AOCS Operations Preparation for the BepiColombo Mission to Mercury

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Abstract
The 2017 ESA/JAXA BepiColombo mission to Mercury features a complex modular design, with two scientific Mercury orbiters and a cruise module. The spacecraft and mission design lead to a number of challenges for the attitude and orbit control system (AOCS), including electric propulsion usage during cruise to Mercury, AOCS capability to deal with several spacecraft configurations, and strict attitude constraints owing to the harsh thermal environment.
This paper presents the activities for AOCS operations preparation by ESA/ESOC, covering the current preparation status as well as an outlook on upcoming activities before launch.

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, also including a dedicated propulsion module (MTM). MPO and MTM are developed under ESA contract by an international consortium led by Airbus Defence and Space Germany.

BepiColombo is planned to be launched in 2017 with Ariane-5 from Kourou. The launch will be followed by a 7 years cruise phase, including planetary swingbys at Earth, Venus and Mercury, eventually achieving a weak capture by Mercury in January 2024 (Fig. 1). During the cruise phase electric propulsion will be used for extended periods of time. This is provided by the MTM module, which will be jettisoned at Mercury arrival. A set of complex manoeuvres will deliver the MMO to its operational orbit, and finally the MPO will be put into its 1500x480 km polar orbit (orbital period of about 2.2h) to start its scientific mission, planned to last for one Earth year (1 year extension possible).

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

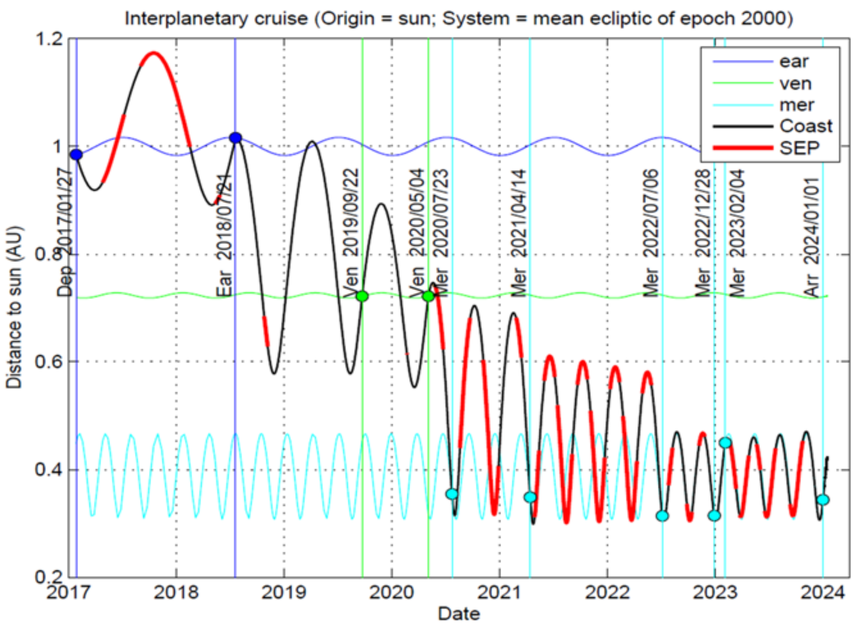

Figure 1: Cruise trajectory for Jan 2017 launch, showing sun distance, electric propulsion usage ("SEP"), and planetary flybys (at Earth, Venus, Mercury).

1.2 The BepiColombo Spacecraft

Fig. 2 shows an artist's impression of BepiColombo. 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.

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.

