BepiColombo – Solar Electric Propulsion System Operations for the Transit to Mercury

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C. Steiger[1], E. Montagnon[2], F. Budnik[3]
European Space Agency, Darmstadt, Germany

S. Manganelli[4]
Vitrociset (c/o ESA/ESOC), Darmstadt, Germany

A. Altay[5]
Terma GmbH (c/o ESA/ESOC), Darmstadt, Germany

F. Striedter[6]
Airbus Defence and Space, Immenstaad, Germany

H. L. Gray[7]
Airbus Defence and Space Ltd., Portsmouth, Hants, PO3 5PU, UK

J. Bolter[8]
Airbus Defence and Space Ltd., Stevenage, Herts, SG1 2AS, UK

N. Wallace[9], O. Sutherland[10]
European Space Agency, Noordwijk, The Netherlands

Abstract: Launched in October 2018, the ESA/JAXA BepiColombo mission is set to arrive at Mercury in late 2025. The modular S/C consists of two scientific Mercury orbiters and a cruise module. The mission relies on electric propulsion (EP) in cruise, employing 4 gridded ion thrusters mounted on pointing mechanisms. This paper outlines the EP system operations approach, focusing on the constraints imposed by other spacecraft system and mission considerations. This includes complex EP mode entry/exit operations, interruptions of thrusting needed for performing orbit determination, constraints on S/C visibility when in the attitude required for EP usage, and limitations on power available for EP.

[1] BepiColombo Spacecraft Operations Engineer, OPS-O, Christoph.Steiger@esa.int
[2] BepiColombo Spacecraft Operations Manager, OPS-O, Elsa.Montagnon@esa.int
[3] BepiColombo Flight Dynamics Manager, OPS-G, Frank.Budnik@esa.int
[4] BepiColombo Spacecraft Operations Engineer, OPS-O, Silvano.Managnelli@esa.int
[5] BepiColombo Spacecraft Operations Engineer, OPS-O, Alkan.Altay@esa.int
[6] BepiColombo Power & Electric Propulsion Engineer, Airbus Defence and Space, Fabian.Striedter@airbus.com
[7] BepiColombo EP Architect, Propulsion Department, Howard.Gray@airbus.com
[8] BepiColombo MPB Project Manager, EO Science SSA & Exploration for ESA, Jerry.Bolter@airbus.com
[9] Senior Electric Propulsion Engineer, TEC-M, Neil.Wallace@esa.int.
[10] Mars Sample Return - Earth Return Orbiter Study Manager, HRE-X, Orson.Sutherland@esa.int

I. Introduction

ESA's BepiColombo mission is a 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 (Ref. 1). Following a long development phase, the mission was launched in Oct 2018 and is set to arrive at Mercury in late 2025.

A. Mission Overview

The BepiColombo 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. Flight operations are performed by ESA/ESOC.

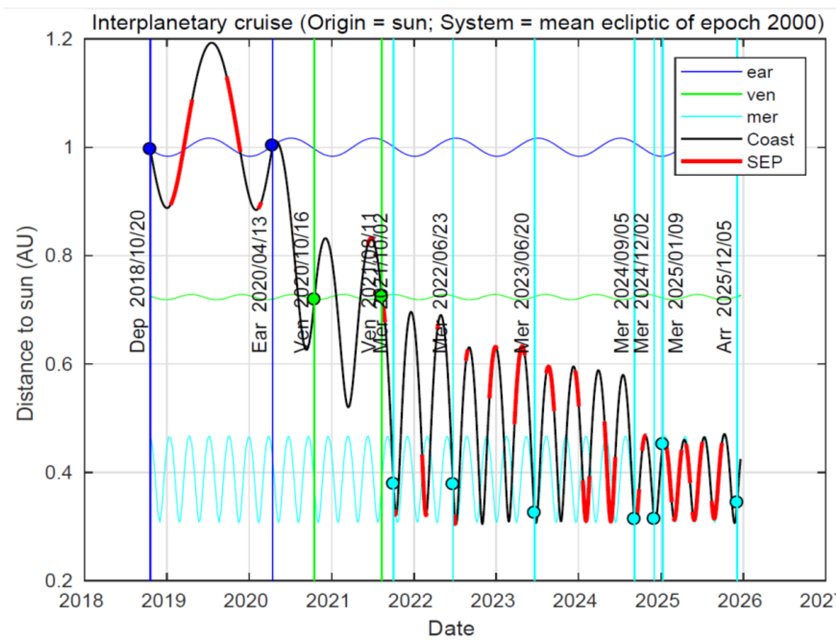


Figure 1. BepiColombo cruise trajectory, showing Sun distance, electric propulsion usage ("SEP"), and planetary flybys at Earth, Venus, Mercury.

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 (EP) is provided by the MTM module (Ref. 2). EP is used continuously during 22 "thrust arcs" to adjust the trajectory (highlighted in red in Fig. 1), lasting from several days up to 2 months, with a total deltaV of 2731 m/s required.

Shortly before Mercury arrival, the MTM module will be jettisoned. 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).

