrusters
- Calibration of IMU scale factor, alignment and drift bias
- Star Tracker inter head alignment and focal length calibration activities
- MTM solar array drive "run in", including several full rotations of the array to recover full performance of the slip ring in the mechanism
- "Nudging" of the MPO solar array, performing a small movement to verify health of the array drive mechanism
- Electric propulsion commissioning, including a stepwise commissioning of the various SEPS elements, culminating in firing each thruster in EPCM, as well as one EPCM entry with dual thruster usage (see Fig. 8 for an overview of EP)

Figure 8: Electric propulsion commissioning 20th Oct – 7th Dec 2018.

**SEP1 arc:** the end of NECP was driven by the need to start the first solar electric propulsion arc of the mission (SEP1) in December 2018, constituting the first extended EP usage in flight. This SEP arc was run in dual thruster mode, first using thrusters 1 and 3, later on thrusters 2 and 4. The arc was completed in early March 2019. EP operations are characterised by (i) complex EPCM entry/exit operations requiring several hundred commands to configure the S/C, (ii) regular interruptions of thrusting (i.e. requiring transition from EPCM back to NM) for performing orbit determination, and (iii) constraints on S/C visibility with MGA or HGA when in the attitude required for thrusting. Along with a few unplanned thrust interruptions linked to tuning of FDIR settings, this meant that the SEP1 arc required the full attention of the operations team.

Following completion of SEP1 arc, currently a series of delta NECP

DOI: 10.13009/EUCASS2019-218



activities is under way, which could not be run in the original NECP slot that was constrained by the start of the SEP1 arc. For GNC, this includes MGA and HGA pattern calibration activities to check and correct the antenna alignment, as well as characterisation of MTM solar array flexible modes by inducing torque pulses around the various S/C axes with the MTM SA in different positions.

# 4. GNC Operations Challenges and In-Flight Experience

## 4.1 S/C Modularity

Through its life, the spacecraft undergoes configuration changes that have an impact on the AOCS controllers, i.e. throughout the mission, see section 1.2, the AOCS must be able to handle five spacecraft configurations. Together with the different AOCS modes and mission phases, this results in a theoretical total of 70 controllers to be designed and tuned for the applicable performance and stability requirements: 3 controllers are needed in MCSS (in SASM only), 19 controllers are needed in MCSC (8 in SASM, 4 in SHM, 3 in NM, 2 in OCM and 2 in EPCM), 16 controllers are needed in MCSA, MCSO or MPO (8 in SASM, 4 in SHM, 2 in NM and 2 in OCM).

The AOCS is in charge of the attitude and orbit control using sensors and actuators for autonomous attitude determination and correction as well as pre-programmed delta-Vs. The AOCS hardware architecture and interconnections are shown in Fig. 5. The AOCS controls a total of 58 actuators and processes input from 15 sensors (incl. redundancy) [5].

**Impact on Functional Verification:**

The duplication of equipment such as RIUs and PCDUs as well as AOCS actuators, sensors, modes and control laws significantly affected the functional verification concept and test campaign both at industry and at ESA/ESOC. Furthermore, the introduction of the redundant on-board computer FCE required a full validation of a second platform for Survival Mode and equipment management.

The BepiColombo assembly, integration and test flow was characterized by parallel activities for all spacecraft modules on the Structural/Thermal model (STM), the Engineering Test Bench (ETB) including the Avionics Test Bench, and the final Proto-Flight-Model (PFM) campaign. Considering the individual models, STM and PFM campaign were scheduled sequentially. In general, a two-stage approach was implemented, i.e. tests on element/module level were followed by stack tests. Execution of functional tests on the spacecraft PFM was only possible in limited time slots, because a dedicated electrical configuration had to be established to allow connection of RTE for stimulation of actuators and sensors as well as interconnection of MTM, MPO and MMO for MCS tests, see Fig. 9. These slots were also exploited by ESA/ESOC to execute the SVTs on PFM.

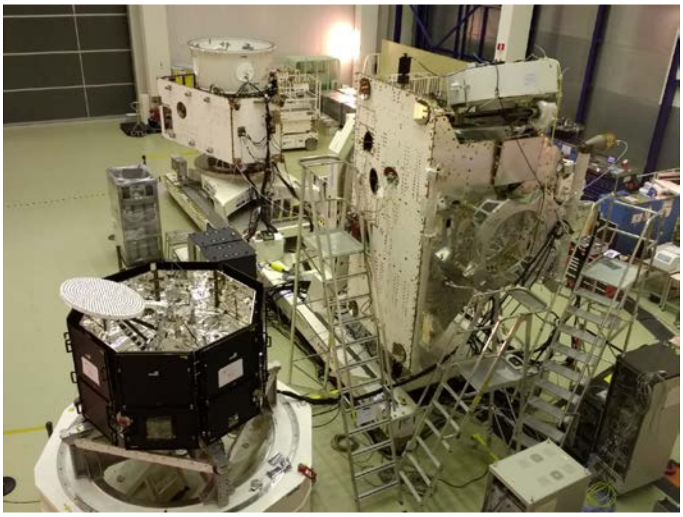

Figure 9: MCS Electrical Stack.

