Planning Drivers for the BepiColombo MPO Science Payload Operations

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Abstract

BepiColombo is an interdisciplinary mission to Mercury scheduled for launch in 2015, arriving at Mercury in 2021. It is a joint mission between ESA and JAXA consisting of 2 complementary spacecraft, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO).

BepiColombo MPO scientific payload comprises 11 instrument packages comprising 17 experiments that will investigate the Mercury planet interior, surface composition and morphology, the intrinsic magnetic field and the composition of the exosphere and the coupling between all of these fields. The BepiColombo MPO has a relatively short nominal science mission of 12 months with the possibility of a 12 months extension. The harsh environment of Mercury is expected to limit the operational lifetime of the spacecraft beyond 2 years.

The elements that will drive the planning consist of operational constraints (power, data-rate, etc.), mission characteristics (orbit, subsystems, etc,) and science observations requests (where and when to observe). This paper will discuss these elements in more detail and illustrate the level of complexity the BepiColombo science planning will have to cope with.

Introduction to BepiColombo Mission

BepiColombo is an interdisciplinary ESA mission to explore the planet Mercury in cooperation with the Japan Aerospace Exploration Agency (JAXA). The mission consists of two separate Mercury orbiters: ESA's Mercury Planetary Orbiter (MPO, Figure 1) and JAXA's Mercury Magnetospheric Orbiter (MMO), which are dedicated to the detailed study of the planet and its magnetosphere. The MPO/MMO complement is to be launched from Kourou in August 2015.

The duration of the interplanetary cruise phase (from launch until insertion into the operational Mercury orbit) will be approximately 6 years. The MPO is a three-axis-stabilized and nadir-pointing spacecraft designed for an operational lifetime of one Earth year (with a possible extension of one year).

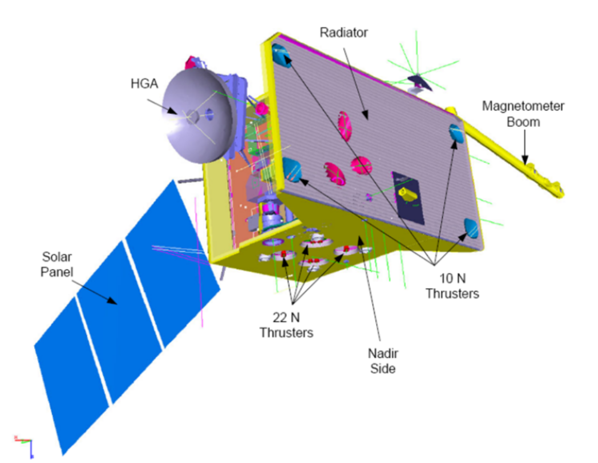


Figure 1: MPO Spacecraft Configuration

The MPO orbit (Figure 2) is in an inertially fixed polar orbit; the spacecraft has one axis aligned with the nadir direction for a continuous observation of the planet. The MPO's 2.3-hour low-eccentricity orbit (400 x 1500 km) will provide excellent spatial resolution over the entire planet surface.

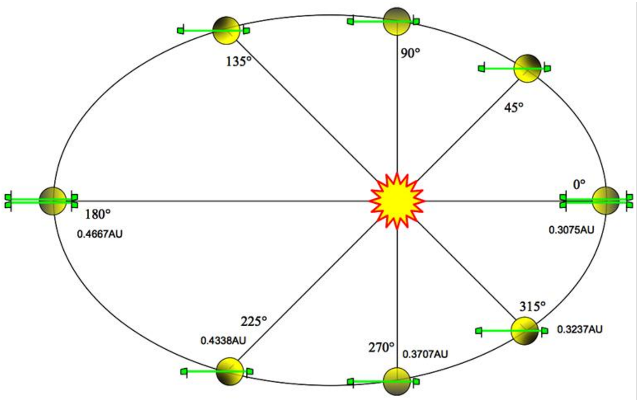


Figure 2: Mercury and MPO orbit

The MPO payload comprises 11 instrument packages consisting of 17 sensors. The complementary payload will investigate the interior, the surface composition and morphology, the intrinsic magnetic field, the composition of the exosphere and the coupling between all of these aspects of the innermost planet.

The MMO is a spin-stabilized spacecraft to be placed in a high-eccentricity (400 km to 12000 km altitude) polar orbit with its spin-axis perpendicular to Mercury's equator. The MMO operational lifetime will be at least one Earth year. The MMO accommodates 5 instruments/instrument packages dedicated to the study of fields, waves and particles in the Mercury environment: a magnetometer (MGF), plasma particle and plasma wave experiments (MPPE, PWI), a sodium atmospheric spectral imager (MSASI), and a dust monitor (MDM).