B. 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

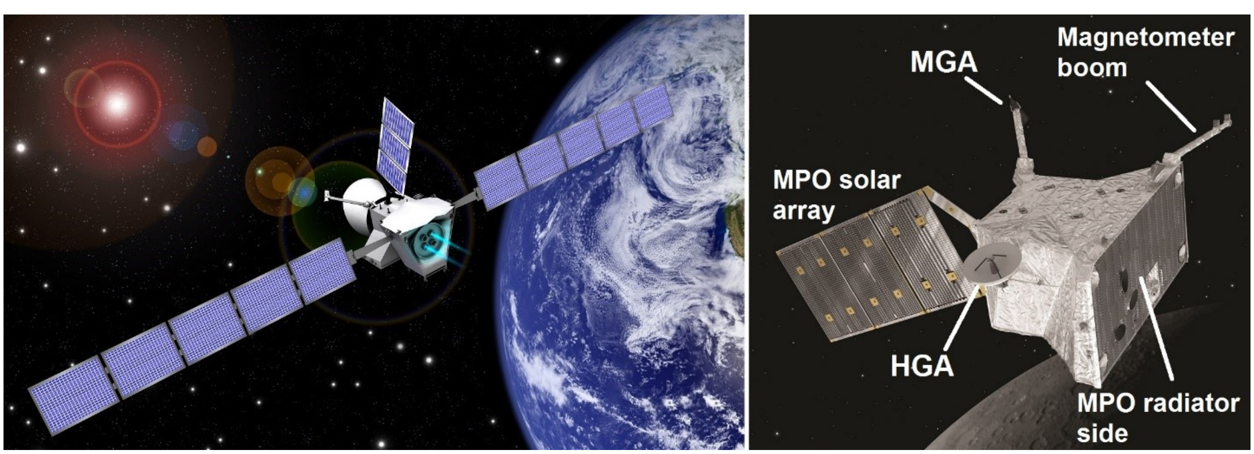


Figure 2. BepiColombo in cruise configuration (left), MPO at Mercury (right).

- 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 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.

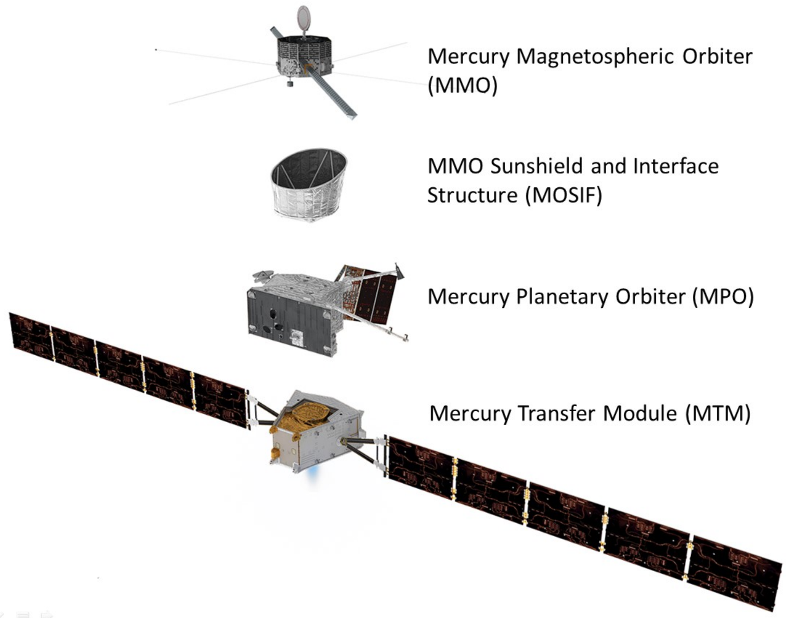


Figure 3. BepiColombo spacecraft in exploded view.

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 by 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).

The MTM provides propulsion means for cruise. Apart from dual mode bipropellant chemical propulsion, it features electric propulsion with 4 moveable thrusters based on the Kaufman-type electric bombardment ion motor (125 mN thrust). 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.

See Ref. 3 for a more detailed description of the spacecraft.

C. 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-like hardware for all electrical equipment and is used for operations validation when the S/C simulator is not considered representative enough.

Contact with the spacecraft is established making use of the ESA 35m network of ground stations, located in Madrid (Spain), New Norcia (Australia) and Malargüe (Argentina).

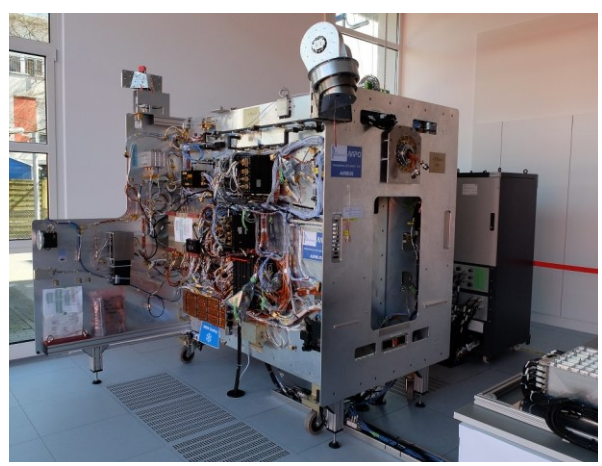


Figure 4. MPO element of the BepiColombo Engineering Test Bed (ETB) at ESOC.

A ground station contact typically has a duration of around 10 hours. Depending on the level of activities, the number of station passes varies greatly. For quiet phases in cruise, the baseline is to have one station pass per week. Combined with significant propagation delays of up to 13 min one way (maximum distance to Earth in cruise is at about 1.6 AU), an "offline" operations approach is required: there is only occasional monitoring of the spacecraft by ground, and virtually all routine operations are uplinked for time-tagged execution from the on-board "Mission Timeline (MTL)", typically executing out of ground coverage. Correspondingly, the S/C has been designed with a significant degree of autonomy, allowing it to deal with failures which might occur when ground is not there to react.

The portion of the downlink telemetry rate allocated to Spacecraft non-science telemetry –i.e. all telemetry providing S/C status information required for operating the mission– amounts to about 2 kBit per seconds (256 Bytes per seconds), meaning that the S/C status information available in flight is typically much more limited than what is relied upon during ground testing.

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 AOCS operations activities.

II. Overview of Electric Propulsion and Attitude & Orbit Control System

A. MTM Electric Propulsion System (MEPS)

To achieve the required thrust range and life capability, a system of 4 thrusters is used. The thrusters have been qualified for operation up to 145 mN; however, the life test has been conducted at 125 mN in line with the mission requirements, which also avoids high beam-out rates induced by test facility impacts (in particular, high rates of sputter material being deposited on the thruster during the life test). Depending on the available power, usage of either a single thruster or two thrusters in parallel is possible to achieve the required thrust levels of between 75 mN and 250 mN. 3 thrusters are required to achieve the overall mission life, the 4th thruster is provided for redundancy.