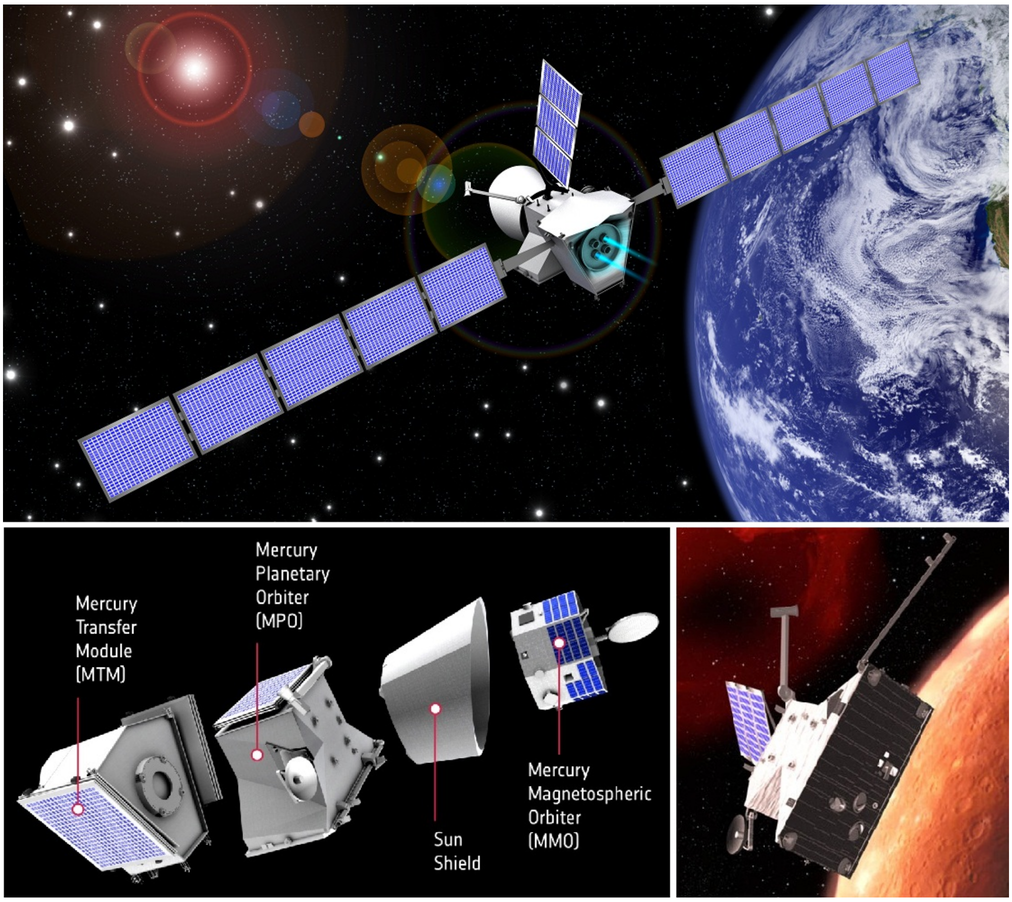

Figure 2: Artist's impression of the BepiColombo spacecraft in cruise configuration (top). with the various elements of the cruise stack in exploded view (bottom left), and the MPO at Mercury (bottom right).

1.3 The BepiColombo Mission Operations Centre at ESA/ESOC

Operations of the composite spacecraft and the MPO will be conducted from the European Space Operations Centre (ESOC) in Darmstadt, Germany. See Fig. 3 for the main elements of the BepiColombo Mission Operations Centre (BCMOC) at ESOC. It features the typical setup for ESA/ESOC 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 a key tool for operations preparation, as it is running the platform on-board software on a processor emulator, allowing testing with very high fidelity [3]. The "Engineering Test Bed (ETB)" shown in the figure will only be delivered from industry to ESOC after launch.

Operations of BepiColombo are performed by the Flight Control Team (FCT), consisting of about 10 engineers and controllers at launch, led by the Spacecraft Operations Manager. The FCT is interfacing with various multi-mission support groups at ESOC, including flight dynamics, ground segment software and hardware support (e.g. mission control system), and ground station operations. For deep space missions, there is a particularly close relation to the flight dynamics team due to the complex navigation and AOCS operations activities.

Prior to launch, the FCT deals with all aspects of operations preparation. Key activities include the following:

- Specification and acceptance testing of mission control system, planning system and simulator.
- Preparation of operational products: writing of the Flight Operations Plan (FOP) based on inputs provided by the prime S/C contractor as well as population of the spacecraft database.
- Execution of tests with the spacecraft flight model as well as the engineering test bed, with the prime objective of validating the ESOC ground segment and operational products.

BepiColombo is very challenging for operations, as the mission is highly constrained and the S/C is complex. An overview of the operational challenges is provided in [2].

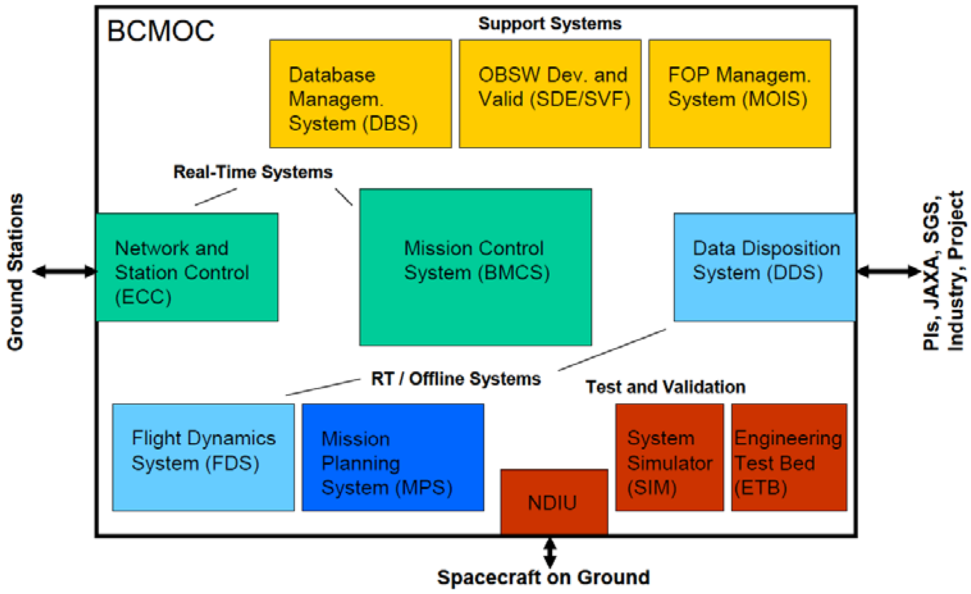

Figure 3: Main elements of the BepiColombo ground segment at ESOC.

2. The Attitude and Orbit Control System (AOCS)

The BepiColombo AOCS performs 3-axis stabilised attitude and orbit control. While it shares many commonalities with AOCS design for previous ESA interplanetary mission like Rosetta, Venus Express and Mars Express, the following peculiarities make the BepiColombo AOCS particularly challenging:

- *S/C modularity:* the AOCS has to deal with various S/C configurations, with significantly different S/C properties and several sensors and actuators duplicated on MTM and MPO. The S/C attitude in survival and safe mode differs depending on the S/C configuration.
- *Initial attitude acquisition in safe mode:* in the harsh thermal environment at Mercury, there would be no time for the AOCS performing an attitude acquisition from "lost in space" conditions (e.g. by performing a sun search using sun sensors) at safe mode entry. Instead, the last known S/C attitude and dynamics are continuously stored in safeguard memory (SGM), and are then retrieved in case of safe mode entry. Another

consequence of the severe attitude constraints is that at safe mode entry, when the S/C is not controlled by the on-board computer (which is being reinitialised), the FCE is taking over control for a few minutes, running a simplified AOCS software able to damp S/C rates and ensure correct sun pointing.

