18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025.

SpaceOps-2025, ID # 231

Spacelink operations planning and engineering analyses with ESA link budget tool automation

Martin Unal[a], Fabian Burger[a], Maria Montagna[a]*, Stefano Finocchiaro[b], Alessio Coppotelli[c], Stefano Milani[b], Andrea Nardocci[b], Guillermo Lorenzo[a], Ignacio Clerigo[a], Marco Lanucara[a]

[a] *European Space Operations Centre/ESA, Darmstadt, Germany,* martin.unal@esa.int, fabian.burger@esa.int, maria.montagna@esa.int, guillermo.lorenzo@esa.int, ignacio.clerigo@esa.int, marco.lanucara@esa.int
[b] *Arpsoft SRL, Via della Stazione di San Pietro 65, Rome, Italy,* finocchiaro@arpsoft.it, milani@arpsoft.it, nardocci@arpsoft.it
[c] *LSE Space @ European Space Operations Centre/ESA, Darmstadt, Germany,* alessio.coppotelli@ext.esa.int
* Corresponding Author

Abstract

The ESA link budget tool is the reference link budget application for the agency engineering and operations teams, since its launch as ESA-wide online tool in 2021. The tool is based on a core software application running on a centralized virtual environment in charge of the link budget calculations, which interacts with several databases for space link data exchange. Apart from a web-based graphical user interface, the tool offers REpresentational State Transfer Application Programming Interfaces (REST APIs) for machine-to-machine interaction, to enable automated analysis execution and exchange of input and output files or analysis results. The current work highlights the automated use of the ESA link budget tool in the context of routine mission operations for BepiColombo, the ESA/JAXA cornerstone mission to Mercury, pioneer for advanced operations at ESA. The described approach is in use for BepiColombo operations since November 2024. The motivation of the work and the expected performance improvements for the science phase are also discussed.

Keywords: link budget, BepiColombo, spacelink operations, Ka-band, automation, APIs.

Acronyms/Abbreviations

API	Application Programming Interface	LBT	ESA Link Budget Tool
AOS	Acquisition Of Signal	LOS	Loss Of Signal
AU	Astronomical Unit	LTP	Long Term Planning
DB	Database	MCS	Mission Control System
DBT	Distance-bit-rate lookup tables	MMO	Mercury Magnetospheric Orbiter
DOY	Day Of the Year	MPO	Mercury Planetary Orbiter
EGOS	ESA Ground Operation System	MPS	Mission Planning System
FD	Flight Dynamics	MTM	Mercury Transfer Module
ESA	European Space Agency	MTP	Medium Term Planning
ESOC	European Space Operations Centre	PM	Phase Modulation
ESTRACK	ESA Tracking Network	PN	Pseudo Noise
HGA	High Gain Antenna	PUS	Packet Utilization Standard
I	Interleave depth	R-S	Reed-Solomon code
ITU	International Telecommunication Union	S/C	Spacecraft
LDPC	Low Density Parity Check code	SP-L	Split phase modulation
GMSK	Gaussian Minimum Shift Keying modulation	STP	Short Term Planning
G/S	Ground Station antenna	TM	Telemetry
G/T	Antenna Gain over system noise Temperature	TT&C	Telemetry, Tracking, and Command
JAXA	Japan Aerospace Exploration Agency		

1. Introduction

Satellite missions devoted to Science and Exploration in the Solar System undertook a critical transition during the last decades for what concerns spacelink communications and tracking, evolving from a context of moderate data rates/volume and relatively simple satellite tracking solutions, to scenarios with large downloads of science data and sophisticate tracking solutions to fulfil increasingly demanding tracking requirements, beyond the consolidated needs of satellite navigation. Furthermore, the increasing number of missions around Earth, Moon, Mars and other planets (e.g. Venus, Jupiter and beyond) emphasized the need of managing the radio frequency spectrum, leading to the use of bandwidth efficient modulations and new (uncongested) frequency allocations.

Such evolution of the space communications link and associated operations concept is best illustrated by comparing three interplanetary Science missions of the European Space Agency (ESA): Mars Express [1] and BepiColombo [2], launched on 2nd June 2003 and 20th October 2018 respectively and part of the ESA's Horizon 2000 Plus programme, and the coming EnVision [3], part of ESA's Cosmic Vision programme and to be launched in December 2031. The comparison is summarized in Table 1 below.