The functional verification campaign was optimised to maximise coverage of all nominal and FDIR functions along the various S/C configurations and for both platforms. As simple examples, 6 Mission Simulation Tests were implemented to envelop all 5 S/C configurations and the relevant operational scenarios, System Functional Tests were duplicated to cover MPO standalone as well as a series of MCSC, MCSA and MCSO closed-loop tests, and the number of ISTs and unit level tests naturally increased with the higher number of equipment and with the two OBC/FCE platforms.

**Impact on In-Flight Operations and Unit Commissioning:**

The in-flight commissioning has been performed during the Launch and Early Orbit Phase (LEOP) and during the 3 months Near Earth Commissioning Phase (NECP) for all units needed to reach higher operational modes and to confirm full performance of the spacecraft as far as possible. Due to stringent thermal and thus Sun pointing constraints in the varying environment, the following MPO equipment can’t be commissioned fully before Mercury arrival respectively separation of the transfer module MTM or the MOSIF interface structure:

DOI: 10.13009/EUCASS2019-218



- *MPO CPS*, both 5N tilted thrusters as well as 22 N axial thrusters are partially oriented towards MTM
  In particular, the 22 N thrusters are located at MTM-MPO interface plane, i.e. no firing is possible without potential damage to and contamination of the S/C. Axial thrusters will be commissioned only after MTM separation. Pressurisation and 5N thruster commissioning is planned shortly before MTM separation. On MPO CPS, no maintenance operations can be performed during cruise phase except for pressure monitoring
- *MPO +X Fine Sun Sensor*, located outside the Sun illumination domain during Cruise
  No check-out possible until MTM separation. The MPO +X FSS will be used as the reference Sun sensor immediately after MTM separation
- *MPO -Z Fine Sun Sensor*, located on top of MPO and obstructed by MOSIF
  No check-out possible until MOSIF separation due to illumination constraints on MMO. The MPO -Z Fine Sun Sensor will be used as the reference after MOSIF separation
- *MPO Solar Array*, kept in YZ plane and not rotated throughout the cruise phase for the following reasons:
  1) SA backside illumination (harness, diodes, Sun trapping) becomes critical at Sun distance below 0.7 AU,
  2) risk of FSS disturbance on MTM,
  3) reduced projected area to cope with solar irradiance reflection and infrared radiation from MTM MLI,
  4) risk of uncontrolled thruster plume feedback by MPO SA in case of thruster-based Survival Mode in MCSC configuration.
  The latter limitation had to be implemented to safeguard the MCSC configuration. The MPO SA must remain in YZ plane when MTM thrusters start firing to avoid instabilities through plume impingement on the MPO SA. The FCE reacts within approximately 3 sec to enter thruster firing phase, which is not sufficient time to move the MPO SA back into its cruise position even if operated at maximum speed of 6 deg/sec. The default position and available guidance option for MPO SA thus excludes large movements of the MPO SA. Nevertheless since it is essential for the MPO SA Drive Mechanism to be regularly moved throughout the 7 year cruise phase, a small rotation of few degrees is available and utilised for a dedicated maintenance activity called MPO SA nudging. The offset is autonomously removed by AOCS in case of a Survival Mode before start of thruster firing.
- *Failure Control Electronics (FCE)*: no full commissioning of functionality without Safe Mode
  As the FCE is the redundant on-board computer designated to only take over in case of an emergency on the spacecraft and to safeguard the OBC reset duration, the FCE interaction with the relevant actuators such as MTM/MPO SADE, MTM/MPO RIU, MTM/MPO CPS and MTM/MPO FSS is excluded from commissioning operations. An early Safe Mode in LEOP allowed commissioning the FCE Control Mode and its communication with equipment successfully.

**Changing S/C Configuration - An Outlook to MOI Operations:**

Throughout the cruise phase of 7 years, the BepiColombo satellite will remain in the Mercury Composite Spacecraft Cruise (MCSC) configuration with all 4 modules stacked together, see Fig. 2. After the final SEP manoeuvre and shortly before capture at Mercury the transfer module MTM will be separated from the stack. This marks the beginning of a complex sequence of events, called Mercury Orbit Injection (MOI), alternating between orbit insertion manoeuvres and module separations (ref. Fig. 10): with MMO being placed into its own science orbit, followed by ejection of the MOSIF, and descend into final MPO science orbit.

Ejection of MTM, MMO and MOSIF to achieve the final MPO configuration is planned through three dedicated module separation sequences. Their execution will be thoroughly prepared by ground and final separation and S/C saving handled by autonomous on-board applications implemented as On-board Control Procedures (OBCPs).

Since physical configuration and thermal constraints vary with the spacecraft configuration, guidance laws, controller gains, spacecraft attitude and related essential parameters must be reloaded once the new spacecraft configuration is achieved. To ensure immediate recovery of the spacecraft under the harsh environmental conditions at Mercury, a planned transition into a Safe/Survival Mode will be performed by re-entry into the main system initialisation sequence without OBC reboot. The sequence loads key on-board parameters and guidance information from Safe Guard Memory based on the spacecraft configuration detected by breakwires. Deployable Thermal Covers equipped with HT MLI will close the interconnection gaps in the spacecraft MLI once the physical separation has been completed. Again, the closure of these covers will be done autonomously onboard through OBCPs

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Special care will be taken for MMO separation: a dedicated spin-ejection device will introduce the angular acceleration around the planned spin axis as well as the lateral velocity required to separate and stabilise the MMO. The three-axis stabilised MPO will need to tolerate the resulting angular rates with attitude control disabled until the MMO has achieved clearance from the MOSIF. The sequence is time critical for the MPO Solar Array which will be exposed to non-optimal Sun illumination during the tumbling phase.