- *Solar array control:* owing to technological limitations, the MPO solar array can't be pointed directly to the sun. Instead, it has to be off pointed such that sufficient power is obtained, yet maximum temperature limits are not violated. This is achieved by ground-provided polynomial SA steering profiles continuously adjusting the solar array position throughout the MPO's orbit around Mercury.
- *Attitude and solar array guidance for safe mode:* correct attitude and solar array pointing after safe mode entry is crucial for S/C survival. As the orbit around Mercury is left to drift and the margins available are very limited, guidance for safe mode requires frequent updates (about once per week). A mistake in the updated settings could lead to an end of mission.
- *Electric propulsion:* BepiColombo is the first ESA interplanetary mission using electric propulsion.

Fig. 4 gives an overview of BepiColombo AOCS modes and mode transitions:

- *Standby Mode (SBM):* the AOCS is inactive with all units switched off. SBM is used for ground testing, and is only entered transiently during flight (e.g. after safe mode entry).
- *Sun Acquisition and Survival Mode (SASM):* ultimate backup mode ensuring S/C 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. In SASM, the S/C rotates around the sun line (in line with the orbital motion around Mercury when in MPO configuration), pointing the medium gain antenna such that it sweeps over the Earth once per revolution.
- *Safe Hold Mode (SHM):* the S/C is pointed according to ground provided polynomial profiles. At mode entry, attitude control is done with thrusters, while later reaction wheels are brought into the loop. This is the highest mode that may be entered autonomously following S/C safe mode entry. The medium gain antenna is pointed permanently to Earth based on ground-provided Earth ephemerides.
- *Normal Mode (NM):* nominal operating mode. Attitude estimation and control as in the later stages of SHM. The steerable high gain antenna is used for communications.
- *Orbit Control Mode (OCM):* mode for performing trajectory correction manoeuvres using chemical propulsion. Attitude estimation as in NM. Attitude control performed with thrusters, while reaction wheels are kept at constant speeds.
- *Electric Propulsion Control Mode (EPCM):* mode for electric propulsion usage (MCSC configuration only). Attitude control and estimation as in NM.

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.

Fig. 5 gives an overview of the various MPO and MTM units used by the AOCS. The on-board software implementing all AOCS tasks is running on the MPO on-board computer (OBC), controlling all MPO and MTM equipment.

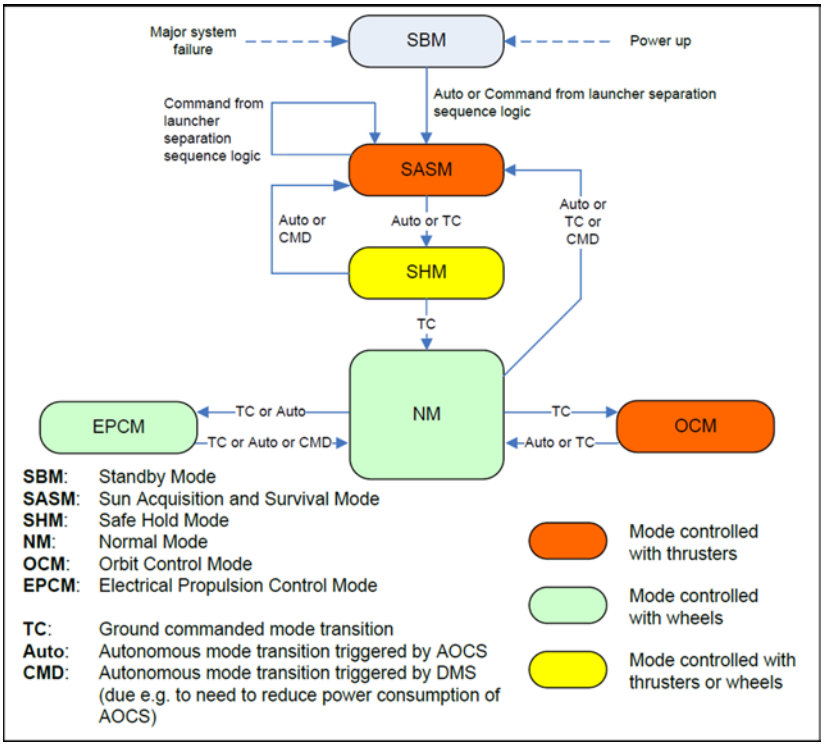

Figure 4: AOCS modes overview.

