Science Operations Strategy for BepiColombo MPO Selective Data Downlink

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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).

Some of the instruments on the MPO either rely on certain solar events or are interested in variations of the magnetic or plasma environment around Mercury, which cannot be predicted or planned for. Traditionally, these instruments would measure continuously, downlink all their data back to Earth and the Scientists would identify the interesting periods.

The Selective Data Downlink approach would allow experiments to have the possibility to detect these variations in a way that only interesting data will be selected for downlink. This approach would make far better use of the limited available data downlink volume, returning only high-resolution science data for the interesting periods.

To achieve this, the instruments would have to generate simultaneously low-resolution and high-resolution data of the same observation that will be stored in the on-board SSMM (Solid State Mass Memory). This high-resolution science data will be stored in a dedicated instrument packet store that will not be automatically returned to the Earth. Low-resolution science data, which will include selective downlink support data from the observation, used for quick-look data analysis on ground, will be downlinked, typically via the X-band, arriving at Earth nominally 1 or 2 days after its generation. If the low-resolution science data, data from other MPO instruments, or even MMO data indicate an interesting feature, a selection of the high-resolution data stored on-board can be copied to a separate packet store for subsequent downlink via Ka-band. This concept would guarantee that only scientifically useful data will be downlinked.

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I. 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).

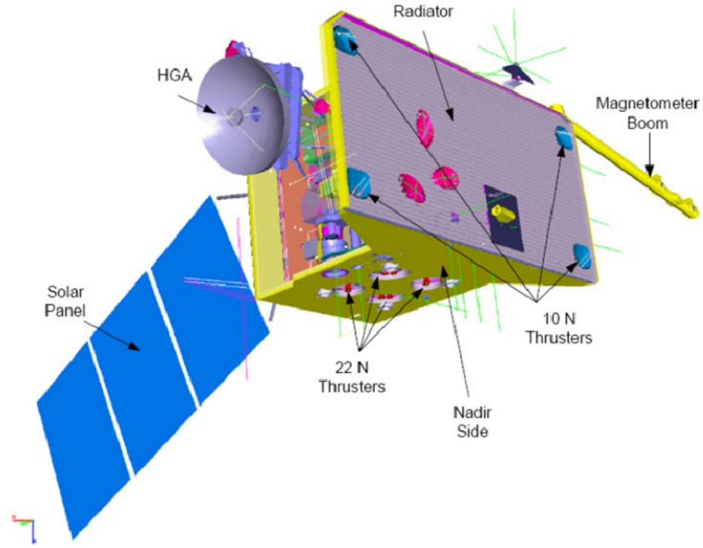

Figure 1. MPO Spacecraft Configuration. *The MPO is a three-axis-stabilized and nadir-pointing spacecraft.*

The MPO orbit (See 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. 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.