A total of 15 orbit insertion manoeuvres between 26 and 92 m/s deltaV is required to reach MPO science orbit. Between manoeuvres, synchronisation of the spacecraft attitude with its orbit around Mercury is required for thermal safety. As a precaution against a Survival Mode during a manoeuvre, a guidance correction function is available in the on-board software, which - in case of emergency - will estimate the achieved orbit on the basis of achieved deltaV as measured by the accelerometers and correct the on-board guidance accordingly. These data will need to be prepared and uploaded to Safe Guard Memory by the Flight Control Team in addition to the Flight Dynamics products for nominal manoeuvre execution.

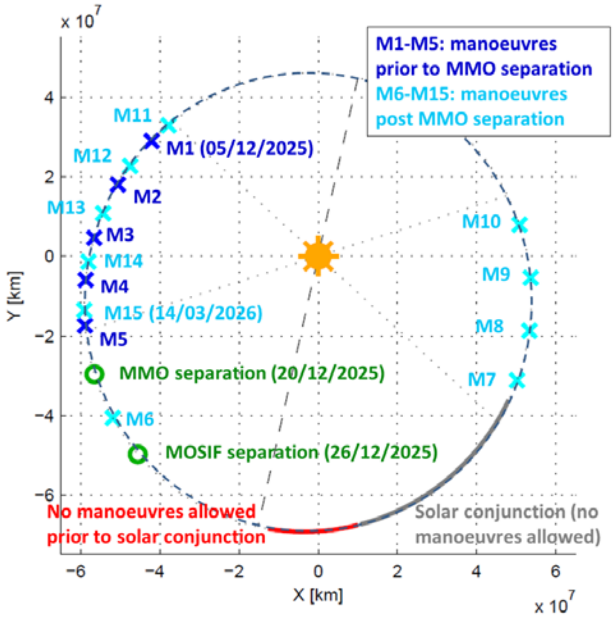


Figure 10: Mercury Orbit Insertion (MOI) sequence (depicted in ecliptic J2000 frame).

## 4.2 Electric Propulsion Operations

Electric Propulsion operations on BepiColombo are driven by the following characteristics:

- **Complexity of transitions between NM and EPCM:** Fig. 11 shows the mode transitions between NM and EPCM. Entering EPCM requires slewing to the EPCM attitude in phase ETP-A1, rotating the MTM solar array to the EPCM position to maximise power in phase ETP-A2 (it is typically offpointed in NM to reduce degradation), and starting up the selected thrusters in phase ETP-A3. Likewise, for EPCM exit the thrusters are switched off in EPCM, the MTM solar arrays are rotated back in phase ETP-B2, and the S/C slews back to NM attitude in phase ETP-B1. Each thrust arc requires a custom spacecraft attitude, with the attitude and solar array guidance profiles commanded by ground for (i) the chosen thruster selection, (ii) a backup thruster selection (if desired), and (iii) the "fallback" guidance profile in NM. A transition to the backup thruster selection or a fallback to NM can be triggered autonomously by FDIR. Including highly configurable EP settings, entering EPCM requires about 650 telecommands and takes up to 5.5 hours (1.5h required for thruster switch ON, up to 4h required for the attitude slews from NM to EPCM ).

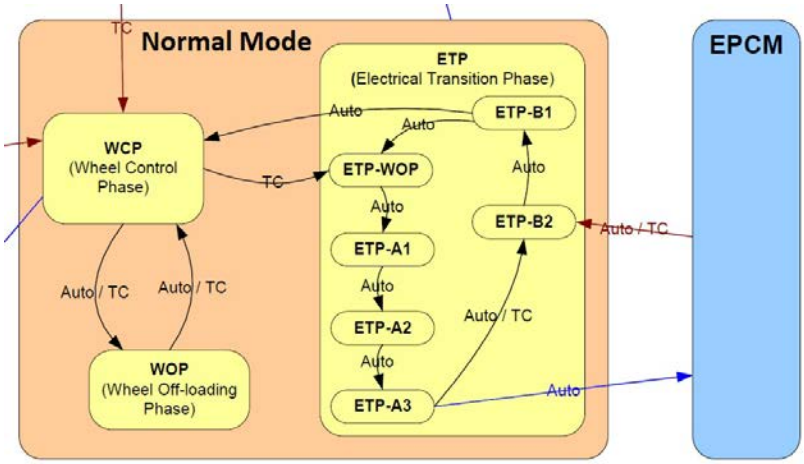


Figure 11: AOCS mode transitions for EPCM entry/exit.

- **Visibility constraints in EPCM:** the attitude required for thruster firing is driven by trajectory needs and the set of thrusters used (out of the 4 thrusters available). Despite two moveable antennae (MGA and HGA), visibility with either of them it is not guaranteed in the firing attitude, due to antenna movement constraints or blockage by other parts of the S/C body. It may hence not be possible to get S/C telemetry when in EPCM, i.e. S/C status can only be checked after exiting EPCM, retrieving playback telemetry.