Although some coordination will be needed for particular observations (for example, for synchronous operations when the two spacecraft are radially aligned), after Mercury arrival, the two spacecraft will be independently operated and controlled from the MPO Operations Ground Segment (OGS) located at the European Space Operations Centre (ESOC) and the MMO Operations Centre at ISAS/JAXA Sagamihara Space Operations Centre (SSOC). The science operations for MMO will be prepared by the MMO Science Operations Centre at SSOC while the MPO operations by the MPO Science Ground Segment (SGS), located at the European Space Astronomy Centre (ESAC) in Madrid, Spain.

BepiColombo MPO Scientific Payload Overview

The MPO scientific payload comprises 11 instrument packages:

- BepiColombo Laser Altimeter (BELA)
- Italian Spring Accelerometer (ISA)
- Mercury Magnetometer (MPO-MAG)
- Mercury Thermal Infrared Imaging Spectrometer (MERTIS)
- Mercury Gamma-Ray and Neutron Spectrometer (MGNS)
- Mercury Imaging X-ray Spectrometer (MIXS)
- Mercury Orbiter Radio Science Experiment (MORE)
- Probing of Hermean Exosphere by Ultraviolet Spectroscopy (PHEBUS)
- Search for Exospheric Refilling and Emitted Natural Abundances (SERENA)
- Solar Intensity X-ray and particle Spectrometer (SIXS)
- Spectrometers and Imagers for MPO BepiColombo Integrated Observatory System (SIMBIO-SYS)

BELA

The main goals of BELA are to measure: the figure parameters of Mercury to establish accurate reference surfaces; the topographic variations relative to the reference figures and a geodetic network based on accurately measured positions of prominent topographic features; the tidal deformations of the surface and surface roughness and the local slopes and albedo variations, also in permanently shaded craters near the poles.

ISA

ISA will measure the non-gravitational disturbances/accelerations acting on the satellite trajectory. The main sources of these disturbances are the incoming solar radiation and Mercury's albedo.

MPO-MAG

MPO-MAG is a dual fluxgate magnetometer, which shall be used to measure DC and low frequency perturbations of the magnetic field. There is a very similar instrument onboard MMO (MGF). The major scientific objectives of MPO-MAG concern studies of the internal magnetic field of Mercury and its magnetosphere.

MERTIS

The scientific objective of MERTIS is to provide detailed information about the mineralogical composition of Mercury's surface layer by measuring the spectral emittance of different locations in the spectral range from 7-14µm.

MGNS

The main goals of MGNS are to determine the Hermean surface composition and hydrogen abundances with a resolution of ~400km by measuring characteristic neutron (up to 10MeV) and gamma-ray emissions (0.3 – 10MeV) from the uppermost (~1m) layer of the lithosphere of Mercury. Also, this instrument will be used to detect/determine near-polar depositions of volatiles within permanently shaded regions.

MIXS

The main goal of MIXS is to measure the X-ray fluorescence emission from the Hermean surface induced by solar X-ray irradiation as well as by the solar wind and other high energy particles interacting with the Mercury surface.

MORE

The MORE is a system level experiment, involving flight and ground-station hardware, as well as dedicated orbit determination software. The resulting science will mainly be based on range and range-rate observables derived from the radio link between the S/C and the Ground Segment.

PHEBUS

PHEBUS observes the UV emission from Mercury's exosphere to characterise its composition, structure and dynamics, and the surface-exosphere connections.

SERENA

SERENA is an instrument composed of four units of complementary neutral and ionised particle detectors; Two neutral particle analysers (Emitted Low Energy Neutral Atoms (ELENA) sensor and STart from a ROtating FIeld Mass SpectrOmeter (STROFIO)) and two ion spectrometers (Miniature Ion Precipitation Analyser (MIPA) and Planetary Ion Camera (PICAM)). This instrument deals with some of the main scientific objectives of the BepiColombo mission: composition, origin and dynamics of Mercury's exosphere and polar deposits; and structure and dynamics of Mercury's magnetosphere.

SIXS

The main goals of SIXS are the measurement of the solar X-ray corona, flares, solar energetic particles (electrons and protons), and (indirectly) the magnetosphere of Mercury, and for providing information on solar X-ray flux (1 – 20keV) and high-energy (p+:0.3 – 30MeV, e-: 30keV – 3MeV) particle emission states to other BepiColombo instruments.