Table ***1***: Comparison of communications and tracking solutions for three deep-space ESA Science missions spanning through three decades.

Parameter	**Mars Express**	**BepiColombo**	**EnVision**
Mission scientific goal	Study of the Martian atmosphere and climate, of the Mars' structure, mineralogy and geology, and search for traces of water.	Global characterization of Mercury through the investigation of its interior, surface, exosphere, and magnetosphere.	Holistic view of planet Venus from its inner core to its upper atmosphere, studying the planet's history, activity and climate.
Maximum information rate	229 kbps	696 kbps	95 Mbps (goal 145 Mbps)
Frequency bands	• S/X-Band uplink • S/X-Band downlink	• X/Ka-Band uplink (*) • X/Ka-Band downlink	• X -Band uplink • X/Ka-Band downlink
High rate downlink modulation	• Residual carrier (SP-L/PM) Not bandwidth efficient	• Residual carrier (SP-L/PM) Not bandwidth efficient	• Suppressed carrier (GMSK BT = 0.5) Bandwidth efficient
Channel coding	• Concatenated: R-S 255,223 with I = 5, and convolutional rate 1/2, k = 7	• Concatenated: R-S 255,223 with I = 5, and convolutional rate 1/2, k = 7 • Turbo codes with coding rates 1/2, 1/4	• Turbo codes with coding rates 1/2, 1/4, 1/6 • LDPC codes with coding rates 1/2, 2/3, 4/5
Ranging	• ESA code ranging on transparent channel	• PN regenerative ranging	• PN regenerative ranging • GMSK+PN

(*) Ka-band uplink used for radio-science experiments only, not for commanding.

From the above summary the following trends emerge:

1. Access to progressively larger frequency segments around higher frequencies.
2. Increasingly efficient exploitation of the channel bandwidth, with data rates approaching the Shannon channel capacity.
3. Growing complexity of the communications and tracking operations at higher frequencies, with larger impact from pointing performance and atmospheric conditions.
4. Increased complexity of the receiver synchronization and detection algorithms, linked to the need of operating at very low signal-to-noise ratio and with heavily filtered signal waveforms.

The increase of operational complexity, even though justified by the need of maximizing the system performance (date rate, data volume), ultimately leads to a multiplicity of spacelink configurations, responding to diverse scenarios of distance, reference or predicted atmospheric effects at different elevations, bandwidth limitations, Doppler dynamics etc. Such multiplicity has to be managed by appropriate spacelink settings of on-board and ground systems, in an attempt to best exploit the communications channel during every pass as well as maintain adequate robustness of the TT&C operations.

In such a context it becomes essential to incorporate a link budget calculation tool into the day-to-day operations, able to provide optimized spacelink configurations based on the planned mission operations [4]. The above illustrated transition of the spacelink communication solutions therefore corresponds to a paradigm shift in the use of link budget calculation, from "mission requirements verification" during the mission preparation phase, to "optimized channel exploitation" during the mission operation phase. As a direct consequence of the above, the link budget calculations have to be rendered by an operational system, able to interface during routine operations to ground segment systems (ground stations, mission planning, etc), and to be operated in an automated manner, with adequate level of availability and reliability.

The present paper describes the transformation of the ESA link budget tool (LBT) in such an automated operational system, with the specific pilot use case of the BepiColombo mission quoted in Table 1, however with the clear goal of achieving a multi-mission capability.

The paper is organized as follows: analysis modes and related required inputs for the use of the ESA link budget tool in the proposed workflow are illustrated in section 2; sections 3 details the workflow implementation starting from the Ka-band BepiColombo link; the advantages of the new methodologies are discussed in section 4, where the application to the BepiColombo X-band link is also addressed; concluding remarks are reported in section 5.

2. Link budget analysis modes and required inputs

Link budget calculations in the ESA link budget tool are based on the classical link design tables used to predict spacelink performance in satellite communications [5], which represent a point-to-point link between spacecraft and ground station antenna, at a given time (static) and at a fixed distance.