DOI: 10.13009/EUCASS2019-218



- **Orbit Determination needs:** slight variations in thrust direction and magnitude when using electric propulsion impact the accuracy for orbit determination in deep space based on radiometric data (Doppler and ranging). To work around this, regular acquisition of radiometric tracking data over periods with the thrusters off was introduced, requiring to exit and re-enter EPCM.

Following Electric Propulsion commissioning in late 2018, the first thrust arc of the mission started on 17th Dec 2018 and was completed in early March 2019. Refer to Fig. 12 for an overview, showing the periods of thruster usage as well as the thrust levels used:

- This thrust arc allowed for dual thruster operations. While balanced thruster usage was also a consideration, thruster selection was mainly driven by MGA/HGA visibility, with thruster pair [1,3] allowing HGA coverage in EPCM up to 23/12/2018, and thruster pair [2,4] allowing MGA coverage from 10/01/2019 up to the end of the thrust arc. In the period from 24/12/2018 to 09/01/2019 with neither MGA nor HGA allowing coverage in EPCM attitude, a special TT&C configuration was established with the S/C transmitting a carrier-only signal via LGA when in EPCM, allowing ground to check presence of that signal to confirm the S/C was still in EPCM. This special approach was only possible for this thrust arc close to Earth, with the link budget on LGA insufficient for this at further distances.

- In terms of ground station contacts, a weekly so-called "navigation pass" was taken, when EPCM was interrupted to gather radiometric data for orbit determination (i.e. transition to NM before the pass, and re-entry to EPCM after the pass). On top of these passes, two ground station contacts were taken per week to monitor S/C status in EPCM, allowing a regular check of S/C performance and faster reaction time to unexpected EPCM interruptions. The number of these "monitoring" passes may be reduced for future SEP arcs, once there is more confidence in the performance of the system.

- Overall thruster performance in the arc was nominal. In particular, the number of beam outs –visible as "spikes" in Fig. 12 to a reduced thrust level– was well within specs. Three unexpected interruptions of thrusting in EPCM triggering a fallback to NM and a recovery by ground to re-enter EPCM occurred in this thrust arc. These were believed to be caused by thruster-related software FDIR triggering too early, with ground tuning the settings accordingly thereafter. The gradual change of thrust level visible over time in Fig. 12 was due to the change of distance to the Sun, limiting the maximum power available for firing the thrusters (ref. section 4.4 for details).

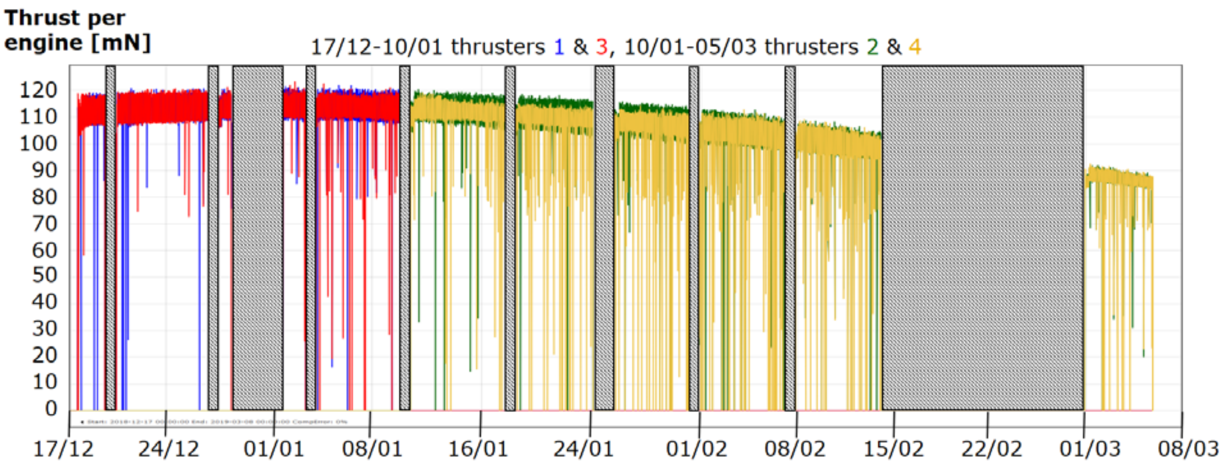


Figure 12: Thrusters and thrust levels used during the SEP1 arc. Greyed out periods indicate when the thrusters were OFF (S/C in NM). The large period before the last few days of thrusting in early March was to do an orbit determination with full accuracy prior to performing the final touch up manoeuvre of the arc.

## 4.3 On-board Guidance for Safe and Survival Mode

During the entire mission, strict Sun pointing constraints must be observed. When in orbit around Mercury, the attitude with respect to the planet is also highly constrained. The solar array pointing has to be controlled with respect to Sun and Mercury to avoid overheating. A consequence of these constraints is that the default safe and survival mode guidance for SASM and SHM can't rely on simple principles as on other deep space missions (e.g. to always point the solar array to the Sun), and the accuracy requirements on the guidance are particularly high.