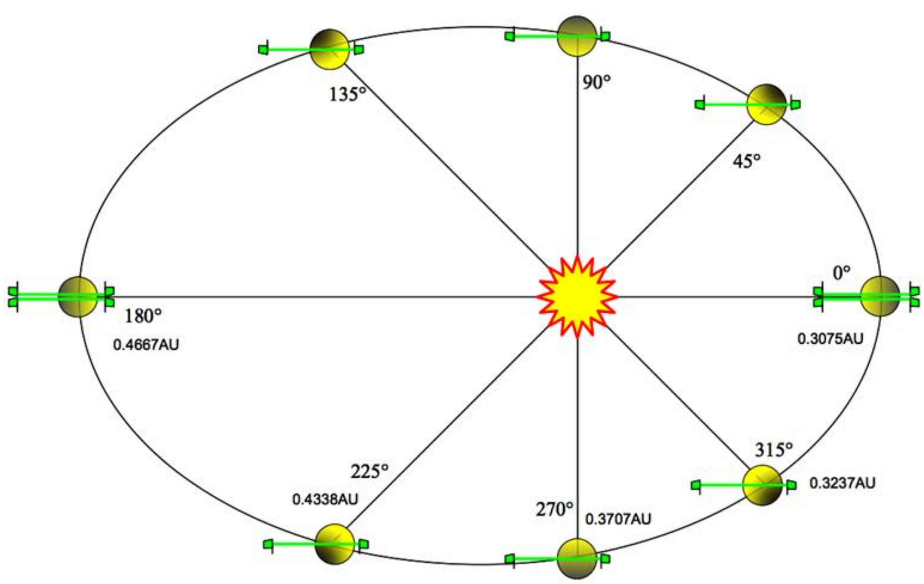

Figure 2. Inertially fixed MPO orbit. *The best conditions for high-resolution imaging are at aphelion when periherm is on the daylight side of Mercury.*

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.

II. BepiColombo MPO Payload Overview

The MPO payload comprises 11 instrument packages. The instruments that have indicated interest in the Selective Data Downlink approach are shown in Table 1. The justification for using Selective Data Downlink is provided in the following sections with the instrument descriptions.

Instrument	**Selective Data Downlink**
BepiColombo Laser Altimeter (BELA):	
Italian Spring Accelerometer (ISA):	
Mercury Magnetometer (MERMAG)	✓
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)	

Table 1: Instruments interested in Selective Data Downlink. *A number of instruments have already indicated an interest in the Selective Data Downlink approach.*

A. 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.

B. ISA

ISA will measure the non-gravitational disturbances/accelerations acting on the satellite trajectory. These will be removed in post-processing from the movement of the satellite enabling the MPO to be regarded as a drag-free S/C. The main sources of these disturbances are the incoming solar radiation and Mercury’s albedo.

C. MERMAG

MERMAG (MPO-MAG) is a dual fluxgate magnetometer, which shall be used to measure DC and low frequency perturbations of the magnetic field. It therefore consists of two sensors, an inboard and an outboard sensor, mounted on a 2.9 m long boom. The two separate sensors are necessary to determine the magnetic interference (AC and DC) from the spacecraft. There is a very similar instrument onboard MMO (MGF).

The major scientific objectives of MERMAG concern studies of the internal magnetic field of Mercury and its magnetosphere. For the former objective, higher resolution measurements could be taken whilst closer to the planet, and lower resolution data recorded at higher altitudes. However, such a rigid operations plan would not be helpful for the latter objective. The position of the magnetosphere changes with solar activity and is therefore unpredictable on a fine scale. The data could therefore show featureless or expected content in inactive or well-understood areas of the magnetosphere. On the other hand, it could show very interesting observations of boundary crossings, for example, for which high-resolution data would be very valuable. Data covering the science phase (nominal mission, one Earth year) at the highest resolution would be too large to downlink within the available resources. This is why use of the Selective Data Downlink approach would be practically essential for efficient use of MERMAG.

In addition, the high-priority/support data (low-resolution data) for the MERMAG instrument could also prove to be very useful for other instruments that observe the environment around Mercury both as a general monitor but also to assist with selection of their own selective data downlink store.

D. 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.

MERTIS has four main science goals: Study of Mercury's surface composition; Identification of rock-forming minerals; Global mapping of the surface mineralogy; Study of surface temperature and thermal inertia.

E. 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.

MGNS intents to use the Selective Data downlink approach, since this mechanism could be used to return high-resolution data during gamma-ray flares that are rare and very transient in nature and unpredictable. The MGNS mechanism for Selective Data Downlink will be very similar to MERMAG.

F. 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. Data from the instrument consists of X-ray spectra in the energy range of 0.5 – 7.5 keV and will be used to determine the elemental composition of the topmost layer of the lithosphere of Mercury

G. MORE

MORE is a system level experiment, involving flight and ground-station hardware, as well as dedicated orbit determination software. The on-board Ka-band transponder (KaT) is the key instrument of the radio science experiment. 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.