The basic block of the link design table can be used for optimization analyses considering several spacelink scenarios, changing with time, with different spacecraft and ground station antenna performances to be expected under those scenarios, and with varying atmospheric and celestial bodies conditions affecting radiofrequency wave propagation at the selected frequency. Within LBT, these analyses are possible thanks to a versatile software architecture and model parameterization of spacecraft, ground station, atmosphere and celestial bodies [4]. The analysis mode is called "Telemetry (TM) rate optimization mode" and determines the optimum downlink data rate and encoding scheme for each of the link scenarios provided as inputs. If required, also the time window to actually transmit the downlink data during the ground visibility pass can be optimized: in fact, a higher downlink rate with downlink transmission start at a higher elevation angle to avoid longer paths through the atmosphere could compensate the shorter transmission time and provide larger data return.

The TM rate optimization mode is the analysis mode selected by BepiColombo for routine operations with LBT. The definition of the analysis scenarios requires:

- Spacecraft orbital information, to calculate the link distance and the ground station elevation profile during the visibility pass, provided as input file by the flight dynamics team, called input event file.
- Line of sight interruptions, if any, due to orbital characteristics or due to spacecraft configuration, included in the input event file by the mission team.
- List of downlink data rates and related coding schemes available on the spacecraft, stored in the LBT mission database.
- Atmospheric statistics of atmospheric attenuation and sky brightness temperature, for the ground station antenna sites, stored as cumulative distribution functions in the LBT atmospheric database. The tool supports statistics aggregated on a year basis [6], or separated on single months, or even representative of a specific time interval, e.g. 24 hours of a specific day, computed on the basis of weather forecast analysis [7].
- Ground station parameters for the calculation of the receiving antenna figure of merit, i.e. antenna gain over system noise temperature (G/T), as function of the elevation angle and sky brightness temperature.
- Spacecraft and ground station general configuration, e.g. spacecraft antenna in use, ground station receiving chain, …, defined by the user in the link budget analysis configuration form, and stored as configuration file.

Two types of TM rate optimization mode analysis are available with LBT:

a. Link availability mode: the selected downlink data transmission configuration guarantees the target availability, e.g. 90%, at the worst conditions of the link, i.e. at the minimum elevation angle during the transmission.
b. Data return optimization mode: the selected downlink data transmission configuration maximizes the received data during the ground pass, in average, considering the different conditions expected during the transmission. The average is computed as statistical expected value with respect to the probability density function of atmospheric attenuation and sky brightness temperature [8]. It is to be noted that since the maximization is

performed in an average sense, the link conditions are not guaranteed throughout the pass as in the case of the link availability mode, therefore data loss could happen for limited time. For this reason, the analysis is constrained by an average amount of data loss expected during the pass, e.g. 5% of the transmitted data. If implemented by the mission, the performance of the retransmission protocol can be considered to set the maximum data loss threshold.

As per recommended link configuration approach, margins to account for additional impairments on all link parameters are included in both types of analysis. At present, a single combination of data rate and coding scheme is selected per each period of uninterrupted visibility defined in the input file.

Once all inputs are available and the optimization mode has been selected, the LBT analysis, called job, can be executed. Input definition, file exchange, job execution, and results retrieval can be performed at LBT via the web-based graphical user interface, but also via command line interface or dedicated scripts thanks to the available REpresentational State Transfer Application Programming Interfaces. In the next section, the details of the analysis set-up as per automated BepiColombo spacelink operations process are described.

3. BepiColombo spacelink operations planning with LBT

This section introduces the constraints associated with BepiColombo's science operations, outlines its historical mission planning workflow, and examines the integration of LBT within the mission planning process for advanced mission operations.

3.1 Introduction of BepiColombo's Routine Science Operations

BepiColombo is currently at the end of its cruise towards Mercury, during which it performed nine flybys of Earth, Venus, and Mercury to reduce orbital energy in a stacked configuration of four components:

- The Mercury Planetary Orbiter (MPO), which is operated by ESA
- The Mercury Magnetospheric Orbiter (MMO), which is operated by JAXA
- The MMO Sunshield and Interface Structure (MOSIF), a solar shield to protect MMO during the cruise phase and
- The Mercury Transfer Module (MTM), which is equipped with solar electric propulsion.