Each thruster is mounted on its own pointing mechanism, mainly used to correct the thrust vector due to center of gravity (CG) evolution over the mission life.

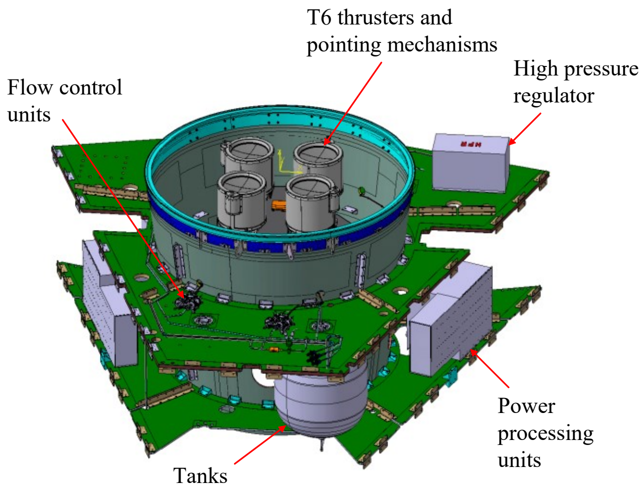
Figure 5. Electric Propulsion Thruster and Pointing Mechanism Configuration.

MEPS Architecture Overview:

- A Xenon storage and feed system, comprising storage tanks, valves, filters, and pipework
- Electric propulsion thrusters, with their associated power supplies and flow control units. This assembly, including interconnecting harness and pipework, is referred to as the Solar Electric Propulsion System (SEPS). The SEPS is supplied by QinetiQ (UK) and includes major equipments from CRISA (Spain) for the power supplies and Bradford Engineering (Netherlands) for the flow control units.
- A pressure regulation system, comprising the high pressure regulator and its driving electronics. This assembly is referred to as the High Pressure Regulation System (HPRS). The HPRS is provided by Airbus Defence and Space UK, with the electronics provided RSA (Austria).
- Pointing mechanisms, each supporting a single thruster, and their associated drive electronics. This assembly is referred to as the Thruster Pointing Assembly (TPA), provided by RSA (Austria).

The MEPS layout and the corresponding product tree is shown in Fig. 5 and Fig. 6. The Pressure Regulation Electronics (PRE) and Thruster Pointing Electronics (TPE) are shown as functionally distinct units; however, these are combined into a single electronics unit designated Thruster Pointing and Pressure Regulation Electronics (TPPRE).

Feed System: the three tanks used to store Xenon are mounted along with 2 tanks for the MTM CPS between 2 structure "floors" (see Fig. 6). The Xenon tanks are joined to a common pipework manifold, which connects them to



Acronym	Name
MEPS	MTM Electric Propulsion System
├ XST	Xenon Storage Tank
├ FDV	Fill and drain valve
├ TIV	Tank isolation valve (NC pyro)
├ XEF	Xenon filter
├ HPRS	High pressure regulation system
│ HPR	High pressure regulator
│ ├ HPT	High pressure transducer
│ └ LPT	Low pressure transducer
│ ├ PRE	Pressure regulator electronics
│ └ PRH	Pressure regulator harness
├ SEPS	Solar electric propulsion system
│ ├ SEPT	Solar electric propulsion thruster
│ ├ FCU	Flow control unit
│ ├ PPU	Power processing unit
│ ├ SEPH	SEPS harness
│ └ SEPP	SEPS pipework
├ TPA	Thruster pointing assembly
│ ├ TPM	Thruster pointing mechanism
│ ├ TPE	Thruster pointing electronics
│ └ TPH	Thruster pointing assembly harness
└ MEPP	MEPS pipework

Figure 6. MEPS layout excluding TPPRE (left), MEPS product tree (right).

the HPRS inlet. A second pipework manifold connects the HPRS outlet to the SEPS Flow Control Unit (FCU) inlets. Fill and drain valves (FDVs) provide access for Xenon filling and system testing at the tanks, HPRS inlet and HPRS outlet.

Solar Electric Propulsion System (SEPS): to provide adequate redundancy and sharing of life between thrusters, the SEPS has been designed with 4 separate functional branches, each comprising a solar electric propulsion thruster (SEPT) and associated flow control unit (FCU). There are 2 power processing units (PPUs) interfacing directly with the thrusters and FCUs. Each PPU is comprised of the following elements:

- Discharge Anode Neutraliser Supply (DANS) (2 off): this contains the control electronics, an AC inverter, high and low voltage referenced thruster supplies, thruster switches, FCU drive electronics, and auxiliary power. The high voltage referenced supplies provide power to the loads within a thruster which are referenced to the discharge chamber (this is at beam potential less the anode voltage).
- Beam Supply Unit (BSU): this contains Beam Supply Modules (BSM) (4 off).

The DANS are combined in pairs, sharing a common beam power supply. Furthermore, to enable maximum flexibility in the event of a unit failure, each DANS is connected to two thrusters via relay switches (see Fig. 7). This enables any pair of thrusters to be operated, ensuring mission requirements can be met after failure of any single unit.

A DANS is considered to be in "local" configuration if it is connected to a thruster with the same index number (e.g. DANS1 connected to SEPT1); the other switch configuration is referred to as "remote". For nominal operations, all DANS are used in "local" configuration, with pairs DANS1+3 and DANS2+4 used alternately. This enables the mission life to be shared between all 4 thrusters without any need for switching of the relays.

The BSU is comprised of 4 Beam Supply Modules (BSM). These BSM are connected in parallel in a "3 out of 4" redundancy scheme; only 3 BSM are required to meet the BepiColombo maximum thrust requirement per thruster, with the fourth module being provided for redundancy. The BSU is able to support either DANS in the same PPU.