H. PHEBUS

PHEBUS observes the UV emission from Mercury's exosphere to characterise its composition, structure and dynamics, and the surface-exosphere connections. PHEBUS will address the following main scientific objectives relative to Mercury's exosphere: determination of the composition and vertical structure of the exosphere including previously undetected species; characterization of the exospheric dynamics: day to night circulation, active to inactive regional transport; study of surface release processes; identification and characterization of the sources of exospheric constituents; detection and characterization of the ionosphere and its relation with the neutral atmosphere; spatial and temporal monitoring of exosphere/magnetosphere exchange and transport processes; study and quantification of escape, global scale source/sink balance and geochemical cycles - synergistically enhanced by measurements from other experiments of BepiColombo (MSASI, MPPE, and PWI on MMO; SIXS, SERENA on MPO).

PHEBUS detectors produce images that must be greatly reduced before being downlinked. This is achieved by using different methods including binning, windowing and compression, all of which must be planned in advance. As the environmental conditions cannot be predicted, neither can the results - the data may have been compressed in an inappropriate way, missing the most interesting features. The use of Selective Data Downlink would allow the whole image to be saved and for interesting data to stay available, rather than automatically lost.

I. 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)). It can provide information on the whole surface-exosphere-magnetosphere system and the processes involved, plus the interactions between energetic particles, the solar wind, micrometeorites and the interplanetary medium. 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.

J. 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. The former is especially relevant to the MIXS instrument which relies on SIXS data for science data calibration.

SIXS will make use of the Selective Data Downlink for the particle spectrometer measurements, such that high-resolution spectral data obtained in Burst mode will be sent through the selective downlink, while low resolution data will still be sent through X-Band. This enables SIXS to downlink high-resolution spectral data from the time periods when the low-resolution data shows high counting rates and/or rapid flux variations.

K. 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

III. BepiColombo MPO SSMM storage and Downlink Overview

A. MPO SSMM

The Solid State Mass Memory (SSMM) is a stand-alone unit in the BepiColombo MPO Data Management System (DMS). The SSMM interfaces with the BepiColombo payload instruments and the On-Board Computer (OBC) via main and redundant SpaceWire links. The SSMM stores telemetry packets according to the CCSDS 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. There are two types of packet stores that can be created in the SSMM: cyclic packet stores - when the packet store is full, old data is overwritten; and non-cyclic packet store - when the packet store is full the data storage is interrupted (that means new data can not be stored and is lost) and an action from ground is necessary in order to free space by deleting old data via tele-command.

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. Figure 3 shows the different packet stores and routing of science data for instruments using and not using Selective Data downlink.

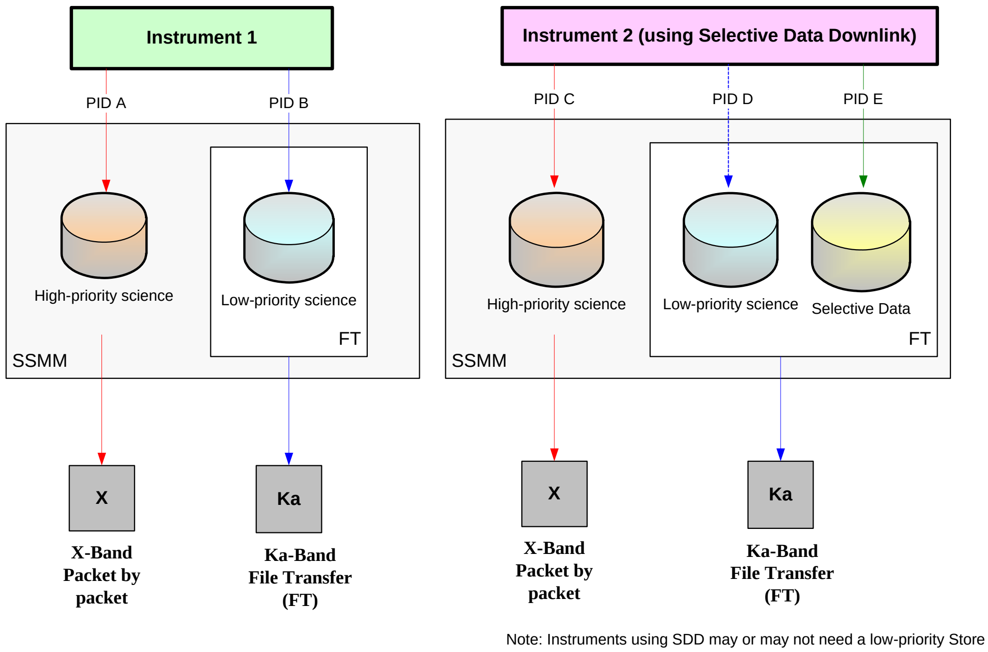

Figure 3. Packet stores downlink. *Depending on the packet store, the science data will be downloaded via X-band (packet by packet) or Ka-band (closed-loop file transfer).*