Upon arrival at Mercury in November 2026, MPO and MMO will be placed in their scientific orbits and a one-month commissioning phase will precede the scientific routine phase, which is planned for one year, with a possible one-year extension. This paper focuses on MPO operations, as it is the only element communicating with Earth during cruise and is under ESA responsibility during the science phase.

Due to the harsh environmental conditions around Mercury, there are a few operational constraints that must be taken into account when operating MPO: on the one hand, the geometry of the spacecraft, Mercury and Earth means that there are cases in which Mercury blocks the direct view between MPO and Earth. These events are known as planetary occultations. In addition, during some mission phases, the orientation of the MPO is constrained in such a way that the High Gain Antenna (HGA) cannot be pointed towards the Earth, as the structure of MPO blocks the direct view. These visual blockages are called antenna body blockages. Due to these limitations, the effective ground station tracking pass duration may be significantly reduced and the visibility between ground station and satellite may be split into several so-called mini-passes, with uninterrupted visibility. Finally, despite the strong solar radiation in Mercury's orbit, MPO does not have enough power in some parts of the Mercury year to supply all the modules with electricity. As a result, Ka-band communication for science downlink must be disabled or traded against instrument operations in some parts of the orbit around Mercury, which results in an upper limit for the mission return. When Ka-band is disabled, TT&C and science downlink are available only via the X-band link.

As mentioned in section 1, Ka-band communications are more sensitive to the interaction with the atmosphere and its particle composition: non precipitating clouds and moderate precipitation in the line of sight can degrade the link, convective rainfall can interrupt communications [9]. To mitigate the larger uncertainties of the Ka-band link performance due to atmospheric impairments with respect to the X-band link, the data handling subsystem of MPO features the Packet Utilization Standard (PUS) service 13 - Large Data Transfer, which allows for automatic retransmission of lost data packets.

MPO to Earth communication is supported by the deep-space antennas of the ESA tracking network (ESTRACK) at the sites of Cebreros, Malargüe and New Norcia. Currently, the New Norcia antenna is equipped only with X-band capability, while Cebreros and Malargüe can both support Ka-band downlink communication. A second deep-space antenna in New Norcia is under final integration and will be ready for X-band and Ka-band links by the end of 2025.

3.2 BepiColombo Mission Planning Workflow

To tackle the described operational challenges, a complex space mission such as BepiColombo requires precise mission planning. In the routine phase of ESA's interplanetary missions, this process is typically divided into long term, medium term and short term planning. While long term planning (LTP) takes place about six months in advance, medium term planning (MTP) covers a period of four weeks, and short term planning (STP) covers a period of one week. The level of detail in the planning continuously increases as the lead time to execution decreases to enable increasingly precise utilization of operational resources such as payload observation time, downlinkable data volume or available power.

To support the mission planning process, the ESA Ground Operation System (EGOS) Mission Planning System (MPS) is used, which works as follows. The MPS processes inputs from various entities of the ground segment by means of so-called operations requests, including science, flight dynamics, mission control, and ground station management. Based on these inputs and on the internal planning rules and constraints that characterize the availability profiles of the spacecraft and ground stations resources, the MPS performs its planning and produces:

- Spacecraft operations schedules, i.e. command files to be uplinked to the spacecraft
- Automation schedules for file transfer management
- Ground station operations schedules for the generation of an automation schedule for the station computer, in charge of the ground station management during the pass.

The historical baseline concept for telemetry bit rate planning, developed for S- and X-band links, is based on Earth distance and ground station performance stored in so-called distance-bit-rate lookup tables (DBT). These tables, derived from static point-to-point link budget calculations assuming a fixed minimum G/S antenna elevation (for BepiColombo,10 degrees for X-band and 20 degrees for Ka-band are considered) ensure a defined link margin (normally 3 dB) for each bit rate. The concept corresponds to the guaranteed link availability mode described in the previous section, but based on pre-defined lookup tables instead of routine LBT use. This implies a manual recalculation of the lookup tables after each significant link parameter change, e.g. ground station performance improvement because of hardware upgrade, use of different lookup table in case the on-board antenna changes. In addition, if the approach of guaranteed link availability at minimum elevation is used for Ka-band, a significant trade-off between bit rate and usable pass duration (minimum elevation) would have to be made, therefore the communication pass would not be fully exploited.