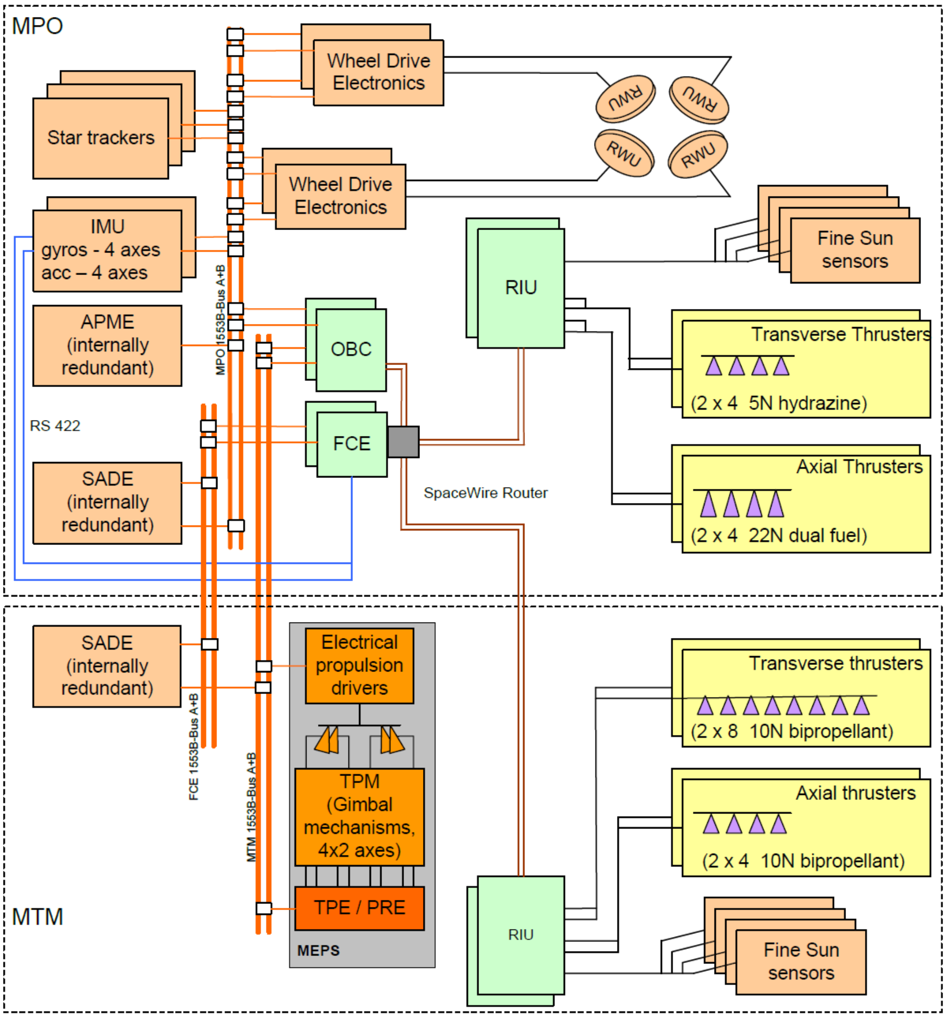

Figure 5: AOCS hardware architecture.

3. AOCS Operations Preparation at ESA/ESOC

3.1 AOCS Operations Preparation Overview

As for other subsystems, AOCS operations preparation by the FCT starts well in advance to launch. The following are the most important preparation activities:

- *Preparation of operational products:* AOCS flight operations procedures are written based on input from the S/C manufacturer, and later validated against the ESOC simulator and the spacecraft in dedicated test slots. The industry-provided S/C database is refined and augmented with operation-specific information (e.g. generation of displays, instantiation of specific TCs, TM parameter out of limits, etc.).
- *Validation of the interface to flight dynamics:* the flight dynamics system comprises all functionality for orbit determination, monitoring of S/C dynamics, and AOCS-specific commanding of the S/C. Commanding products prepared by flight dynamics cover a wide range of activities, for instance guidance for normal and safe mode, reaction wheel momentum management, orbit control manoeuvres with chemical propulsion, electric propulsion operations, etc. The precise set of requests required is iterated between the FCT and the flight dynamics team. For BepiColombo, this commanding interface is complex – its validation hence comprises a major part of AOCS operations preparation.
- *Testing with the flight model and engineering model:* prior to launch, ESOC has been granted 30 days testing with the flight model (currently located at ESA/ESTEC), the so-called System Validation Tests (SVT). In addition, ESOC can also access the engineering test bed (ETB) (located at the premises of the S/C manufacturer) for 30 days, the so-called Integrated Ground Space Tests (IGST). Tests in the various slots are carefully prepared and iterated with the S/C manufacturer and the project team at ESA/ESTEC, starting

months before a slot. ESOC performs testing activities in these slots with the same ground segment systems as used for flight, resulting in highly representative test results. For AOCS operations preparation, these test slots are used to validate AOCS procedures and operational products provided by flight dynamics.

In addition, a significant amount of work is invested by the AOCS spacecraft operations engineer in supporting development of the ESOC simulator, ensuring the modelling is flight-representative for all AOCS-related aspects.

The AIV schedule for BepiColombo is such that the MPO is in a more mature state earlier, while the full cruise composite including the MTM will only be completed later. AOCS operations preparation at ESOC hence had to initially focus on MPO stand alone, prior to shifting the attention to MCSC configuration (which will have to be operated in the first 7 years of the mission).

3.2 AOCS Flight Procedures and Flight Dynamics Commanding Interface Implementation Status

Work on AOCS flight procedures started in late 2013 based on first inputs received from the S/C manufacturer, and has progressed significantly in 2014/2015, with an initial emphasis on MPO-specific procedures. As for other ESOC missions, flight operations procedures for BepiColombo are written using the MOIS suite of tools [4].

A total number of 290 AOCS procedures is currently expected to be required, out of which 134 have been written, with 78 procedures already run in IGST.

Regarding the commanding interface with flight dynamics, a total of 263 requests have currently been defined, with the interface control document in a stable state. These requests fall into the following categories:

- Commanding of AOCS units (e.g. star tracker alignment matrices, IMU calibration settings)
- Commanding of AOCS parameters (e.g. mass properties, thruster modulation settings)
- Commanding of ephemerides and guidance in RAM and Safeguard Memory (SGM)
- AOCS mode transitions (e.g. entry to OCM, setting all manœuvre parameters as required)

The commanding requests for uplink of AOCS ephemerides (sun and Earth) were implemented in late 2013. Requests for guidance updates for MPO configuration were implemented throughout 2014, followed by the same requests for other S/C configurations in late 2014/early 2015. Implementation of essential commanding requests for unit operations (reaction wheel management and antennae operations) as well as implementation of OCM commanding products has started in early 2015 and is planned to be completed prior to IGST-4 in July 2015.