Basically, the spacecraft has three types of data stored in the SSMM, which have different PIDs assigned:

- **High-Priority Science data:** used for calibration, to test instrument settings or general high-priority science. It will be returned via X-band.
- **Low-Priority Science data**: used for the downlink of normal science data and will be returned via Ka-band.
- **Non-Science data**: used for the downlink of engineering and other non-science data from instruments and subsystems and will be returned via X-band.

Instruments using Selective Data Downlink would have to generate two sets of data in parallel from the same observation: Selective Data Downlink Support data as part of the High-Priority Science data, downlinked via X-band and data for Selective Data Downlink that will be treated as Low-Priority Science data and copied to a dedicated transfer store to be downlinked via Ka-band. This is explained in detail in the following sections. Figure 4 shows the different MPO SSMM data types and packet stores.

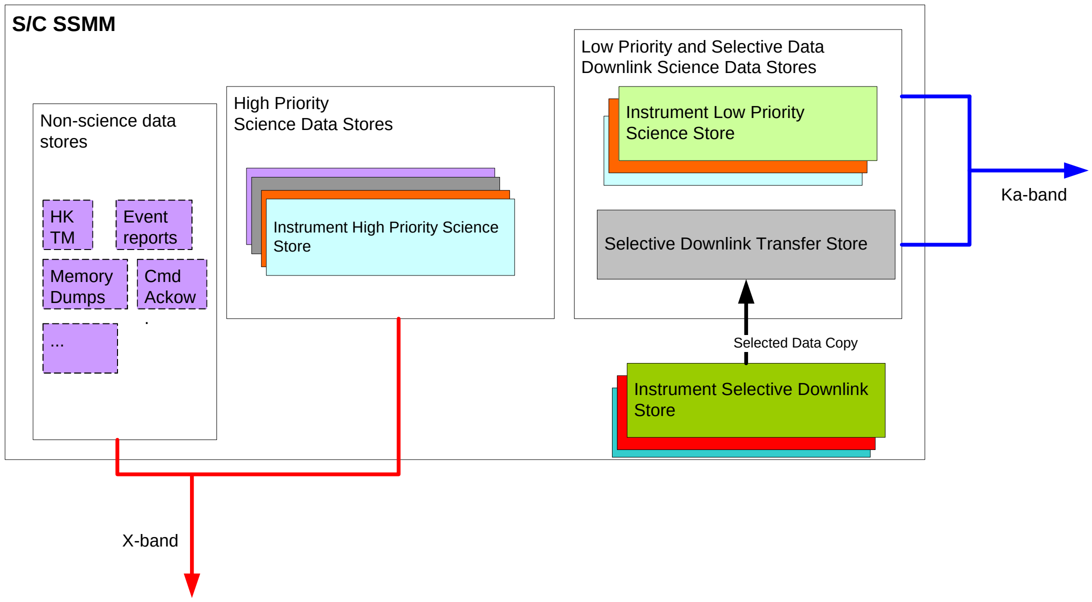

Figure 4. The MPO SSMM data types and packet stores. *The SSMM will store in different packet stores non-science data, high priority, low-priority and selective data downlink data in different packet stores.*

B. MPO Downlink Overview

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.

IV. Selective Data Downlink Process Description

A. Selective Data Downlink Process Overview

Selective Data Downlink is an approach which would allow instruments returning high-resolution science data to make better use of the limited available downlink data volume. To achieve this, the MPO scientific payload would have to generate and store low- and high-priority science data of the same observation. The high-priority science data (which includes Selective Data Downlink Support data used for quick-look data analysis on ground), will be downlinked via the X-band.