To overcome these limitations in spacelink exploitation and operations, a link-budget driven bit rate optimization was implemented by integrating the ESA LBT into the mission planning process, starting with the Ka-band downlink. This optimization performs a full link budget analysis and dynamically adjusts the bit rate based on the available link margin or achieved accumulated data volume. The link budget analysis takes the following parameters into account:

- Emitted signal power of the spacecraft and on-board antenna in use
- Spacecraft-Earth distance
- Atmospheric statistics over a defined period
- Ground station performance
- Elevation profile of the ground station antenna
- Position of the Sun in relation to Earth and the spacecraft, to identify solar conjunction periods, where the spacecraft passes behind the Sun from Earth's perspective (superior solar conjunction) or where the spacecraft remains in between Earth and Sun (inferior solar conjunction).

Among these parameters, the spacecraft-Earth distance is the biggest global influence on selectable bit rate throughout the mission. During a given pass, where this distance remains relatively stable, the dominant factors influencing the usable bit rate are instead the path attenuation and the ground station G/T as a function of elevation. Relying on its databases, LBT can adjust the bit rate for each mini-pass within a pass, effectively leveraging the reduction in path attenuation and the increase in ground station performance as elevation increases.

3.3 Implementation

The system architecture is shown in Figure 1 and consists of the EGOS MPS, which interacts with the ESA LBT, the MCS and the G/S computers. As described in Section 2, all inputs relevant to the planning period are collected at the beginning of the mission planning process. Two essential planning inputs are required: the Flight Dynamics event file and the PLNVIEW file. The Flight Dynamics event file provides ground station visibilities (AOS/LOS events) at different elevation angles, and orbital parameters for the calculation of the ground station elevation profile. It also includes the periods of unblocked antenna visibility for MPOs antennas and planetary occultations (e.g. with Mercury).

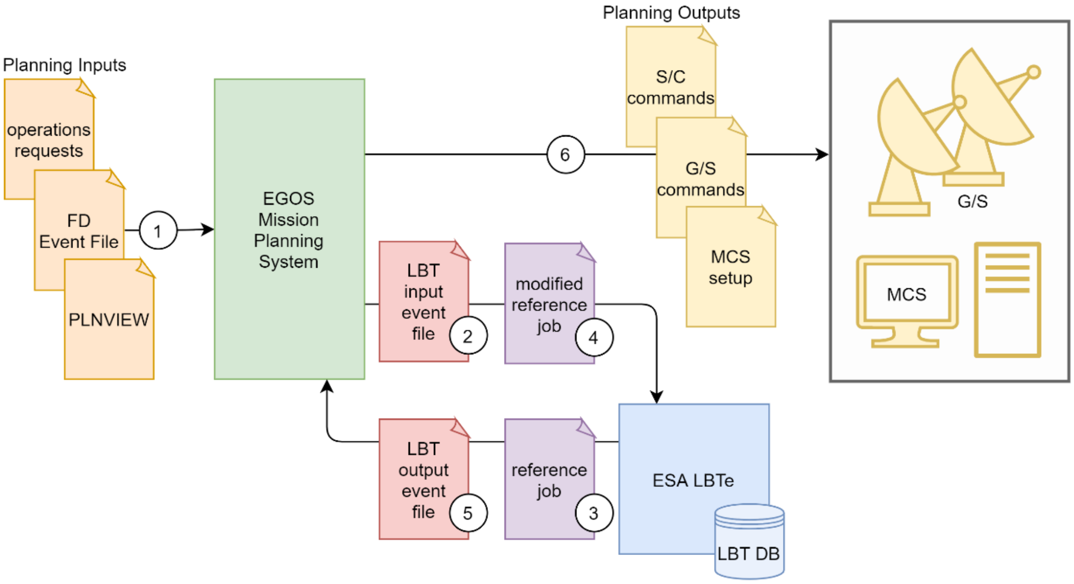

Figure 1: System architecture of the link-budget driven bit rate optimization at planning stage. Numbering visualizes the data flow between the MPS (green), the LBT (blue) and the MCS and the G/S computers (yellow). The planning inputs are marked in orange, LBT input and output files in red and LBT job configuration files in purple.