3.3 AOCS Closed-loop Testing on the ESOC simulator

In late 2013, the ESOC simulator was already capable of running an AOCS closed-loop scenario. This was achieved by implementing an AOCS reference case from the S/C manufacturer used for their AOCS validation. As in the early stages of on-board software development, the system initialisation process loading context information from the permanent safeguard memory (SGM) was not yet ready, these reference cases were performed patching AOCS configuration and guidance information directly in OBC RAM. Hence the set up for these test cases was not fully representative for flight.

The prime objective in 2014 was therefore to obtain the ability for setting up a closed-loop run based on a custom state vector consisting of {epoch, orbital position, S/C attitude, S/C rates}, with the S/C correctly pointing and having correct guidance information stored in SGM corresponding to this state vector (as for flight). This is a key step for AOCS operations preparation, as it requires preparation of AOCS guidance products as well as a thorough understanding of how the AOCS and in particular the AOCS system initialisation process works. For interplanetary missions, this can be intricate owing the significant amount of consistent guidance information needed by the AOCS to perform nominally (e.g. knowledge on Earth direction to point antennae correctly, or ground-provided orbital data). For BepiColombo, an additional complexity is that the AOCS needs context information on the last known S/C attitude and rates when entering safe/survival mode.

The following guidance and ephemeris context is required by the BepiColombo AOCS for functioning correctly following a safe/survival mode entry in MPO configuration:

- *Last known S/C attitude and rates (SGM RAM):* unlike traditional designs, the AOCS does not perform a sun search/acquisition using sensor data when entering SASM (ref. section 2). Instead, it uses context information stored in SGM RAM (the non-permanent area of safeguard memory) at 1Hz when the AOCS is running nominally.
- *Sun ephemerides (SGM EEPROM):* in the early phases of SASM, sun pointing is established based on last known attitude/rates and the sun direction based on ground-provided sun ephemerides.

- *Earth ephemerides (SGM EEPROM):* not used in SASM. In SHM and higher modes, this is required for pointing the medium and high gain antennae to the Earth.
- *MPO SASM attitude and solar array guidance (SGM EEPROM):* SASM attitude guidance specifies S/C rotation rate and phasing for the rotation around the sun line, which has to be in synch with the orbital motion around Mercury, ensuring the radiator side of the MPO is never facing Mercury. SASM solar array guidance consists of tables with time ranges and commanded sun aspect angles, allowing for a step-wise adjustment of the array position as the S/C rotates around the sun line.
- *MPO SHM attitude and solar array guidance (SGM EEPROM):* SHM is the highest mode reached autonomously after safe/survival mode. For MPO, its attitude and solar array guidance is specified as Chebyshev polynomials. The default guidance for SHM loaded in SGM EEPROM is such that the attitude profile is the same as in SASM.

In summer 2014 a first successful closed-loop run was achieved on the ESOC simulator, with the procedure involving the following basic steps:

1. A custom scenario is agreed, allowing flight dynamics to provide the necessary commanding products.
2. The simulator is started with a configuration in which the AOCS is in SBM.
3. The last known S/C attitude and rates are loaded into SGM RAM, disabling write access beforehand in order to avoid that the information gets overwritten by the AOCS.
4. SGM EEPROM context is configured including AOCS mode transition settings and other essential context (e.g. declaring that the launcher separation sequence has been terminated).
5. The AOCS ephemerides and guidance products are prepared for uplink to SGM EEPROM. This requires time shifting the products according to the desired start time of the closed-loop run. As the mission control system is working in UTC time, yet the guidance products are generated for the future epoch time, a time correlation between these two times has to be maintained carefully to correctly set up the scenario.
6. When the desired start time is reached, a simulator script is started which changes the state vector and commands a reboot of the OBC. Following the reboot, the closed-loop simulation started, with the on-board software loading the necessary context information from SGM

In early 2015, an AOCS-closed loop in MCSC configuration was also achieved on the ESOC simulator. In the future, the steps to set up a closed-loop run on the simulator for a new state vector are planned to be simplified by script, allowing to automatically load the products provided by flight dynamics and setting the state vector according to a dedicated input file.

3.4 Testing Activities on the S/C Engineering Test Bed and Flight Model

Following successful establishment of a custom scenario for AOCS closed-loop testing on the ESOC simulator, in December 2014 a first AOCS closed-loop run was achieved on the ETB in the frame of the 2-day IGST-3 slot. The purpose of this test slot was to exercise a wide range of AOCS operations activities in modes SASM, SHM and NM, with the S/C in MPO configuration.

The AOCS closed-loop run on each IGST-3 day was set up based on an ESOC-provided initial state vector. As the set up of a closed-loop run had never been done before with industry, two IGST-3 dry runs were required in Nov 2014 to sort out the basic procedure and interaction between AIV and ESOC, also discovering an on-board software problem linked to restoring the AOCS guidance from safeguard memory, which had to be worked around. The closed-loop was set up on each day according to the following steps, similar to the process with the ESOC simulator:

1. In advance to IGST-3, the state vector was provided to AIV for inclusion in the setup of the AOCS SCOE.
2. On the testing day, AIV configured the ETB for “Basic Test Mode” with AOCS in SBM.
3. After TC handover, ESOC loaded the context information on S/C attitude and rates into SGM RAM.
4. ESOC configured various SASM/SHM mode transition settings in SGM EEPROM, governing terminal AOCS mode and transition duration settings (some of which were shortened to avoid long wait times).
5. A UTC time for starting the closed-loop simulation was agreed with AIV. The AOCS guidance products were then shifted from simulation epoch time (e.g. 2024 Mercury orbit case) to UTC time accordingly by ESOC and uplinked to

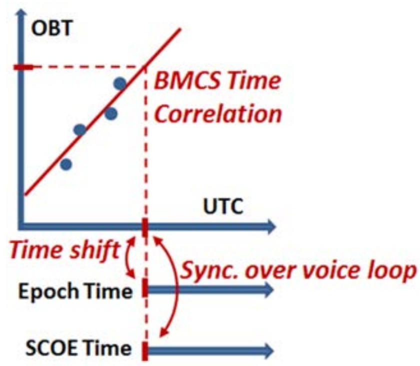

Figure 6: Time correlation in IGST-3.