SIMBIO-SYS

This instrument consists of three separate channels: High-Resolution Imaging Channel (HRIC), Stereo Channel/Camera (STC) and Visible and Infrared Hyper-spectral Imager (VIHI).
The scientific objectives of SIMBIO-SYS can be grouped under the following areas of study: Surface geology and stratigraphy; Surface composition, regolith properties and crustal differentiation; Impact crater population and degradation processes; Surface age; Volcanism; Crustal dynamics and lithosphere mechanical properties; surface exosphere interaction.

BepiColombo MPO Science Mission Overview

MPO orbit

The MPO orbit is in an inertially fixed low-eccentricity orbit (400 x 1500 km) of 2.3-hour period.

The next figure provide information about the MPO orbit from two different views:

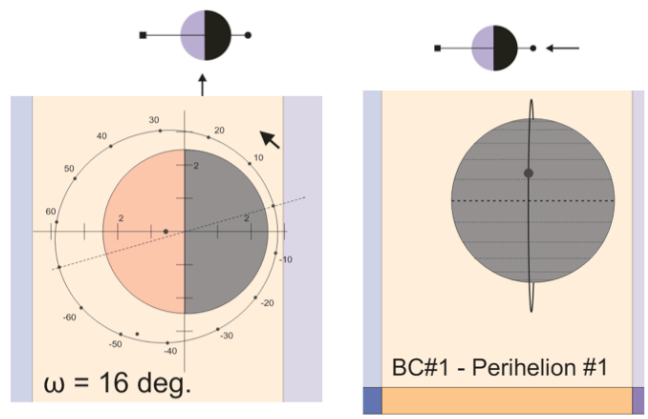


Figure 3: MPO orbit views

Mercury Surface Mapping

The mercury surface will be mapped after aphelion and perihelion seasons. The figure 4 shows the mercury surface mapping, where:

- More transparency means higher phase angles
- Most transparent (edges) = 45 deg. Phase angle
- Least transparent (middle) = 0 deg. Phase angle

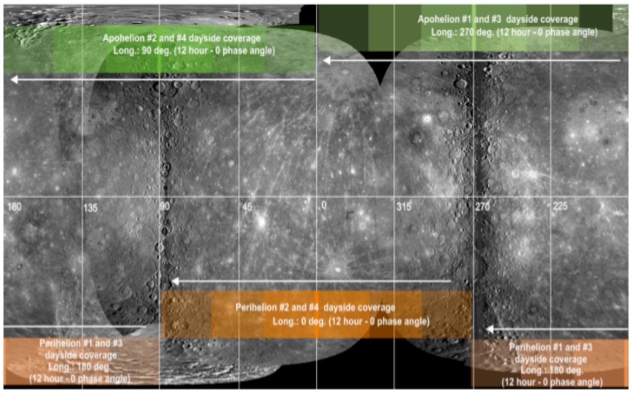


Figure 4: Mercury Surface mapping after perihelion and aphelion seasons

MPO Science Operational Timeline

The figure 5 depicts the MPO science operational timeline showing high data-rates during aphelion and low during other seasons (red line). The figure 5 also shows the Solid state mass memory on board (SSMM) fill state figures to illustrate how peaks up during the mission (orange line).

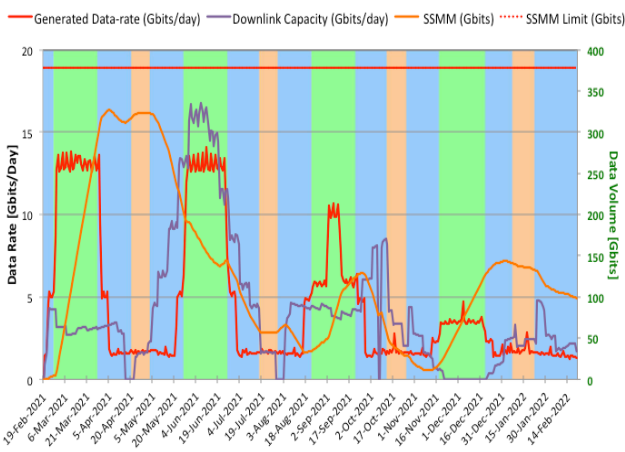


Figure 5:MPO science operational timeline and SSMM fill state

BepiColombo MPO Science operations planning drivers

In the following subsections of this paper, the drivers of the science operations planning are described. These drivers can be classified as follows:

- **Operational constraints**, including power constraints, data downlink constraints, pointing constraints, thermal constraints and wheel off-loading constraints.
- **Mission characteristics**, like mission duration, experiment characteristics, Solid state mass memory characteristics, science data downlink mechanisms, two RF- bands for downlink and MPO Orbit characteristics.
- **Science observations** performed by the scientific instruments on board required to fulfill the MPO Science Objectives.