The PLNVIEW file contains the actual booked ground station passes. As part of the bit rate planning workflow, the MPS processes the injected inputs and generates so-called mini-passes, which are defined as an intersection of the booked passes and the antenna visibilities (considering body blockages and occultations). In order to retrieve optimized TM bit rates and TM coding for each mini-pass, the MPS interfaces with the ESA LBT using its REST APIs. In this way, first a so-called LBT input event file is passed to the LBT, which contains the station visibilities and the passes to be optimized. Next, a preconfigured so-called reference job configuration file is downloaded, which specifies the required key optimization parameters of the LBT job, such as used atmospheric statistics, optimization settings, and link budget constraints. For the Ka-band jobs, the yearly average atmospheric statistics as recommended by the ITU are used [6], for the sites of Cebreros and Malargüe. As analysis method, the data return optimization approach is selected, as it is best suited for the Ka-band transmission. Furthermore, the optimization is allowed to shorten the mini-passes if this allows a higher bit rate to be selected for a shorter duration, which results in an overall higher data volume. The starting elevation for the optimization is set to 10 degrees with a step size of 2 degrees. The key optimization parameter is the number of maximum lost frames, which is set to 5 %, which, according to [8], achieves the best trade-off between data rate and expected retransmissions for MPO.

Once the optimization job is executed, the process is monitored and logged. After completion, the resulting LBT output event file is downloaded, containing optimized mini-passes characterized by their adjusted bit rates, coding schemes, and potential modifications to start/end times. Figure 2 shows a visual representation of the optimization. It can be seen that bit rates vary over time and mini-passes are shortened to maximize data return (see second mini-pass in the graph with a reduced transmission duration). The MPS then injects the optimized events and resumes the planning process, generating command files for both the spacecraft and ground segment. Spacecraft commands include:

1. Bit rate change sequences – defining when and to which bit rate the spacecraft should switch.
2. Dump start/end sequences – specifying when telemetry (housekeeping and science data) should be transmitted.
3. File transfer system control – enabling or suspending the file transfer protocol as needed.

Ground station commands, delivered via so-called EVFM files, define station setup, including bit rate and coding settings for each pass and, if needed, configuration changes between mini-passes. Additionally, the mission control system is updated with the expected bit rate changes to ensure proper configuration.

The described LBT driven bit rate optimization for Ka-band downlink is now implemented in the MPO mission planning as baseline method, active since November 2024. The DBT driven optimization is also implemented as back-process, in case LBT is not available and the baseline planning workflow cannot be executed.

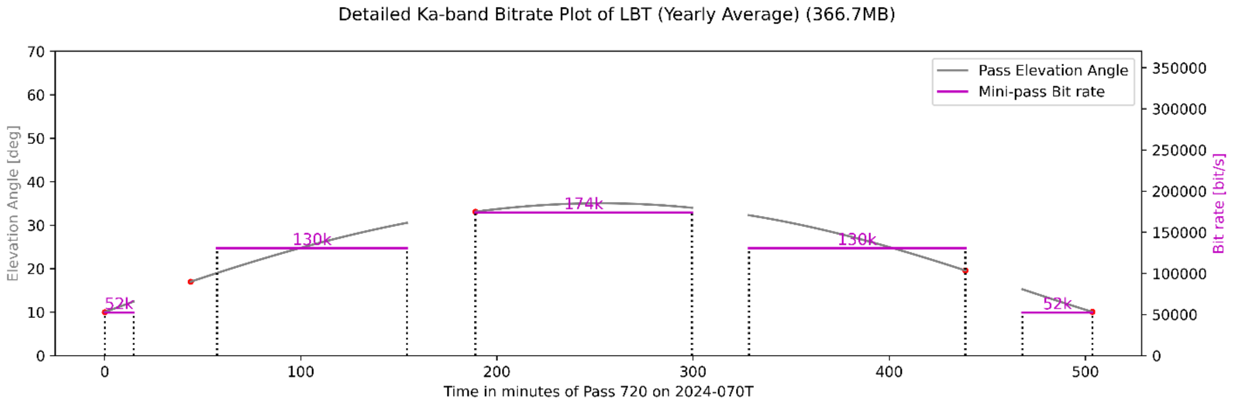

Figure 2: Visual representation of optimization result of a Ka-band pass. The evolution of the pass elevation is shown in grey, where each line segment represents a visibility slot between satellite and ground station. The purple lines depict the mini-passes, their optimized bit rate, and the optimized duration.