All internal control within the SEPS is provided within the PPU, using an FPGA controller. All SEPS electrical and communications interfaces to the S/C are through the PPUs.

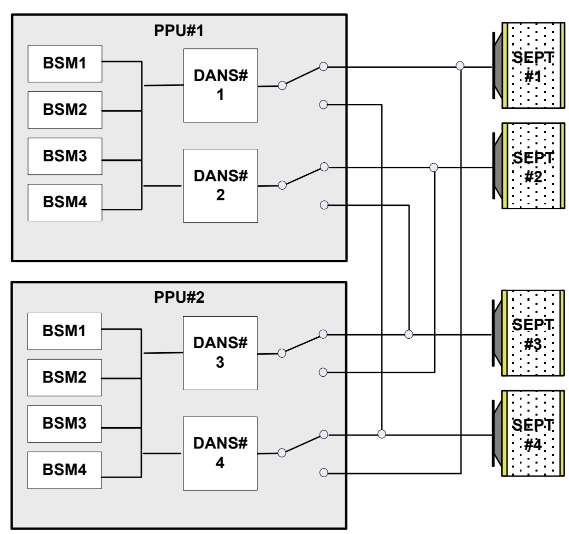


Figure 7. SEPS architecture.

High Pressure Regulation System (HPRS): an electronic regulation system designated HPRS is used. This is a "bang-bang" type regulator; plenums are filled with Xenon on opening a regulation valve; when the pressure reaches a pre-defined threshold, the regulation valve is closed and the plenum pressure drops as Xenon is consumed by the thrusters.

The regulation is controlled by the TPPRE; an FPGA in this unit stores the upper and lower regulation thresholds and provides all the control logic, whilst the PRE includes all the valves drivers and pressure sensor acquisition circuits. All HPRS electrical interfaces to the spacecraft are through the TPPRE.

Thruster Pointing Assembly (TPA): the TPA consists of the drive electronics and 4 thruster pointing mechanisms. Each pointing mechanism supports an individual T6 thruster in the stowed configuration during launch, by means of a dedicated Hold-Down and Release Mechanism (HDRM). Each HDRM is equipped with a single, central release actuator. Upon release of the HDRM, the Pointing Mechanism Platform can be tilted around two perpendicular axes. Two geared high detent torque rotary actuators facilitate this motion. Each TPM has a large pointing range; a total range of >24° around each axis is required to achieve all the various thruster firing combinations and associated pointing requirements. The pointing electronics (TPE) part of the TPPRE consist of one nominal and one redundant side, each able to operate any 2 out of 4 TPMs simultaneously. All TPA electrical interfaces to the spacecraft are through the TPPRE.

See Ref. 4 for more details on MEPS design and operations.

B. 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 with chemical or electric propulsion. Fig. 8 shows the AOCS hardware architecture. 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 Moog - 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 2 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)

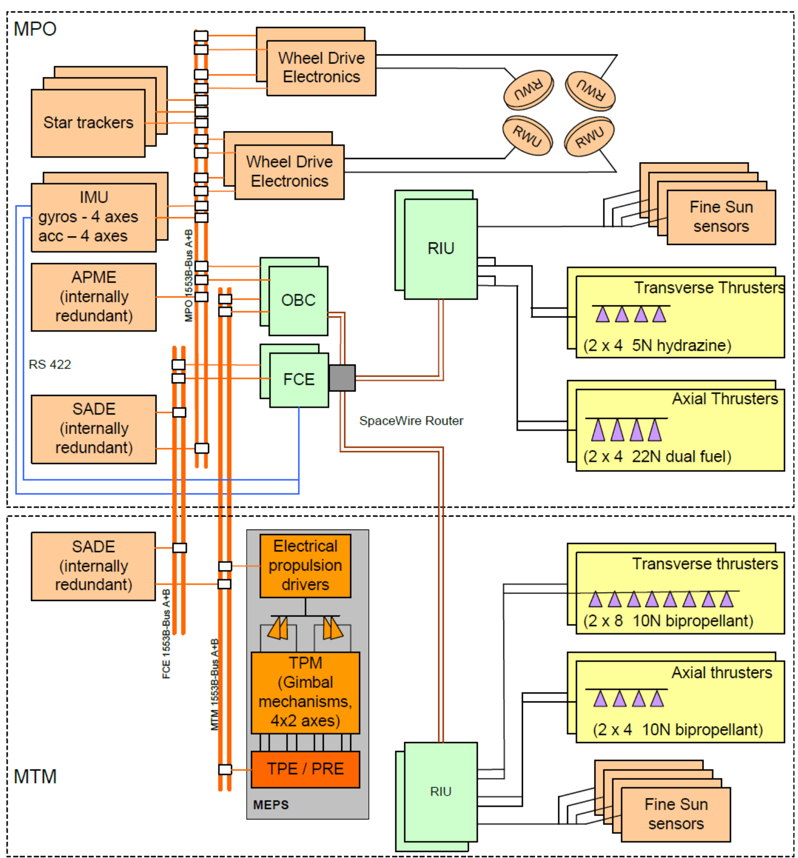


Figure 8. AOCS hardware architecture.

The BepiColombo mission software runs on the OBC processor module

(PM). The fully redundant OBC PM controls the spacecraft under normal circumstances. During an OBC emergency reset, the fully redundant FCE PM takes over attitude and solar array control of the S/C. 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.

An overview of the AOCS modes and transitions is shown in Fig. 9. 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 the ultimate backup mode ensuring survival in case of major on-board contingencies. Attitude control with thrusters only. Initially the S/C is sun pointed purely based on ground-provided sun ephemerides and the last known attitude (propagated in the future by IMU measurements), while sun sensors and then star trackers are brought into the control loop later on. The S/C rotates around the sun line. Intermittent contact is possible via the medium gain antenna (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 contact 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.
- *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. 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).
- *Electric Propulsion Control Mode (EPCM)* is dedicated to performing delta-V manoeuvres using the MEPS. 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.