Number of MPO Scientific Instrument Packages

As described above, the MPO has 11 instrument packages that want to operate in most cases at the same time. The science observations of each instrument will require in some cases different pointing attitude that will not be compatible. Additionally, interdependencies between instrument observations will require the executions of different observations at the same time or in sequential steps.

The large number of instruments and those aspects described above will drive the planning of their operations and how to resolve the conflicts.

Mission duration

The BepiColombo MPO has a relatively short nominal science mission of 12 months with the possibility of 12 months extension. The harsh environment of Mercury is expected to limit the operational lifetime of the spacecraft beyond 2 years.

Many observations depend on particular geometrical conditions, aphelion for example is the most advantageous period for high resolution imaging when periherm is on the dayside. Seasonal peaks in resource demands are also expected.

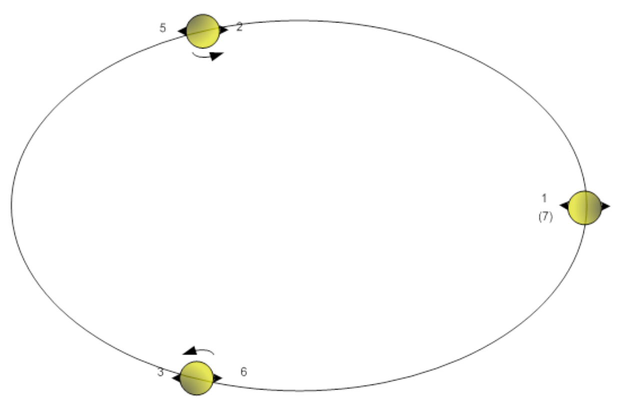


Figure 6: Hermean day lasts approximately twice the orbital period

The solar day on Mercury lasts about twice the Hermean orbital period of 88 Earth days. A reference point (figure 6) at midday at perihelion (1) will be on the night side after

Mercury completes one axial rotation and two-thirds of an orbit around the Sun (3). The same point will be at midnight at the following perihelion (4). It takes 2 orbits (~ 6 months) in total before the reference point sees midday again. Thus availability of feasible opportunities needs to be considered when scheduling operations and resolving planning conflicts, in order to avoid missing opportunities.

Power constraints

Due to high spacecraft temperatures at perihelion and aphelion and thermal limitations of the solar arrays, the power available for payload operations is expected to be limited during periods around perihelion and aphelion (see figure 7). The solar array is in continuous motion and even small changes in spacecraft attitude can result in a significant change in the available power.

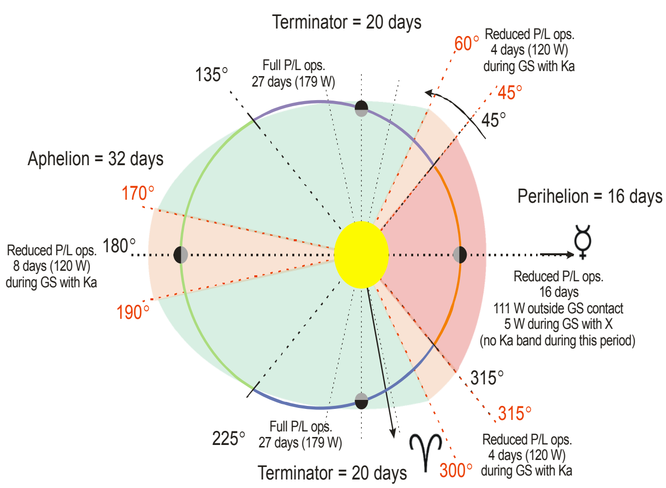


Figure 7: Power limitations in Mercury orbit

Additionally, the Ka-band transmitter, used for science data downlink via Ka-band will be required to switch off due to the lack of enough power (i.e. around perihelion), limiting the downlink of science data during this period, overloading the downlink of data in the periods where it can be switched on.

Thermal Constraints

Around perihelion season, interdependency thermal constraints between instruments have to be also considered, to avoid that switching one instrument overheats another one. Inter-experiment thermal issues at perihelion are currently under analysis.

Data downlink constraints

Data return is via X-band and Ka-band. The majority of science data is downlinked on the Ka-band. Although, the X-band is used primarily for housekeeping data, it may be used to return high-priority science data. The Ka-band downlink capacity and science data generation profile vary considerably over the mission duration. As a consequence, there may be periods when the solid state mass memory (SSMM) may not be fully emptied for several months.