DOI: 10.13009/EUCASS2019-218



To address these needs, the AOCS guidance context for SASM and SHM in safeguard memory (SGM) includes the following main items:

- Sun ephemerides for establishing Sun pointing in the early phases of SASM, specified as time segments of Chebyshev polynomials
- Earth ephemerides and Sun-S/C-Earth (SSCE) angle for pointing MGA to Earth (SSCE angle for MGA strobing in SASM-ESP, Earth ephemerides for autonomous Earth pointing of MGA in SHM), all specified as time segments of Chebyshev polynomials
- SASM attitude and solar array guidance for the later phases of SASM, specifying the S/C rotation rate and phasing for the rotation around the Sun line, as well as the required position for the solar array.
- SHM attitude and solar array guidance, specified as time segments of Chebyshev polynomials and periodic cos/sin series for attitude guidance, as Chebyshev polynomials for MPO and MCSA/O solar array guidance, and as table with time ranges and commanded position for MCSC solar array guidance.
- Auxiliary tables specifying context related to reaction wheel management.

In total, this constitutes over 4000 parameters, stored in the so-called “Segment Tables” in safeguard memory. As consistent update of these tables is critical for the mission, the update service in the on-board software ensures that the tables are stored in quadruple redundancy and are globally consistent (i.e. partial update of the guidance tables leading to inconsistent information is not allowed).

Fig. 13 provides an overview of these tables for the OBC. Many tables are S/C configuration dependent as indicated in the figure, since there are significant differences between the various S/C configurations (e.g. Sun pointing axis in SASM and SHM). Owing to the more limited capabilities of the FCE (only required to establish and maintain correct Sun pointing in SASM in the first few min after safe/survival mode entry), it only needs tables specifying Sun ephemeris and SASM attitude guidance.

Information in some of the guidance tables is trajectory dependent. Owing to the high accuracy requirements (e.g. Sun direction accuracy < 0.1 deg), it turned out that it is not possible to cover all possible 42 launch attempts in the launch window from 19/10/2018 to 29/11/2018. Owing to the high complexity of the guidance and the dependency on the actual trajectory and launch date, it was therefore decided that the spacecraft manufacturer would not produce the default guidance for launch on their own, as is normally done. Instead, the guidance settings would be provided by ESOC, for installation on the spacecraft by the AIT team prior to a specific launch attempt. While this introduces an undesirable dependency between ESOC and the launch site, this was the only practical way to ensure launching with a correct guidance set.

| Id | S/C mode | Table name | Nb seg |
|---|---|---|---|
| 1 | Common | SC-Earth ephemeris | 5 |
| 2 | Common | SC-Sun ephemeris | 100 |
| 3 | Common | Sun-SC-Earth angle | 100 |
| 4 | MCSC | SASM SA Guidance | 20 |
| 5 | MCSC | SASM Attitude Guidance | 1 |
| 6 | MCSC | SHM SA Guidance | 20 |
| 7 | MCSC | SHM Attitude Guidance - Chebyshev polynomial | 3 |
| 8 | MCSC | SHM Attitude Guidance - Periodic Cos/Sin series | 3 |
| 9 | MCSC | RW Target Angular Momentum - Validity Period Start Times | 1 |
| 10 | MCSC | RW Target Angular Momentum - Angular Momentum | 5 |
| 11 | MCSC | RW Target Angular Momentum - Wheel Speed | 5 |
| 12 | MCSA/O | SASM SA Guidance | 20 |
| 13 | MCSA/O | SASM Attitude Guidance | 1 |
| 14 | MCSA/O | SHM SA Guidance - Envelopes / Patterns | 39 |
| 15 | MCSA/O | SHM SA Guidance - Global Data | 1 |
| 16 | MCSA/O | SHM Attitude Guidance - Chebyshev polynomial | 3 |
| 17 | MCSA/O | SHM Attitude Guidance - Periodic Cos/Sin series | 3 |
| 18 | MCSA/O | RW Target Angular Momentum - Validity Period Start Times | 1 |
| 19 | MCSA/O | RW Target Angular Momentum - Angular Momentum | 5 |
| 20 | MCSA/O | RW Target Angular Momentum - Wheel Speed | 5 |
| 21 | MPO | SASM SA Guidance | 20 |
| 22 | MPO | SASM Attitude Guidance | 1 |
| 23 | MPO | SHM SA Guidance - Envelopes / Patterns | 39 |
| 24 | MPO | SHM SA Guidance - Global Data | 1 |
| 25 | MPO | SHM Attitude Guidance - Chebyshev polynomial | 3 |
| 26 | MPO | SHM Attitude Guidance - Periodic Cos/Sin series | 3 |
| 27 | MPO | RW Target Angular Momentum - Validity Period Start Times | 1 |
| 28 | MPO | RW Target Angular Momentum - Angular Momentum | 5 |
| 29 | MPO | RW Target Angular Momentum - Wheel Speed | 5 |
| 30 | MPO | MPO MGA Parameter | 1 |

Figure 13: Tables in OBC safeguard memory with guidance for all S/C configurations. The FCE has dedicated tables corresponding to ID 2, 5, 13 and 22 (Sun ephemeris and SASM attitude guidance).