SGM EEPROM. For uplinking this guidance to the spacecraft, it is crucial to have a correct "time correlation" in the mission control system, i.e. the correlation between UTC and spacecraft on-board time (ref. Fig. 6 for a schematic overview of time correlation activities).

6. Coordinating on the voice loop, at the agreed time the dynamic simulation was started by AIV in the AOCS SCOE, and ESOC commanded an OBC reboot at the same time.

This setup was successful for the different state vectors used on each of the two days. The ensuing testing activities in SASM/SHM/NM were also executed successfully, with only minor problems found regarding the procedures or the on-board software. Fig. 7 gives a high-level overview of the IGST-3 testcases. Thanks to the effort spent earlier in 2014, most operations in IGST-3 could be done using actual flight procedures (rather than writing IGST-specific testing procedures), unusual for this early stage of operations preparation.

h	min	ISGT-3 Day 1	IGST-3 Day 2
		<u>ETB setup by ASD</u>	<u>ETB setup by ASD</u>
09	00	<u>ETB handover and start of closed loop simulation</u> Status at the end of SY-SVT-300: - AOCS closed loop kicked off - Valid guidance for SASM, SHM, NM loaded - ETB configured following nominal reset - AOCS transitions settings: AOCS stops in SASM-SAPP-3 (flag STR_USAGE=FALSE), exit SASM to SHM disabled (STAP_SHM and ESP_SHM are FALSE), autonomous transition SHM-TCP to SHM-WCP disabled (shmIsRwTransAlwd = FALSE) - SSMM packet store reads open	<u>ETB handover and start of closed loop simulation</u> Status at the end of SY-SVT-300: - AOCS closed loop kicked off - Valid guidance for SASM, SHM, NM loaded - ETB configured following nominal reset - AOCS transition settings: STR_USAGE = TRUE, exit SASM to SHM enabled (STAP_SHM = TRUE), autonomous transition SHM-TCP to SHM-WCP disabled (shmIsRwTransAlwd = FALSE) => terminal mode is SHM-TCP - SSMM packet store reads open
	15		
	30		
	45		
10	00		
	15		
	30		
	45		
11	00	<u>SASM operations</u> - FSS activities in SASM-SAPP-3 - Transition from SASM-SAPP3 to SASM-StAP - Guidance-related commanding in SASM-ESP - MGA activities in SASM-ESP - RW checkout in SASM-ESP - STR activities in SASM-ESP - CPS activities in SASM-ESP	<u>SHM operations</u> - Switch on wheels in SHM-TCP and perform transition to SHM-WCP - RW activities in SHM - MGA activities in SHM - IMU activities in SHM - Transition from SHM to NM
	15		
	30		
	45		
12	00		
	15		
	30		
	45		
13	00		
	15		
	30		
	45		
14	00		
	15		
	30		
	45	<u>Operations in SHM-TCP and mode transitions</u> - Transition from SASM-ESP to SHM-TCP by setting ESP_SHM to TRUE - RW checkout in SHM-TCP (leave RW function switched ON) - Transition from SHM-TCP to SHM-WCP, back to TCP, and finally again into SHM-WCP - Transition from SHM to NM	
15	00		<u>NM operations</u> - HGA activities in NM - Miscellaneous activities in NM (STR, GSE, SADP)
	15		
	30		
	45		
16	00		
	15		
	30		
	45		
17	00	<u>Handover to ASD, test debriefing</u>	<u>Handover to ASD, test debriefing</u>

Figure 7: Schedule of IGST-3, first AOCS-closed loop testing with the engineering testbed (ETB) in Dec 2014.

Each IGST-3 test case is designed to address different routine and contingency operations expected to be performed in flight. An example is the guidance commanding in SASM that addresses a critical part of survival mode recovery. In a typical survival mode scenario, the spacecraft is expected to be found in SASM, with its medium gain antenna strobing the Earth in each rotation of S/C around Sun line. In such a case, ground would need to be able to stop the rotation, perform small attitude corrections, update the SASM guidance, etc, in order to establish an uninterrupted communication and eventually recover the spacecraft. The corresponding IGST-3 test case was designed accordingly to include all AOCS operations likely to be performed in such a scenario. Fig. 8 shows the operations exercised. The first plot on top is the magnitude of the spacecraft angular rate, which is expected to be around 2.6 deg/min for the given test scenario. The second plot gives the angle between spacecraft -z axis and the Sun direction, which is kept at 6 deg in MPO safe mode guidance. The following operations are visible in these plots:

1. Epoch+2700 sec: a tighter attitude deadband (+/-1 deg) is commanded for more precise attitude control;
2. Epoch+3500 sec: SASM guidance is updated to introduce ca.10 deg offset to the reference attitude around Sun line, which leads to an increase in S/C rate;
3. Epoch+4500 sec: rotation around Sun line is stopped and then an attitude correction is introduced, which projects as a 4 deg offset on S/C -Z axis, causing the attitude to leave the deadband;
4. Epoch+4700 sec: attitude correction is set back to zero;
5. Epoch+4900 sec: rotation around Sun line is restarted. Spacecraft rate increases to 7 deg/min to catch up with the commanded SASM guidance;
6. Epoch+5200 sec: 10 deg offset is removed, which causes the spacecraft rates to stay below 2.6 deg/min until the new guidance is converged.