The effects of resource consumption therefore propagate much further than that of a mission that has the ability to regularly empty its mass memory. An operation added to the plan in one slot may result in an overflow of the mass memory many months later.

For this reason, the planning will take into account the accumulation of resource usage over many months of operations.

Another effect of the data limitation is that the science data may stay onboard for several weeks (data downlink latency). The limited lifetime of the mission and the added constraint of latency of data return require a rapid and efficient re-planning process in order to correct or reschedule necessary science operations before the end of the mission.

Solid State Mass Memory on-board

The Solid State Mass Memory (SSMM) is a stand-alone unit that stores telemetry packets for later downlink via X- or Ka-band. The SSMM also routes tele-command (TC) packets from the On-Board Computer (OBC) to the relevant payload instrument and the returning telemetry reports from instruments to OBC.

The maximum storage area of the spacecraft SSMM is 384 Gb (note that in this paper 1 Gbit = 1024x1024 bit). This storage area is organised in packet stores (maximum 50 packet stores active in parallel) for telemetry data storage.

The telemetry science data packets are stored in the SSMM packet stores based on PIDs (Process ID). One PID can only be associated to one SSMM packet store at a time, but several PIDs can be routed to the same SSMM packet store. The instruments will generate low- and/or high-priority science data and store it in different packet stores based on the PIDs (see figure 8).

The science data packet stores are cyclic - when the packet store is full, old data is overwritten; therefore, they will be sized such that they are compatible with science operations plan prepared before Mercury arrival. Once at Mercury orbit, changes in operations and new plans (and science data generation and downlink) must be compatible with the predefined size of the science data packet stores, since a redefinition of the SSMM packet stores will mean the loss of the existing data stored in the memory from previous operations that has not been dumped yet.

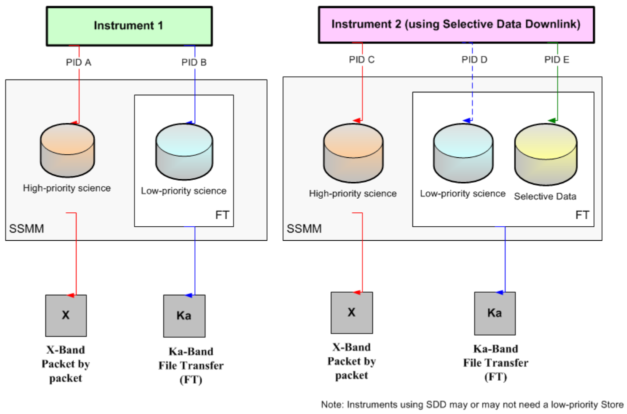


Figure 8: SSMM, packet stores & PIDs

2 RF-bands for science data downlink

BepiColombo MPO has, two different radio frequency (RF) bands are available for data return. The X-band channel is used to return near real-time data needed on ground to check the spacecraft status/health and operate the commanding protocols, as well as to return of stored engineering data and high-priority science data. In addition, a Ka-band downlink channel is available, used only to return low-priority science data.

For each packet store the routing will be configured such that the science data will be downloaded via X-band (packet by packet) or Ka-band (closed-loop file transfer).

- The X-band Downlink is done packet by packet and it is very predictable and flexible, since it is possible to define a downlink priority of the packet stores (maximum 16 priority levels allowed). The priority of engineering data for health/status/control is always given a higher priority than science data.
- The Ka-band is used for downlink of stored low-priority science data. It is affected by Earth weather conditions and therefore does not have the predictability of the X-band. Therefore a dedicated file transfer downlink function/protocol will be used, allowing an autonomous transmission between the MPO spacecraft SSMM and the ground segment. This file transfer mechanism is controlled by a file transfer session table, that defines up to 12 files (normally corresponding normally with the science packet stores of the payloads) and the data volume per file to be transferred. No priorities can be set for the File Transfer.

Latency is the time between the TM packet generation on-board and the TM reception on ground. The latency between the X-band and Ka-band downlink is very different by definition. Non-science data and high-priority science data are typically downlinked via X-band within one or two days after they have been generated (except for solar conjunction periods that could cause outages of up to 10 days). Low-priority science data (and selective data downlink data) are downlinked via Ka-band, and the latency for Ka-band stores will increase whenever the data generation rates are larger than the daily downlink rate on Ka-band. Therefore the data latency for Ka-band is closely linked to the science data generation profile and the seasonal bandwidth capabilities. Taking into account a science data generation profile (1 Gbit/day, increased to 10 Gbit/day during periods of 33 days around aphelion) and the data volume that can be downlinked, it can be concluded that the Ka-band latency could be up to 40 days.