If the analysis of this high-priority science data and/or other MPO instruments data and MMO data indicate an interesting feature, a selection of the low-priority science data stored on-board in the instrument Selective Data Downlink Store (one for each instrument using the Selective Data Downlink) 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. The Instrument Selective Downlink Stores are cyclic, which means that the science data is stored for a limited time. For this reason, the Instrument Selective Downlink Store will be sized appropriately for each instrument to allow enough time for analysis, selection and copying to the Selected Data store.

In exceptional cases in which the selected data could not be downlinked to ground in the expected time, and the relevant instrument teams detects that interesting data is still available in the Instrument Selective Data Downlink Store with threat of being overwritten, they might decide to stop the storage of science data in the Instrument Selective Data Downlink Store, such that the currently stored data is not overwritten. This will be commanded from ground.

The copy of data from the Instrument Selective Data Downlink Store to the common Selective Data Downlink Transfer Store is also commanded from ground.

In order to implement Selective Data Downlink, spare memory space in the SSMM needs to be reserved for the Selective Data Downlink packet stores. This was investigated by the SGS and the SWT with the conclusion that with the expected data generation profile and the resulting SSMM utilization over the mission, the SSMM would be large enough to accommodate these packet stores.

B. Selective Data Downlink Process Detailed Description

In order to quickly identify potentially interesting data contained in the Instrument Selective Downlink Store, tools for the analysis of raw data and data processing pipelines will be implemented within the SGS and the MPO instrument teams. This will allow them to quickly detect interesting events, such as flares or magnetospheric boundaries.

High-priority data (i.e. quickly available via X-band from all MPO instruments) plus MMO input data will be analysed with the support of quicklook systems and if a relevant event is detected, a selection of data from the Instrument Selective Downlink Store will be copied to the common Selective Data Downlink Transfer Store for Ka-band downlink to ground. The selection of data will be based on a time period, such that the time search on the Selective Data Downlink store finishes on the science packet with the specific time range or the last science packet with time less than the specific time range.

The selected data copy requests will be prepared on ground using TC sequences that will contain as parameters the ID of the Instruments Selective Data Downlink Store to be copied from, the ID of the separate Selective Data Downlink transfer store that the data is to be copied to and the start and end reference times. The intended return of selective high-resolution science data is in the order of 10% of all stored high resolution science data. The detailed description is shown in Figure 5.