4 Overview of data volume return analyses with automated spacelink operations planning

In order to assess the performance gains resulting from the integration of LBT bit rate optimization in the mission planning process, a reference scenario was considered, which reflects the extended two-year scientific phase of BepiColombo but contains some simplifications that increase the comparability of the optimization methods. First, it was assumed that all passes are carried out over the Cebreros deep-space station. This eliminates the different station performance between Malargüe and Cebreros from the evaluation, also related to the usage in different seasons over the year. Furthermore, a provisional Flight Dynamics event file containing the ground station visibilities of the science phase is used as input for the evaluation, which does not provide the precise event timings necessary for operational use but preserves the fundamental characteristics of the events. The input file covers a science scenario in years 2022 and 2023, instead of the actual one starting in 2027. Moreover, as no ground station allocation has yet been agreed, there is no PLNVIEW file with the booked ground station contacts. For this reason, a provisional PLNVIEW file was created assuming full utilization of the theoretical Cebreros ground station visibility. This cannot be used in real-world operations; however, it is adequate for the purposes of the presented analysis. Lastly, as described earlier, in some parts of the orbit around mercury Ka-band communications have to be traded against payload operations, which are not taken into account in this performance evaluation. It must therefore be noted that the results of the evaluation only allow statements to be made about the relative increase in science return of the BepiColombo mission due to the methodology used for spacelink configuration.

In the following sections, Ka-band downlink performance is discussed first, then considerations about application of the approach for X-band are reported.

4.1 Ka-band performance evaluation

Figure 3 shows the amount of data returned per pass and the cumulative amount of data over time for the bit rate selection based on static distance-bit-rate lookup tables (green) and LBT driven optimization (yellow), using yearly averaged atmospheric statistics. As the results are highly dependent on pass duration and distance, these are shown at the bottom of the figure and are discussed first. The pass duration is shown in blue. The dashed line indicates the theoretical maximum pass duration and the solid line the actual pass duration, which takes the antenna body blockages and planetary occultations into account. The two lines are identical if no interruptions occur. To be noted that long duration passes are normally characterized by high elevation angles, well above 30 degrees for most of the visibility. In order to fairly compare the methods, superior solar conjunctions are excluded from the analysis, as solar conjunction scenarios can only be taken into account automatically by LBT, and not by DBT. These phases are indicated by the grey bars and are defined by a Sun-Earth-Spacecraft angle of 5 degrees or less. The spacecraft-Earth distance, shown in red, varies between 0.52 AU and 1.48 AU during the science phase. The greatest distances occur when Mercury is on the opposite side of the Sun, which means that these phases coincide with superior solar conjunctions. The same relationship can be observed for the closest distances and inferior solar conjunctions (not shown in the Figure).

The results of the baseline bit rate selection based on DBT is shown in green. As expected, the variation in the amount of data returned is a direct function of distance and pass duration.

The result of the LBT driven bit rate optimization at planning stage is depicted in yellow: the implementation of this concept yields 30.9 % of increased returned data compared to the DBT concept. The improvement can be traced back to the data return maximization methods which optimize the link budget for each pass and each mini-pass. This allows the highest possible data rates to be used, taking into account the elevation-dependent atmospheric effects and the defined maximum tolerable frame loss. To ensure data integrity, the file transfer protocol is used to recover data gaps automatically.