When an observation is planned, it has to be considered also via which band the data will be downloaded (high priority or low priority), taking into account the large latency of the Ka-band. This will be performed by using a different PID when the generation of data occurs.

Science Data downlink mechanisms

The SSMM will be partitioned in data-stores for the experiment for the different types of data that will be produced, such as high priority, low priority, selective, etc. The data stored in the SSMM will be dumped via Ka and X band and this provides a challenge in SSMM management in order to be sure that there is always enough data in the SSMM packet stores in order to keep the X and the Ka band fully utilized.

During the mission (1) the data downlink will vary going from zero to 15 (TBC) Gbits per day and (2) the data-generation of the experiment will vary with the Seasons at Mercury. In general we see that the SSMM will need to be used to buffer data-generation peaks in periods of low downlink. However, this occurs only at specific periods in the mission. During the other periods not the full SSMM will be utilized, although currently the SGS is investigation ways to also keep utilizing these parts of the SSMM for other operational purposes, such as Selective Data Downlink, or storing specific observations in such data-stores

The following mechanism will be used for science data downlink and are described in the next subsections:

- Nominal Data Downlink
- Flexible data downlink
- Re-routing of Ka-band stores to X-band
- Selective data downlink

Nominal Data Downlink

Nominal Data Downlink refers to the downlink process that will be used by default in the science phase of the mission.

The instruments ISA, MERMAG, MGNS and SIXS will nominally send the science data to packet stores to be dumped via X-band.

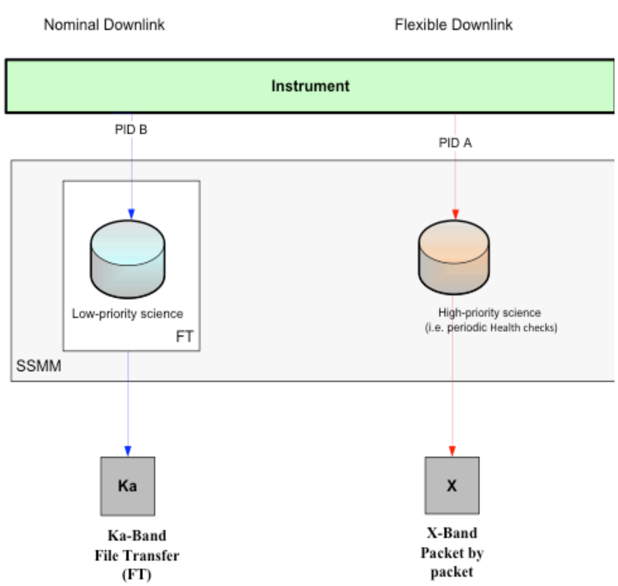
The instruments BELA, MERTIS, PHEBUS, SERENA, SIMBIO-SYS and MIXS will nominally send the data to packet stores to be dumped via Ka-band.

Flexible Data Downlink

Flexible data downlink allows the instrument team to actively decide to which packet store the data should be send, by changing the PID of the science data.

Flexible Downlink is only used for defining High Priority Data, since it will be send via X-band to ground within 1-2 days. This mechanism is particularly useful for health checks of the instrument operations that can be done periodically. This data sent via X-band will be analyzed using Quicklook tools on ground, such that next planned operations can be updated/modified base on this analysis.

An instrument that nominally sends its data to a low priority Ka-band store can temporarily send its high priority data to the X band store (using a different PID). After all high priority data has been sent the science data flow will be resumed again on the low priority band.



The experiments that will use the Flexible Downlink are the instruments that by default use the low priority Ka band stores for their data (BELA, MERTIS, MIXS, PHEBUS, SERENA and SIMBIO-SYS)

One of the advantages of the flexible downlink mechanism is that instruments that nominally send the science data via Ka-band can send science data (high-priority) via X-band (i.e. MERTIS, SIMBIO-SYS, PHEBUS).

The science data received via X-band can be used to make a quick scientific publication (i.e. interesting picture of Mercury) or to perform health checks of the science operations such data modifications can be incorporated quickly to the next planned instrument observations.

Re-routing of Ka-band stores to X-band

In general, X-band bandwidth will be fully utilized. But:

- The data-volume that can be downloaded via de X band changes over the mission, and the amount of generated high priority science data will not follow this one to one
- The amount of high priority science data to be generated is likely to be also seasonal (aphelion, perihelion, etc.) which does not align with the seasons with high data-volume downlink.