A dedicated interface was put in place and fully validated prior to start of the launch campaign. Delivery of guidance products included the following steps for ESOC and the S/C manufacturer:

1. Preparation of guidance products by ESOC Flight Dynamics: for an individual launch attempt, this is linked to a so-called “Flight Dynamics Init”, an initialisation of the system for a specific launch attempt, including generation of all related products (like orbit prediction or station pointing files). While it is not feasible to run such an Init in advance for all possible 42 launch attempts, the approach chosen to

DOI: 10.13009/EUCASS2019-218



reduce time criticality for this interface was to always have product sets ready covering the next 3 launch attempts, preparing a new product set for a further launch attempt in case launch was delayed.

2. Delivery of guidance products in an ESOC-internal format used for providing commanding products from Flight Dynamics to the Flight Control Team at ESOC.
3. Conversion of the products into the agreed custom delivery format, performing a print out of the guidance products loaded on the mission control system. Some confidence checks on the products are run as well.
4. Delivery of the output format from ESOC to the Spacecraft Manufacturer at the launch site.
5. Conversion of the output format into a script to be executed by the central checkout system used by AIT for operating the S/C on the launch pad.
6. Upload of the products on the Spacecraft during pre-launch preparations.
7. During the last 8 hours before launch with ESOC listening in to the final launch preparations, the guidance settings loaded on-board would be dumped, allowing ESOC as well as the Project Support team located at ESOC to doublecheck the settings.

As BepiColombo could be launched at the very start of the launch window, it was fortunately not required to use this complicated interface many times.

Since launch, two routine guidance updates in safeguard memory were performed on 09/11/2018 and on 01/04/2019 to keep updating the time-dependent settings of the guidance tables.

## 4.4 Solar Array Control, Trajectory and Power Management during EP Operations

Despite approaching the Sun, the mission is highly power-constrained. A unique aspect is that the S/C trajectory is dependent on the available power:

- Technological limitations on the solar arrays require to offpoint the MTM solar array at closer Sun distances to avoid overheating, constraining the maximum amount of power available. See Fig. 14 for an overview of the allowed MTM solar array position depending on the Sun distance: above 0.62 AU distance, there are no constraints, while below that distance significant offpointing of the array may be required.
- During SEP arcs in cruise (see Fig. 1), baseline is to use maximum possible thrust to minimise the duration of the arc, reducing the risk of not achieving the desired deltaV in time for the next planetary swingby. This is particularly relevant for thrust arcs between Mercury swingbys later in cruise. Unfortunately, the power available generally does not allow firing the thrusters at the max thrust level they're capable of.

This creates some intricate dependencies, as (i) the available power depends on the Sun distance evolution (in turn dependent on the actual S/C trajectory), and (ii) the commanded thrust levels allowed by the available power impact the trajectory. Therefore, MTM solar array pointing and EP thrust level commanding during SEP arcs have to be managed carefully, to get the most out of the system under the narrow margins typical for the mission.

This is handled as part of the planning processes between Flight Dynamics (FD) and the Flight Control Team (FCT) during SEP arcs. Unlike for typical manoeuvre command generation (e.g. for chemical propulsion burns) fully done on FD side up to delivery of the products for uplink by the FCT, this includes more FCT involvement for aspects linked to S/C power generation:

- Using a dedicated tool, the FCT generates the "Max EPCM power" file, containing records with information on the maximum power available for EP operations, in the range of Sun distances relevant for the current planning cycle. This power figure is calculated taking into account (i) the required offpointing of the MTM solar array (leading to a reduction in the power available), (ii) the actual solar array degradation so far in the mission, (iii) the overall power consumption of the S/C. The "Max EPCM power" file is delivered from FCT to FD over a standard interface.

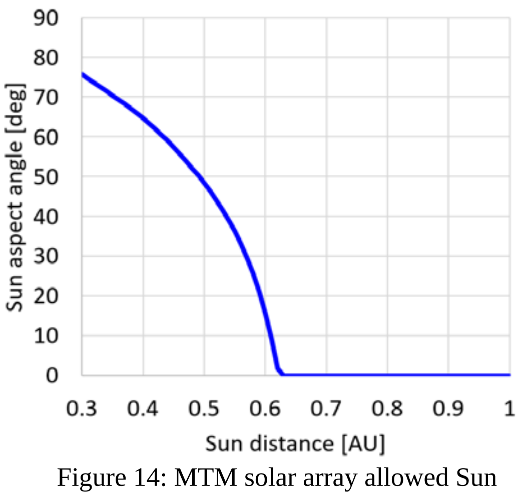


Figure 14: MTM solar array allowed Sun aspect angle depending on Sun distance (SAA of 0 deg means MTM SA is facing the Sun).

DOI: 10.13009/EUCASS2019-218



- Taking the “Max EPCM power” file as input, as part of the EP arc optimisation and command generation FD calculates the thrust levels and MTM solar array positions to be commanded. The curve shown in Fig. 14 is represented by a polynomial, and is discretised for generating the actual MTM solar array guidance commands, which only allow to command a fixed MTM SA position for a specific time range. This discretisation is done applying a well-defined margin philosophy, to ensure sufficient power is provided for the commanded thrust levels. FD generates the “MTM SA Control” file, containing a time series of records with the Sun distance, the commanded thrust level, and the commanded MTM solar array Sun aspect angle covering the current planning period, which is transferred back to FCT for doublechecking.