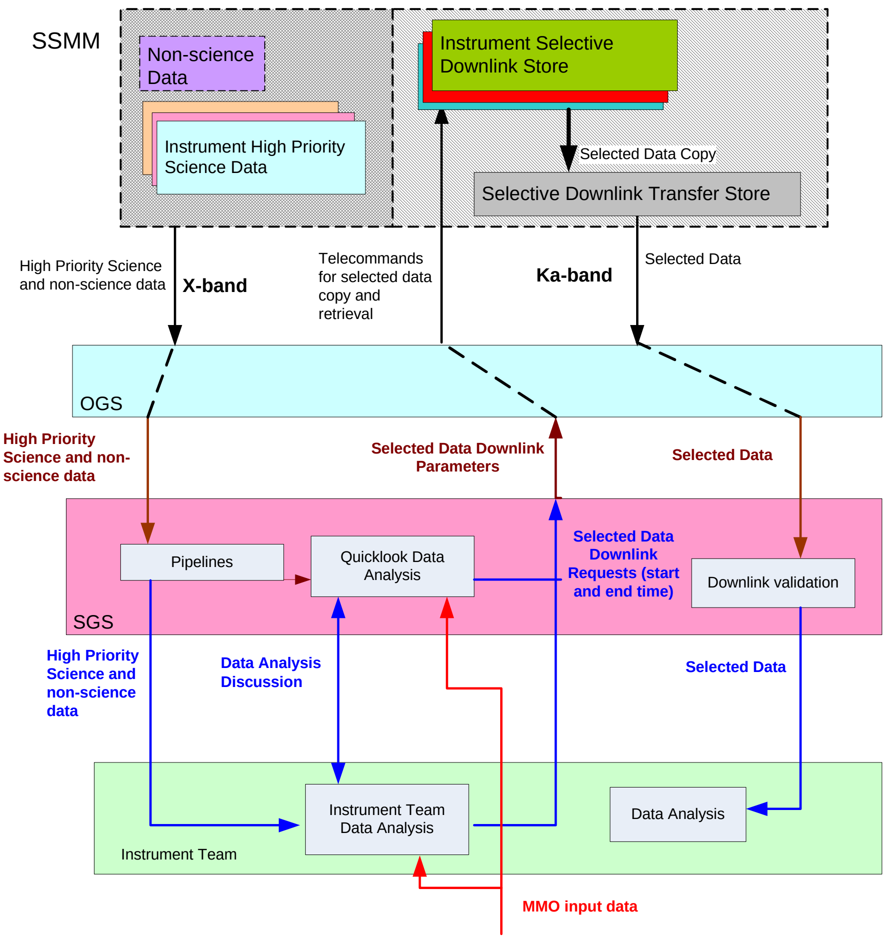

Figure 5. Selective Data Downlink Detailed Process. *High-priority data available quickly via X-band from all instruments will be analyzed with the support of the quicklook system and a selection of data from the Instrument Selective Downlink Store will be copied to the common Selective Data Downlink Transfer Store for Ka-band downlink to ground.*

C. Selective Data Downlink Process Timeline

The Selective Data Downlink Process Timeline works as follows, and as shown in Figure 6:

- **Step 1:** Instrument Selective Downlink Support data will be returned to ground via the X-band within an interval of 24-48 hours since its generation (week 1).
- **Step 2 & 3:** The Quicklook analysis system will provide the elements allowing the relevant instrument team together with the SGS to analyse the Instrument Selective Data Downlink Support data (1 week of science data) and to select the low-priority science data from the Selective Data Downlink Store to be retrieved to ground. Science data from other instruments and MMO data (if available) will be considered in the analysis as well. This will be around one week after the generation of the data (week 2).
- **Step 4:** The SGS will incorporate the selection requests into the next OGS short term plan inputs which have to be sent to the OGS one week before the OGS uplink them (week 3).
- **Step 5:** The OGS will send the necessary tele-commands to copy the selected data from the Instrument Selective Data downlink store to the common Selected Data Downlink transfer store (week 3).
- **Step 6 & 7:** The selected data will be copied to the Selective Selected Data Downlink transfer store and queued for downlink to ground, via Ka-band (week 3). Once on ground, it will be validated and processed by the SGS and transferred it to the appropriate instrument team for further analysis (week 4).