Another example for operations exercised in IGST-3 is reaction wheel activities in SHM, including reaction wheel offloading operations and isolation of a reaction wheel from the AOCS loop. Fig. 9 gives the reaction wheel unit angular momentum profiles and the magnitude of the total angular momentum of the RW cluster. The following operations are performed:

1. Epoch+9600 sec: wheel offloading is commanded to remove the excessive momentum on RW cluster;
2. Epoch+9750 sec: wheel offloading is completed successfully.
3. Epoch+9750 to 10500 sec: the momentum of each wheel keeps increasing although there is no significant change in the total momentum of the RW cluster. This increase is due to the on board null space management, active whenever all 4 wheels are in the loop. The target null space magnitude was set to 7.5 Nms by Ground for this test scenario, thus wheel momentums keep drifting until this target is achieved.
4. Epoch+10500 sec: RW4 is taken out of the AOCS torque control loop and commanded in speed mode, i.e. at constant momentum. The null space drift is also stopped with only 3 wheels in the loop.

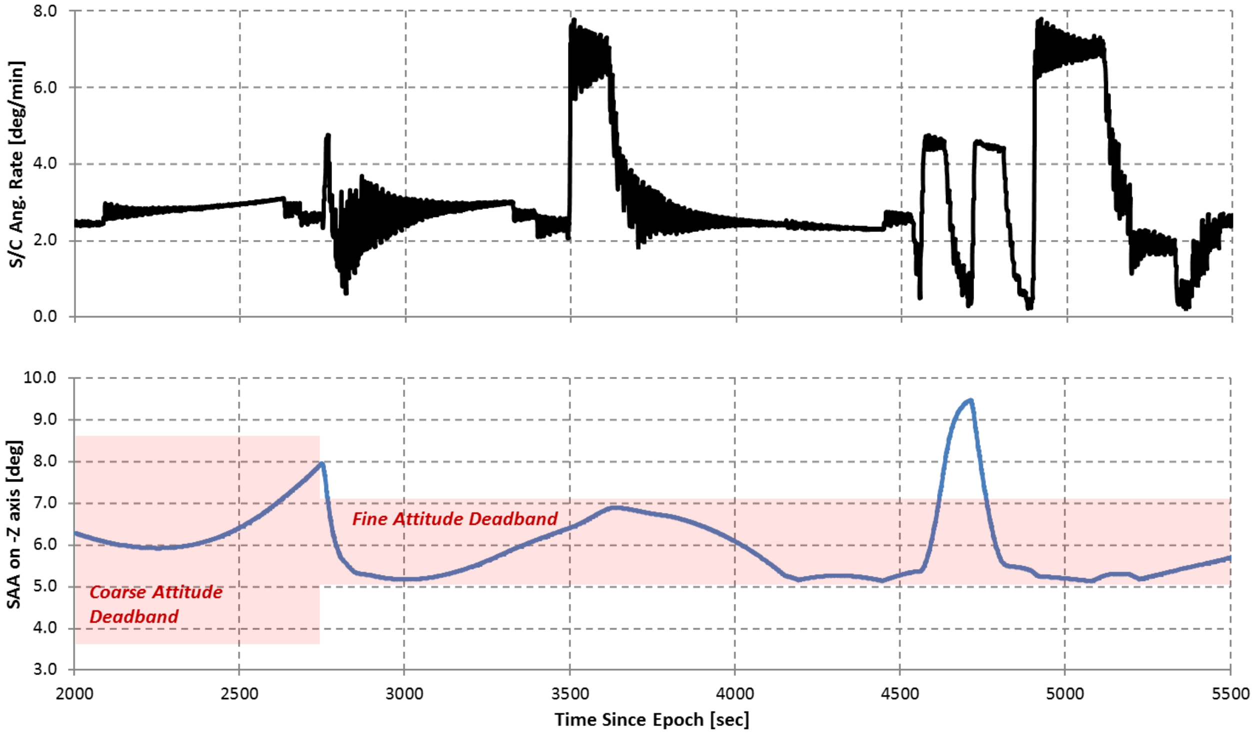

Figure 8: Spacecraft rate and orientation w.r.t. Sun during SASM guidance commanding on day 1 of IGST-3.

5. Epoch+10700 sec: RW4 momentum is changed to -1.5 Nms to see other wheels absorbing the change in its momentum, with the total angular momentum remaining constant.
6. Epoch+10800 sec: RW4 is switched off, which creates a a jump in the total angular momentum, as RW4 is not anymore considered part of wheel cluster.
7. Epoch+11600 sec: RW4 is switched on in constant speed mode.
8. Epoch+11800 sec: RW4 is put back in AOCS torque control loop.

As seen in the above examples, IGST-3 provided the first opportunity for the FCT to run a wide range of AOCS operations in a realistic context, using the closed-loop capability on ETB. Several more such test slots are coming up in the near future. IGST-4 is planned for July 2015 and will contain a test of all possible AOCS mode and unit operations in MPO configuration, including activities not run in IGST-3, the most important of which are orbit control manoeuvres in OCM. Flight dynamics commanding requests are planned to be used more extensively in IGST-4, not only covering AOCS guidance, but also unit level operations for reaction wheels and antenna. IGST-4 will also be the first time AOCS closed-loop testing with the FCE in the loop is planned to be done. The very first SVT (i.e. test slot with the flight model) is then planned for the last quarter of 2015, including a rerun of the AOCS operations activities performed in IGST-4.