The AOCS employs a layered Failure Detection, Isolation and Recovery (FDIR) concept, aiming at isolating a failure rapidly with the least reconfiguration overhead.

See Ref. 5 for more details on the AOCS design of BepiColombo.

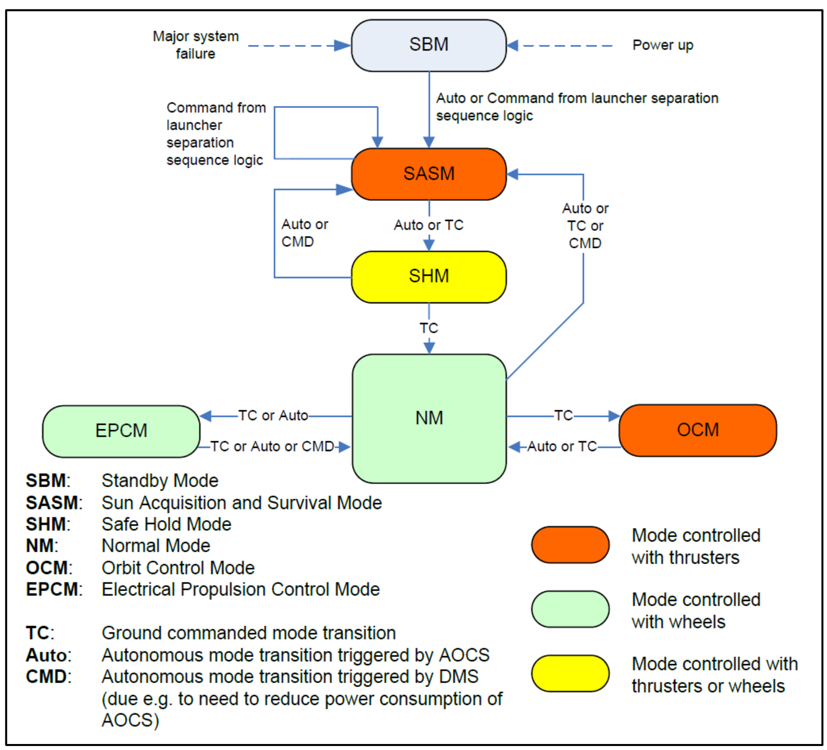


Figure 9. AOCS modes overview.

III. Electric Propulsion Operations Overview

The cruise trajectory with its periods of electric propulsion usage was established years before launch, assuming a maximum thrust level of 125 mN per thruster (250 mN using two thrusters). For pre-launch trajectory planning, 10% margin was taken on the thrust level to account for unexpected interruptions of thrust arcs, and conservative assumptions on the available power (which may constrain the thrust level used, see section IV.D) were used. Fig. 10 shows the resulting planned thrust levels. Prior to each thrust arc in flight, detailed planning of the arc without these additional margins takes place.

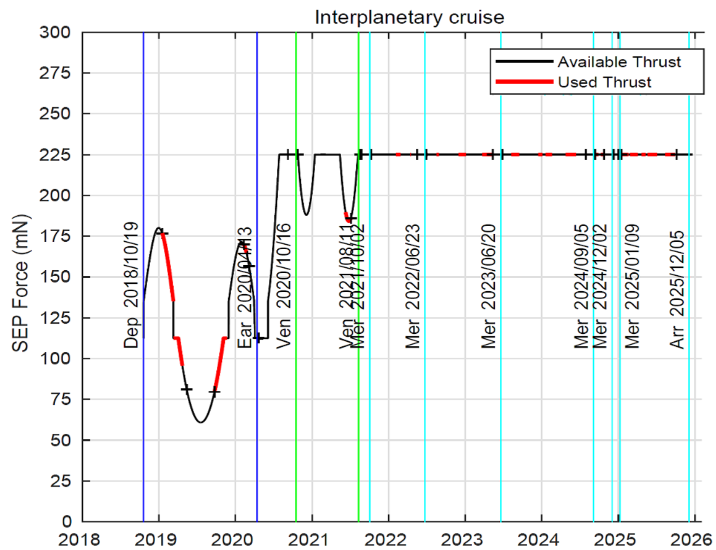


Figure 10. Thrust profile as planned prior to launch for the Oct 2018 trajectory.

EP operations are characterised by (i) complex EPCM entry/exit operations, (ii) constraints on S/C visibility with MGA or HGA when in EPCM, (iii) the need for regular interruptions of thrusting for performing orbit determination, and (iv) constraints on the available power requiring management of the commanded thrust levels. These aspects are discussed in detail in section IV, while this section provides an overview of EP in-flight operations performed so far.

First EP operations took place in the Near-Earth commissioning phase (NECP) after launch, in which a thorough check out of S/C platform and payloads is performed. EP commissioning started with a step-wise commissioning of the various SEPS elements out of the AOCS loop. Eventually, each thruster was fired in closed loop in EPCM, staying for several hours in the mode. Finally, an EPCM entry with dual thruster usage was also performed. See Fig. 11 for an overview of EP commissioning operations from early Nov to early Dec 2018.

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:

- Two thrusters were used in this arc. 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.
- The significantly higher thrust levels compared to the pre-launch planning (ref. Fig. 10) are due to removing the additional margins required for designing a robust trajectory (see above).
- 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 caused by thruster-related software FDIR triggering too early, with ground tuning the settings accordingly thereafter. In the mean time, these settings were fixed permanently in the frame of installing a new on-board software version in July 2019 (addressing a wide range of software issues encountered after launch).
- In terms of ground station contacts, a weekly "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). Two ground station contacts were taken per week to monitor S/C status in EPCM, allowing a regular

Figure 11. Electric propulsion commissioning 20th Oct – 7th Dec 2018.

check of S/C performance and faster reaction time to unexpected EPCM interruptions.