This special processing is embedded in the overall operations planning activities for SEP arcs. Prior to launch, the trajectory of BepiColombo including all SEP arcs has been designed with conservative assumptions on EP (e.g. taking 10% margin by assuming only 90% EP availability). This is refined prior to start of an individual SEP arc, removing the artificial margin and taking into account the current S/C status (e.g. solar array degradation) and trajectory. A full optimisation is then done in the weekly short-term planning cycle, when the actual commanding products are generated based on the latest orbit determination.

The weekly short term planning activities are shown in Fig. 15:

- These activities are built around the baseline approach of interrupting EPCM operations once a week to gather undisturbed radiometric data during a “navigation pass” with AOCS in NM (ref. also section 4.2).
- A key output of the “Mission Planning” activity by the FCT on Wed is a command stack for uplink to the S/C. This stack includes not only FD-generated commanding activities received on Tue (e.g. EPCM exit and re-entry, thrust level updates, MTM solar array pointing updates), but also all other routine operations activities (e.g. routine activities at start/end of ground station passes).
- The “MTL uplink” activity in the Thu navigation pass includes replacing commands still present in the on-board mission timeline (MTL) with a new, fully optimised set of commands based on the latest orbit determination, covering one week further in the future. In case a navigation pass is missed, the S/C will re-enter EPCM using the “old” products from the previous planning cycle still present in the MTL. The margins are such that this does not constitute a safety risk, albeit thrust levels won’t be fully optimal.

The full process described here was run successfully during the SEP1 thrust arc, proving the adequacy of the basic operations concept. As this arc took place at Sun distances above 0.62 AU, MTM SA offpointing was not yet required, thereby the criticality of the planning process was significantly reduced compared to the thrust arcs from 2022 onwards in the inner solar system.

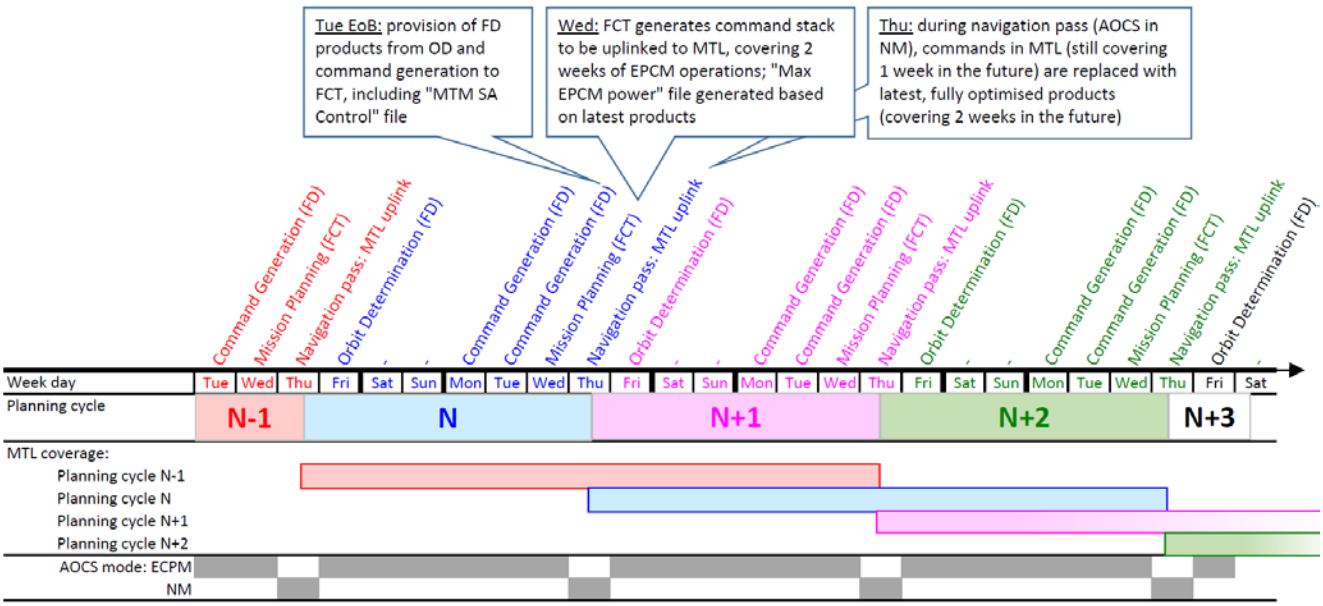


Figure 15: Weekly planning cycle during Electric Propulsion thrust arcs, including special processing for determining the MTM solar array pointing and the corresponding power available for EP thrusting.

DOI: 10.13009/EUCASS2019-218



## 5. Conclusion and Outlook

After a long preparation phase, the ESA/JAXA BepiColombo mission to Mercury was finally launched in October 2018. Following a successful LEOP ($20^{th}$ to $22^{nd}$ Oct 2018), near-Earth commissioning ($22^{nd}$ Oct 2018 to mid Dec 2018) and first solar electric propulsion thrust arc (mid Dec 2018 to early Mar 2019), delta near-Earth commissioning is currently ongoing and the S/C is in excellent shape for the cruise to Mercury, with a planned arrival in Dec 2025.