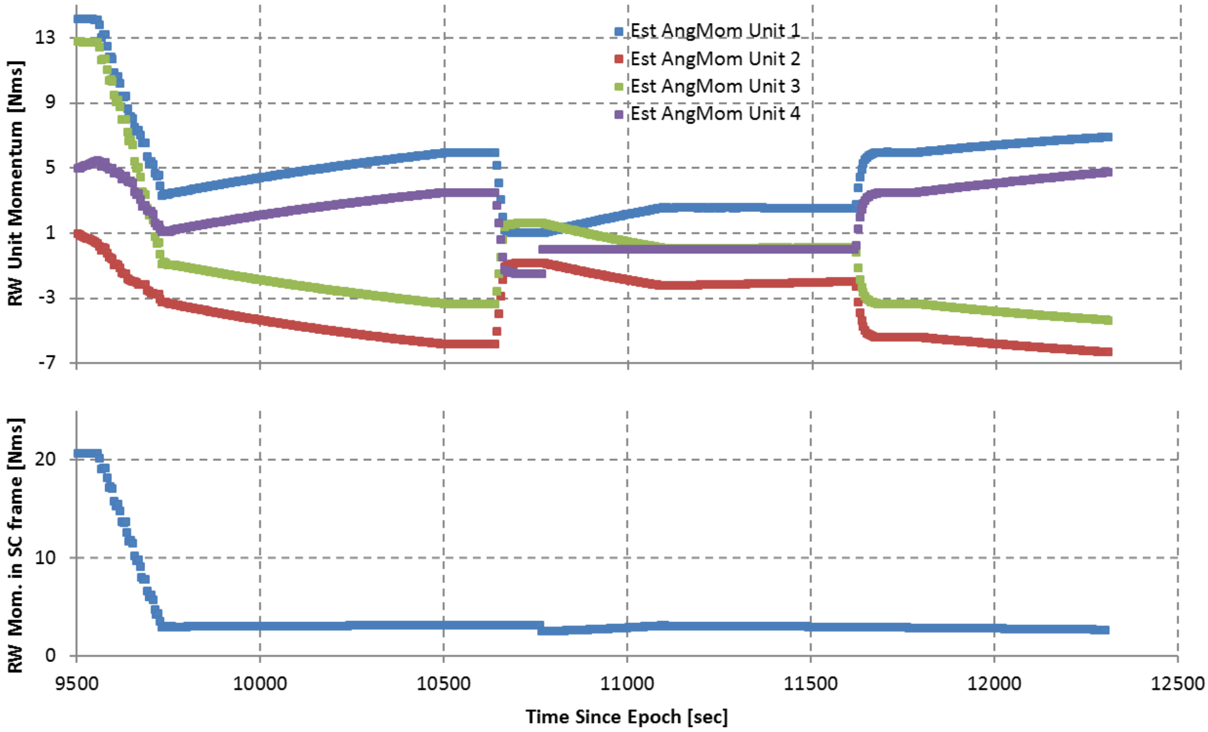

Figure 9: RW momentum profiles during reaction wheel operations on day 2 of IGST-3.

4. Conclusion and Outlook

The 2017 ESA/JAXA BepiColombo mission to Mercury poses a particular challenge for AOCS operations, with the AOCS controlling a highly complex multi-module spacecraft, and strict constraints imposed by the harsh thermal environment leading to complex ground-provided guidance for spacecraft attitude and mechanisms.

AOCS operations preparation at ESA/ESOC is in an advanced state. Generation of flight procedures for standalone operations of the ESA mercury orbiter (MPO) progressed very well in 2014/2015. Given the mature state of the mission control system and the spacecraft simulator, and the ability of flight dynamics to generate essential spacecraft attitude and solar guidance products, in 2014 the execution of custom AOCS closed-loop scenarios was achieved. Extensive AOCS testing was performed on industry’s engineering model of the MPO spacecraft in late 2014, executing the complex collaboration activities between AIV and ESOC required for setting up a closed loop run and performing a wide range of AOCS operations.

In terms of future AOCS operations preparation work, several more tests with the engineering model and the flight model are coming up. Focus will now slowly shift to operations preparation for the cruise stack, including electric propulsion operations.

Acronym List

AOCS	Attitude and Orbit Control System
APME	Antenna Pointing Mechanism Electronics (for High Gain and Medium Gain Antenna)
BMCS	BepiColombo Mission Control System
EPCM	Electric Propulsion Control Mode
ETB	Engineering Test Bed
FCE	Failure Control Electronics
FCT	Flight Control Team
FDIR	Failure Detection, Isolation and Recovery
FOP	Flight Operations Plan
IGST	Integrated Ground Space Test
IMU	Inertial Measurement Unit
LEOP	Launch and Early Orbit Phase
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)
MMO	Mercury Magnetospheric Orbiter
MOSIF	MMO Sunshade and Interface Structure
MPO	Mercury Planetary Orbiter
MTM	Mercury Transfer Module
NM	AOCS Normal Mode
OBC	On-board Computer
OBT	On-board Time
OCM	AOCS Orbit Control Mode
PRE	Pressure Regulation Electronics (of the electric propulsion)
RAM	Random Access Memory
RIU	Remote Interface Unit
RWU	Reaction Wheel Unit
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
SVT	System Validation Test
TPE	Thruster Pointing Electronics (of the electric propulsion)

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