- 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.

The second EP arc of the mission is planned to take place from 12th Sept 2019 to mid November 2019, constituting the final major trajectory adjustment prior to the Earth flyby in April 2020. Owing to the large distance from the Sun during this part of the trajectory (between 1.15 and 1 AU), there is only sufficient power for using a single thruster in this arc.

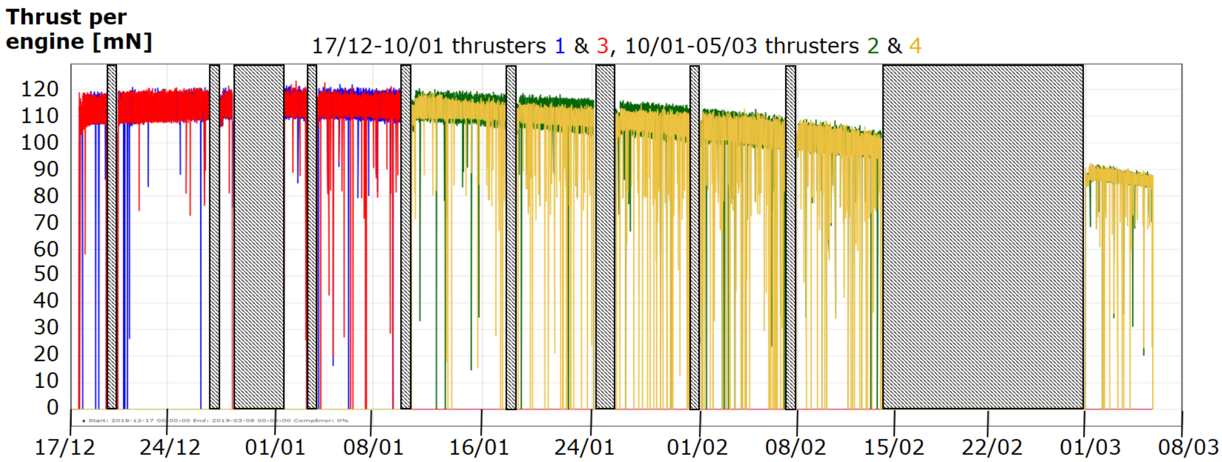


Figure 12. Thrusters and thrust levels used during the EP1 arc. Greyed out periods indicate when the thrusters were OFF (S/C in NM). The large period before the last few days of thrusting in early March was to do an orbit determination with full accuracy prior to performing a final touch up manoeuvre.

IV. Electric Propulsion Operations Challenges

A. Mode transitions from/to EPCM

AOCS mode transitions between NM and EPCM are complex and consist of several subphases as shown in Fig. 13. Entering EPCM requires the following steps:

1. Slewing from the NM attitude to the EPCM attitude in phase ETP-A1, preceded by a wheel offloading in phase ETP-WOP to bring the reaction wheels to levels compatible with performing the slew
2. 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)
3. Starting up the selected thrusters in phase ETP-A3

Likewise, exiting EPCM to NM requires switch off the thrusters in EPCM, rotating the MTM solar arrays back in phase ETP-B2, and slewing back to the NM attitude in phase ETP-B1.

Entering EPCM takes up to 5.5 hours (mainly consisting of 1.5h for thruster switch ON, and up to 4h for performing the attitude slew from NM to EPCM), exiting up to 4h (dominated by slew back to NM attitude).

On-board FDIR active in EPCM can lead to a fallback to NM commanded autonomously in case of problems not allowing to continue thrusting. Depending on the settings, it is also possible to have an FDIR-triggered autonomous re-entry into EPCM, using the so-called "backup" thruster selection. In such a case, a transition

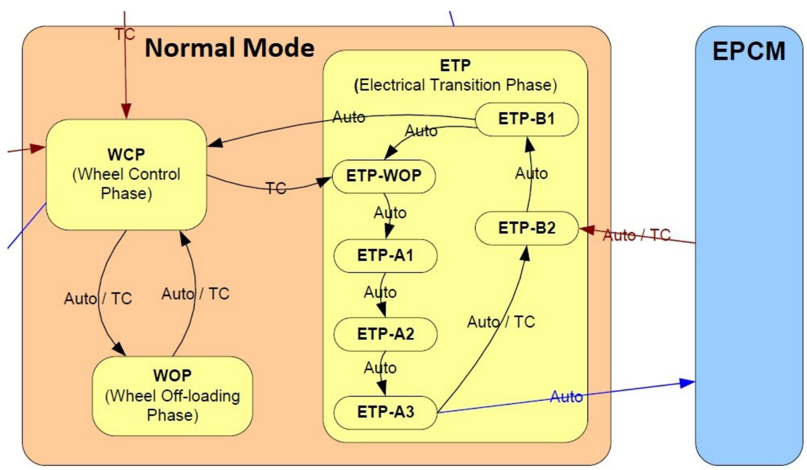


Figure 13. AOCS mode transitions for EPCM entry/exit.

from ETP-B1 to ETP-WOP (instead of going to NM-WCP) is done, followed by the ETP-A* phases prior to resuming EPCM.

In the first EP arc of the mission, entering EPCM required uplinking around 600 telecommands to the "Mission Timeline", an on-board queue of commands with execution time tags in the future. These commands are meticulously prepared and checked for correctness prior to uplink. These TCs cover both settings for the AOCS like attitude and solar array guidance profiles (for the chosen thruster selection, the backup thruster selection and the "fallback" guidance profile in NM), as well as settings for the EP system depending on the accumulated lifetime as well as the set of thrusters used. For the upcoming second EP arc, the number of commands for EPCM entry is expected to be reduced by about 300 –as in-flight experience from the first arc has shown that the update of some of the thrust-dependent parameter settings can be independent from thruster lifetime–, however entering EPCM remains a demanding operation.