Not unexpectedly, the high complexity of the BepiColombo GNC for a modular S/C going to a very harsh thermal environment poses significant challenges, for many of which first in-flight experience has been gathered:

- S/C modularity requiring duplication of GNC sensors and actuators, as well as a high number of dedicated AOCS controllers. With the GNC performing well in MCSC configuration after launch, the units only used in different S/C configurations of later mission phases were checked out as far as possible, with the complex Mercury orbit injection and module separation operations campaign in 2025 yet to come.
- Complex solar electric propulsion operations, requiring weekly interruptions of thrusting for orbit determination purposes and dealing with constraints on S/C visibility via the moveable antennae when in the thrusting attitude.
- Owing to the strict attitude and pointing constraints, the need for a standalone FCE and the complex GNC mode and guidance design, the default safe/survival mode guidance is dependent on the launch date and was provided by ESOC for installation on the S/C, requiring to put in place a custom interface and process. Several routine updates of the guidance in-flight have already been done as well.
- The mission is highly power-constrained, with the MTM solar array requiring to be offpointed at closer sun distances to avoid overheating. During electric propulsion arcs, this requiring special planning to fire the thrusters at maximum thrust level possible with the available power. A dedicated interface between Flight Dynamics and Flight Control Team has been put in place and exercised successfully in the SEP1 thrust arc.

Regarding key upcoming operations, a new platform on-board software for OBC and FCE is planned to be installed in mid July 2019 to correct the various on-board software issues discovered so far, requiring to bring the S/C to safe mode to activate it. The second solar electric propulsion arc (SEP2) of the mission will take place from early Sept to early Nov 2019. Thereafter, preparations for the Earth swingby in April 2020 will start. As from the Earth swingby, the S/C will move into the inner solar system, with a first Venus swingby in October 2020. This will be the first time S/C performance in a hotter environment can be experienced.

## Acronym List

| | |
|---|---|
| **AIT** | Assembly, Integration and Test |
| **AOCS** | Attitude and Orbit Control System |
| **APME** | Antenna Pointing Mechanism Electronics (for High Gain and Medium Gain Antenna) |
| **BMCS** | BepiColombo Mission Control System |
| **CPS** | Chemical Propulsion System |
| **EP** | Electric Propulsion |
| **EPCM** | Electric Propulsion Control Mode |
| **ETB** | Engineering Test Bed |
| **FCE** | Failure Control Electronics |
| **FCT** | Flight Control Team |
| **FD** | Flight Dynamics |
| **FDIR** | Failure Detection, Isolation and Recovery |
| **FOP** | Flight Operations Plan |
| **FSS** | Fine Sun Sensor |
| **GCF** | Guidance Correction Function |
| **HGA** | High Gain Antenna |
| **IGST** | Integrated Ground Space Test |
| **IMU** | Inertial Measurement Unit |

DOI: 10.13009/EUCASS2019-218



| | |
|---|---|
| **JAXA** | Japan Aerospace Exploration Agency |
| **LEOP** | Launch and Early Orbit Phase |
| **MCS** | Mercury Composite Spacecraft |
| **MCSA** | Mercury Composite Spacecraft Approach (stack consisting of (MPO, MOSIF, MMO) |
| **MCSC** | Mercury Composite Spacecraft Cruise (stack consisting of MTM, MPO, MOSIF, MMO) |
| **MCSO** | Mercury Composite Spacecraft Orbit (stack consisting of MPO, MOSIF) |
| **MEPS** | Mercury Electric Propulsion System |
| **MGA** | Medium Gain Antenna |
| **MMO** | Mercury Magnetospheric Orbiter (JAXA-provided orbiter) |
| **MOI** | Mercury Orbit Injection |
| **MOSIF** | MMO Sunshade and Interface Structure |
| **MPO** | Mercury Planetary Orbiter |
| **MPS** | Mission Planning Systm |
| **MTL** | Mission Timeline (queue of time-tagged commands executed on-board) |
| **MTM** | Mercury Transfer Module |
| **NECP** | Near Earth Commissioning Phase |
| **NM** | AOCS Normal Mode |
| **OBC** | On-board Computer |
| **OBCP** | On-board Control Procedure |
| **OBT** | On-board Time |
| **OCM** | AOCS Orbit Control Mode |
| **OD** | Orbit Determination |
| **OSR** | Optical Surface Reflector |
| **PRE** | Pressure Regulation Electronics (of the electric propulsion) |
| **RAM** | Random Access Memory |
| **RM** | Reconfiguration Module |
| **RIU** | Remote Interface Unit |
| **RWU** | Reaction Wheel Unit |
| **SA** | Solar Array |
| **S/C** | Spacecraft |
| **SADE** | Solar Array Drive Electronics |
| **SASM** | AOCS Sun Acquisition and Survival Mode |
| **SBM** | AOCS Standby Mode |
| **SCOE** | Special Checkout Equipment |
| **SEP** | Solar Electric Propulsion |
| **SGM** | Safeguard Memory |
| **SHM** | AOCS Safe Hold Mode |
| **SSCE** | Sun-Spacecraft-Earth |
| **SVT** | System Validation Test |
| **TPE** | Thruster Pointing Electronics (of the electric propulsion) |
| **TPM** | Thruster Pointing Mechanism (of the electric propulsion) |

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