In conclusion, it is likely that at some points in the mission there is not enough science data to be dumped via X-band to fully utilize the X band bandwidth.

In order to ensure that the X band bandwidth is fully utilized, there is the option to re-route a Ka-band data store using the X-band. Instruments using the re-routing mechanism will be the large data-volume producers.

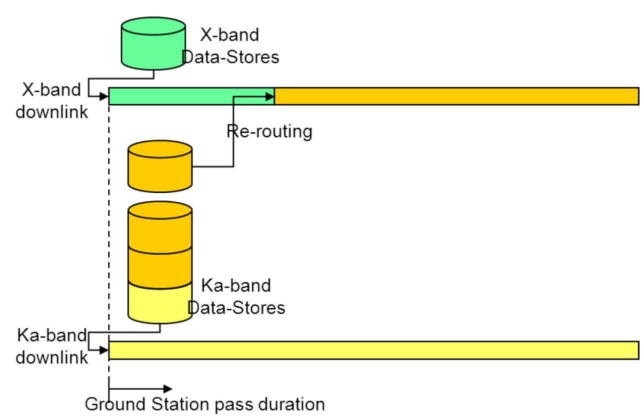


Figure 10: Ka-band data stores re-routing to X-band

Selective Data Downlink

Selective data downlink is a mechanism that allows the instruments the store of both low- and high-resolution data in the SSMM in parallel from the same observation.

The Selective Data Downlink approach would allow experiments to have the possibility to detect certain solar events or variations of the magnetic or plasma environment around Mercury, which cannot be predicted or planned for in a way that only interesting data will be selected for downlink.

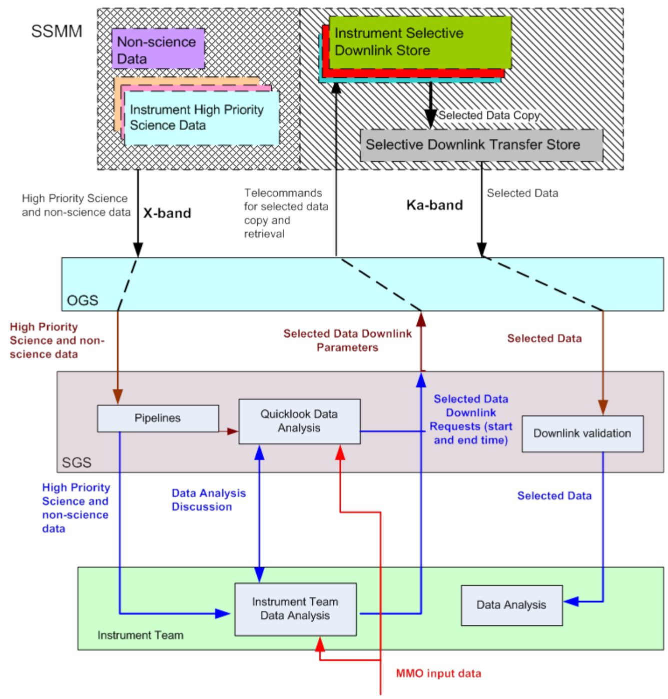


Figure 11: Selective Data Downlink Process Overview

This approach would make far better use of the limited available data downlink volume, returning only high-resolution science data for the interesting periods.

Low-resolution will be stored in a X-band packet store and high resolution in the so-called instrument Selective Data Downlink Store.

The low-resolution data will be downloaded via the X-band as high-priority science data and will include selective downlink support data used for quick-look data analysis on ground) and will arrive at Earth nominally 1 or 2 days after its generation.

This high-resolution science data will be stored in a dedicated instrument packet store that will not be automatically returned to the Earth.

If the high-priority science data or other MPO instruments data or MMO data indicate an interesting feature, a selection of the low-priority science data stored on-board in the instrument Selective Data Downlink Store can be copied to a separate packet store (Selective Data Downlink Transfer Store, common for all instruments using Selective Data Downlink) for subsequent downlink to ground via Ka-band using a closed-loop file transfer mechanism depicted in Figure 11.

Pointing constraints

The BepiColombo MPO mission is considered a nadir-pointing mission; such that the spacecraft has one axis aligned with the nadir direction for a continuous observation of the planet, and is designed to mainly point NADIR. Due to the harsh thermal environment off-pointing attitudes from nadir are severely constraint. Occasional non-NADIR pointing attitudes are foreseen for 2 reasons: (1) Experiment calibration (i.e. figure 12) and characterization purposes and (2) for scientific observations. Examples of non-nadir pointing types are: Cross-Track, Along-Track, and Inertial.