B. Ground contact when in EPCM

The S/C has two antenna moveable with two degrees of freedom –medium gain (MGA) and high gain (HGA), ref. Fig. 2– for ground contact, with HGA used preferably owing to the higher bitrates possible. Due to the complex S/C shape (changing significantly upon Mercury arrival), ground contact with MGA or HGA in any S/C attitude is not guaranteed: antenna movement is constrained by the S/C body, or the antenna beam may be blocked by the S/C body.

The attitude required for thruster firing in EPCM is driven by trajectory needs, with the set of thrusters used the only degree of freedom. In case neither HGA nor MGA allow establishing ground contact, the S/C status can only be checked after exiting EPCM when retrieving telemetry from the mass memory, rendering trend analysis and timely ground reaction to unexpected events difficult.

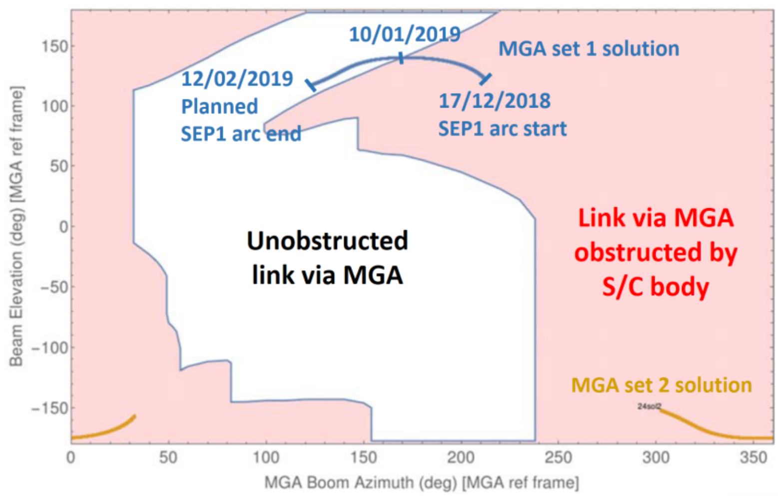


Figure 14. MGA visibility constraints for EP1 arc: as from 10/01/2019, link via MGA in the thrusting attitude became possible.

For each EP arc, expected antennae visibility is analysed to find the best strategy. For the first EP arc, the situation was as follows:

- From 17/12/2018 to 23/12/2018, HGA coverage was possible when using thruster pair [1,3]
- MGA coverage situation is shown in Fig. 14, displaying the MGA movement range: only if using thruster pair [2,4], MGA coverage would be possible from 10/01/2019 up to end of the arc.
- From 24/12/2018 to 09/01/2019, neither MGA nor HGA allowed coverage in EPCM. A special configuration was established with the S/C transmitting a carrier-only signal via a low gain antenna (LGA) when in EPCM, allowing ground to check presence of that signal to confirm the S/C was still in EPCM. This was only possible due to the close distance to Earth, with the LGA link budget insufficient to do this for future thrust arcs.

For the upcoming EP2 arc, the situation is better, as MGA visibility is expected to be possible throughout the arc.

C. Orbit Determination during EP arcs

Orbit determination (OD) is the process of estimating the S/C position and velocity by using tracking data observables. For a deep space mission like BepiColombo, OD is particularly challenging owing to the large distances involved, and the required accuracy for the achieving the planetary flybys (ref. Fig. 1).

Traditionally, OD relies on two tracking methods: ranging and two-way Doppler. Precisely measuring the time it takes radio signals to travel to and from a S/C gives the distance from the ground station ("two-way range"), while measuring the signal's Doppler shift provides the S/C velocity along the line-of-sight ("range-rate"). S/C non-radial velocity components are not measured, and can only be found from how the position changes from day to day. This means that tracking over several days is necessary and calls for very high-fidelity modelling of the S/C motion. For deeps space missions, Doppler and ranging can be augmented by the Delta Differential One-way Range (DDOR) method, allowing to precisely measure the position of the S/C in the sky. DDOR comes with high overhead, requiring to use two deep space ground stations and a suitable quasar for calibration purposes.

When using electric propulsion in EPCM, slight variations in thrust direction and magnitude –up to 0.5 mN in magnitude and 0.1 deg in direction– impact the accuracy of orbit determination based on Doppler and ranging data. The expected impact of these errors on orbit determination was analysed in detail prior to launch, showing that orbit determination errors when only using tracking data acquired in EPCM would lead to position and velocity errors two orders of magnitude higher compared to using non-disturbed tracking data with AOCS in NM, not acceptable for navigation purposes.

The solution chosen was to introduce periods with regular acquisition of radiometric tracking data with the thrusters off. Thus the concept of the weekly "navigation pass" was introduced, exiting and re-entering EPCM around an 8-hour ground station contact, taking place on Thursday's during the first SEP arc. Apart from an undesirable weekly thrust outage and restart of the thrusters, this required to perform the complex EPCM entry and exit operations (see section IV.A) on a weekly basis.

For the upcoming EP2 arc, the weekly navigation pass will continue to be taken. However, ESOC is looking into reducing the number of navigation passes for these later thrust arcs to reduce operations complexity. This may be possible by taking Delta DOR passes when thrusting, alleviating the need for radiometric data collection with electric propulsion off. A first test of this is planned during the upcoming EP2 arc.

D. Power Constraints

Despite approaching the Sun, the mission is highly power-constrained, with the S/C trajectory 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. 15: above 0.62 AU distance, there are no constraints, while below that distance significant offpointing of the array may be required.
- During EP 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 are capable of.