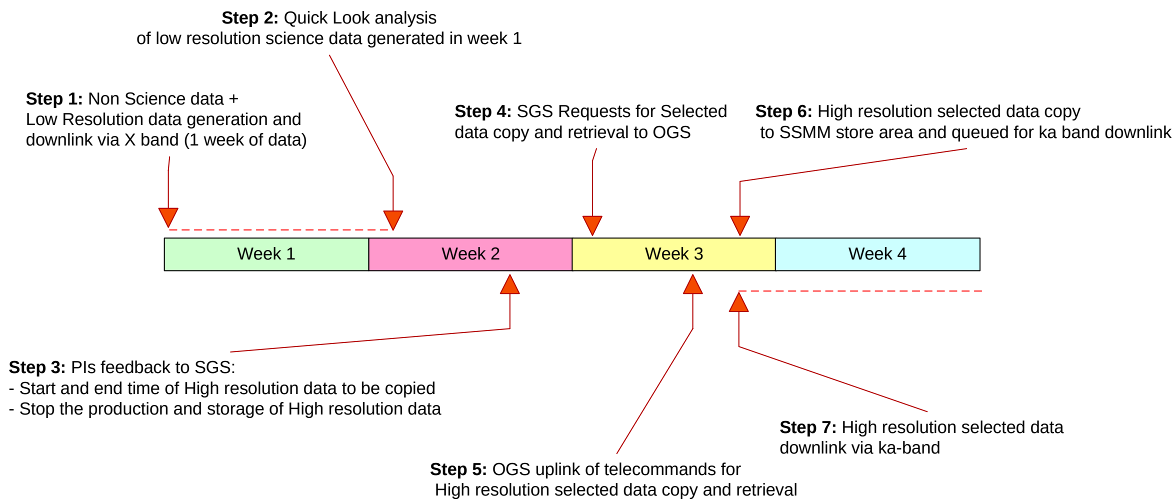

Figure 6. Selective Data Downlink Timeline. *The SGS will incorporate the copy selection requests into the next OGS short term plan inputs one week before the OGS uplink them.*

V. Conclusions

With the use of Selective Data Downlink the quality of science return for the BepiColombo mission can be improved as it would allow the downlink of high-resolution science data selectively for periods of the highest science priority. Some teams having instruments on-board MPO have indicated their interest in using this Selective Data Downlink approach and have implemented the functionality needed to support it (simultaneous generation of both high-resolution and low-resolution science data using different Process IDs).

In order to implement Selective Data Downlink, spare memory space in the SSMM needs to be reserved for the Selective Data Downlink packet stores. After SGS and SWT analysis, it has been concluded that the SSMM would be sufficient to accommodate these packet stores.

Currently the SSMM and instruments are being validated in the MPO spacecraft test campaign, including the functionalities needed for the Selective Data Downlink. When these functionalities have been validated, the ESA project will approve the Selective Data Downlink as a baseline for the mission, such that the SWT will be able to include the Selective Data Downlink operations into their baseline payload operations plan.

As mentioned before, the Selective Data Downlink approach would improve the quality of the Science Data Return and guarantee that only useful science data will be downlinked.

Appendix A
Acronym List

AC	Alternating Current
APID	Application Process ID
BELA	BepiColombo Laser Altimeter
CCSDS	Consultative Committee for Space Data Systems
DC	Direct Current
DMS	Data Management System
ELENA	Emitted Low Energy Neutral Atoms
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESOC	European Space Operations Centre
ESTEC	European Space
HRIC	High spatial Resolution Imaging Channel

ID	Identifier
ISA	Italian Spring Accelerometer
ISAS	Institute of Space and Astronautical Science
JAXA	Japan Aerospace Exploration Agency
MDM	Mercury Dust Monitor
MAG	Magnetometer
MERMAG	Mercury Magnetometer
MERTIS	Mercury Thermal Infrared Imaging Spectrometer
MGF	Mercury Magnetometer onboard MMO
MGNS	Mercury Gamma-Ray and Neutron Spectrometer
MIPA	Miniature Ion Precipitation Analyzer
MIXS	Mercury Imaging X-ray Spectrometer
MMO	Mercury Magnetospheric Orbiter
MORE	Mercury Orbiter Radio Science Experiment
MPO	Mercury Planetary Orbiter
MPPE	Mercury Plasma Particle Experiment
MSASI	Mercury Sodium Atmospheric Spectral Imager
N/A	Not Applicable
OBC	On-Board Computer
OGS	Operational Ground Segment
PHEBUS	Probing of Hermean Exosphere by Ultraviolet Spectroscopy
PICAM	Planetary Ion Camera
PID	Process ID
PWI	Plasma Wave Instrument
RF	Radio Frequency
SDD	Selective Data Downlink
SERENA	Search for Exospheric Refilling and Emitted Natural Abundances
SGS	Science Ground Segment
SIMBIO-SYS	Spectrometers and Imagers for MPO BepiColombo Integrated Observatory System
SIXS	Solar Intensity X-ray and particle Spectrometer
SSMM	Solid State Mass Memory
SSOC	ISAS/JAXA Sagamihara Space Operation Centre
STC	Stereo Channel
STROFIO	Start from a Rotating Field Mass Spectrometer
SWT	MPO Science Working Team
TBC	To be Completed
TC	Tele-command
UV	UltraViolet
VIHI	Visible Infrared Hyperspectral Imager channel

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