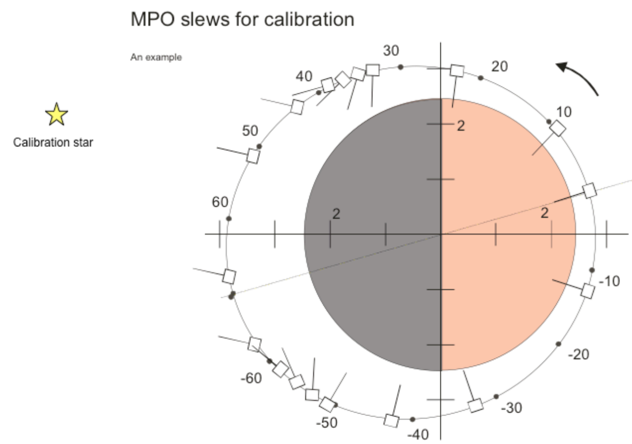


Figure 12: Example of MPO slews for calibration

Every time an observation requires off-pointing attitude from nadir, it has to be checked that the pointing attitude is compatible with the thermal and geometrical constraints and that is compatible with the rest of observations performed by other instruments. In case of incompatibility with the rest of observations planned for the same period, the SGS planning has to evaluate the priority of the observation, if it is possible reschedule it and also how many observations are penalized due to the off pointing.

MPO orbit characteristics

The MPO orbit is not maintained. Solar radiation pressure can cause significant torques on the highly unsymmetrical MPO spacecraft. Additionally, the MPO spacecraft will receive radiation from Mercury (both from Albedo and Infrared radiation). Regular wheel off-loadings (2 per day) need to be performed causing disturbances in the MPO orbit. Orbital perturbations may also be induced in the case of safe-mode switching.

The effect of the Mercury gravitational coefficients J2 / J3 on the MPO orbit should also be considered, since they will impact the orbit altitude evolution in the science mission.

The SGS planning process has to be able to address the issue of poor long-term orbit predictability and assume enough margins when scheduling science payload operations relative to events. These margins will be based on the maximum orbit prediction accuracy that can be achieved on ground.

Wheel-off loading constraints

The MPO reaction wheels have to be off-loaded two times every 24 hours and the science ground segment has to plan when the wheel off-loadings (WOLS) will take place.

However, in MPO science phase, z-axis is pointing nadir to Mercury and there are MPO spacecraft orbit positions (see figure 13) depending on Mercury true anomaly and the argument of periherm where thruster failure during reaction wheels offloading can cause illumination of payload danger zone (depending also on the maximum angular excursion caused by thruster failure in each mission phase). Eclipse phases are not considered and, in principle the offloading could be performed during the eclipse if the eclipse is long enough.

The above considerations have to be taken into account when scheduling the wheel off-loadings.

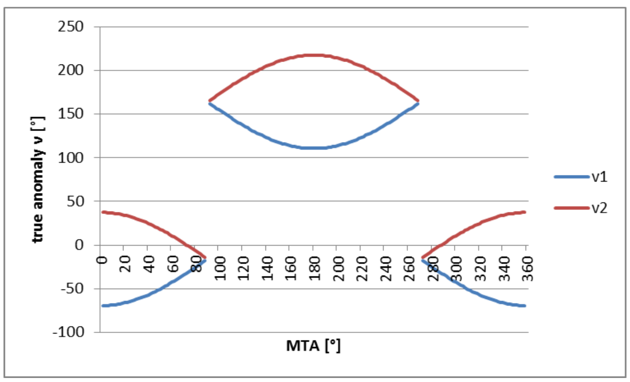


Figure 13: True anomalies when the WOLs should not be performed (BOL)

Conclusions

This paper has described the planning drivers for the BepiColombo MPO spacecraft. It has shown that many aspects have to be considered in order to efficiently plan the science payload operations.

Currently, MPO spacecraft Critical Design Review (CDR) process is still ongoing and there are some mission characteristics and constraints that have not been fully consolidated. Nevertheless, it is very likely that there will be some serious constraints (power, thermal) and in some cases with important interdependencies between them (pointing and power, power and data-rate, etc). These need to be followed up carefully and preliminary planning concepts will have to be able to deal with such constraints.

In conclusion, this paper demonstrates that BepiColombo MPO has some unique drivers the planning system will need to cope with. A specifically adapted science planning approach will be needed to ensure that all constraints and interdependencies are considered while balancing the available resources and maximizing the scientific return of the mission.

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