Therefore, careful management of MTM solar array pointing and EP thrust level commanding during EP arcs is needed to get the most out of the system. This is handled as part of the planning processes between Flight Dynamics (FD) and the Flight Control Team (FCT) during EP arcs. Unlike for typical manoeuvre command generation (e.g. for chemical propulsion burns) fully done on FD side up to delivery of the resulting commanding 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 then delivered from FCT to FD over a standard interface.
- 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. 15 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

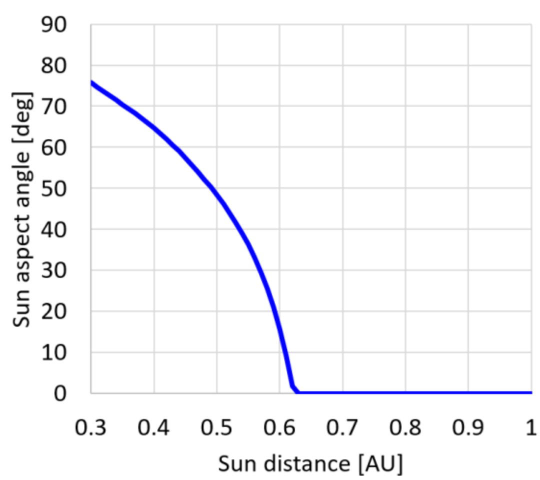


Figure 15. MTM solar array allowed Sun aspect angle depending on Sun distance (SAA of 0 deg means MTM SA is facing the Sun).

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 EP arcs. Prior to launch, the trajectory of BepiColombo including all EP 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 EP 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. 16:

- 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 III).
- 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 EP1 thrust arc. 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

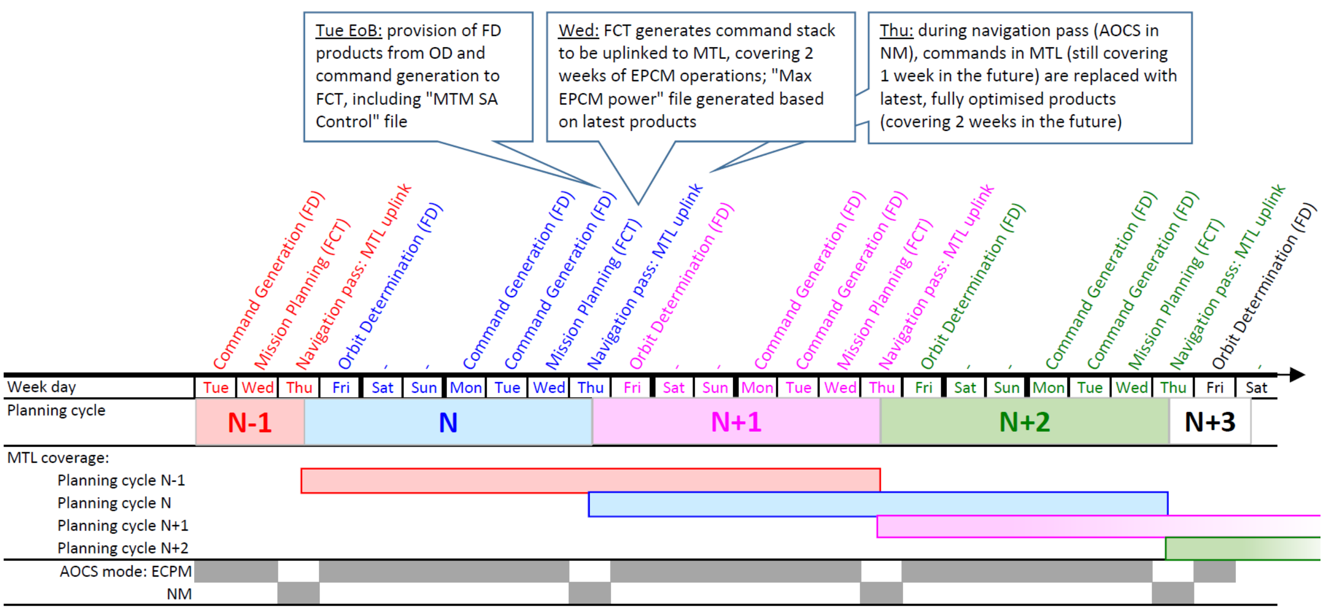


Figure 16. Weekly planning cycle during Electric Propulsion thrust arcs, including special processing for determining the MTM solar array pointing and the corresponding power available for EP thrusting.

V. Conclusion and Outlook

After a long preparation phase, the ESA/JAXA BepiColombo mission to Mercury was launched in October 2018. Following post-launch commissioning operations in late 2018 and in summer 2019, the S/C is in excellent shape and on the way to Mercury, with a planned arrival in Dec 2025.

Electric propulsion (EP) is used to adjust the cruise trajectory, with a total deltaV of 2731 m/s required to be applied in the frame of 22 "thrust arcs" throughout the 7 years cruise. The first thrust arc from Dec 2018 to Mar 2019 has already been completed, the second thrust arc from mid Sept to mid Nov 2019 is about to start. Electric propulsion operations are demanding for a number of reasons presented in this paper:

- Complex operations to enter/exit the AOCS mode for firing EP, requiring several hundred commands to configure the system.
- Constraints on S/C visibility with the moveable medium or high gain antennae when in the attitude required for thrusting.
- The need for regular, weekly interruptions of thrusting for performing orbit determination, as usage of the radiometric data when thrusting leads to inaccuracies too high for deep space navigation purposes.
- Constraints on the available power, requiring careful management of the commanded thrust levels and the corresponding impact on the trajectory.

Following completion of the second thrust arc in Nov 2019, the next major thrust arcs are only planned from 2021 onwards, when the S/C will move to the inner solar system and power management will become more critical owing to the required solar array offpointing. Some thrusts arcs late in the cruise place particular demands on reliable and autonomous EP operations, as even a limited thrust outage could result in missing the next Mercury swingby.

Appendix: List of Acronyms

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
CG	Center of Gravity
CPS	Chemical Propulsion System
DDOR	Delta Differential One-Way Range
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
JAXA	Japan Aerospace Exploration Agency
LEOP	Launch and Early Orbit Phase
MCS	Mission Control System
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
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 system)
TPM	Thruster Pointing Mechanism (of the electric propulsion system)

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