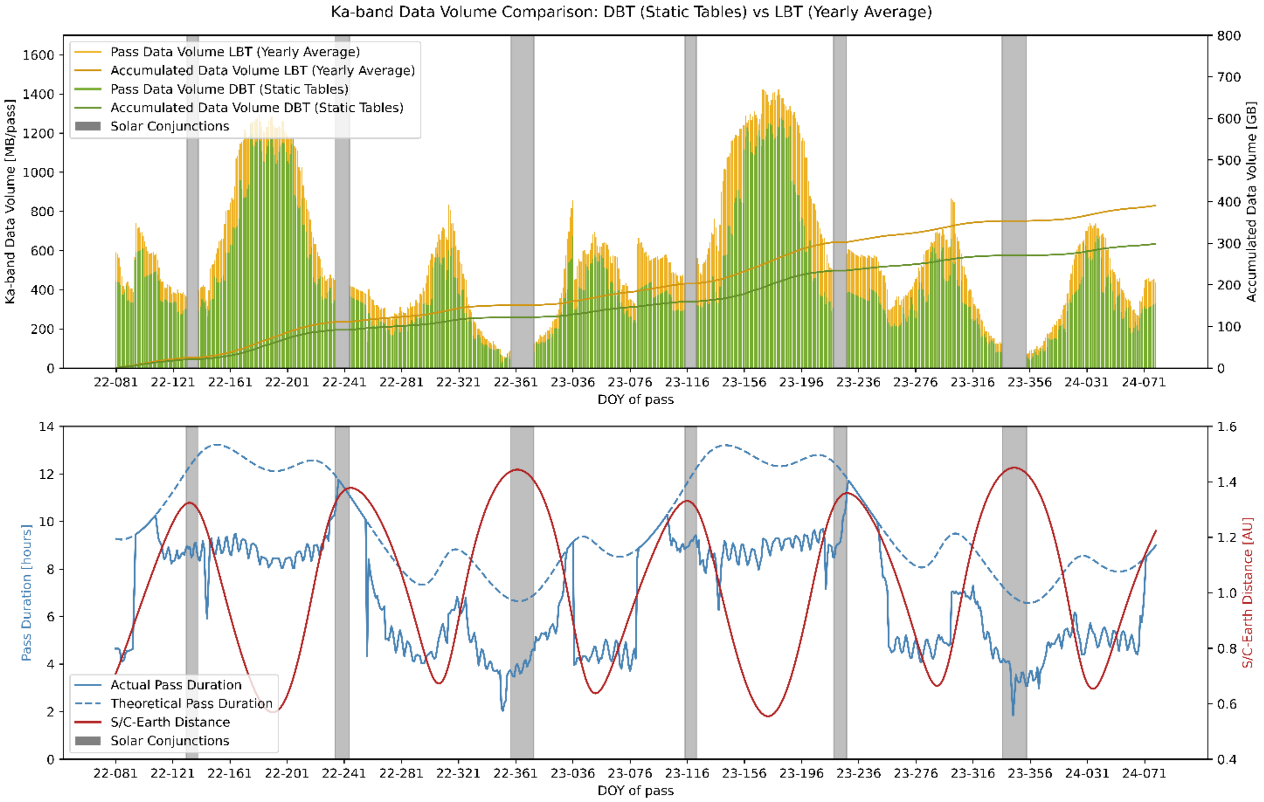

Figure 3: Ka-band data volume comparison for MPO passes over the Cebreros station. The upper part shows the amount of data returned per pass and the cumulative amount of data over time for the bit rate selection based on static DBT (green) and LBT driven (yellow) optimization, using yearly averaged atmospheric statistics. Each bar represents one pass. The lower part of the figure depicts the spacecraft-Earth distance (red) and the pass duration (blue). The dashed line indicates the theoretical maximum pass duration and the solid line the actual pass duration, which takes the antenna body blockages and planetary occultations into account.

Figure 4 shows a detailed comparison between the two spacelink operations planning methods discussed. Each bar represents the amount of data gained or lost during a single pass, whereby a performance gain of the LBT driven over the DBT optimization is shown in green and a loss in red. With a few exceptions, the optimization is superior to the baseline for all analyzed passes. By comparing Figure 3 and Figure 4, it is possible to identify the periods during which LBT settings provide the maximum advantage, corresponding to the passes with multiple visibility interruptions. The reason is that the current MPO spacelink operations strategy is based on the use of one fixed bit rate during each period of uninterrupted visibility; therefore, when interruptions are present and the pass is split into mini-passes, the LBT optimization allows to configure different bit rates per mini-pass, exploiting the improved link performance at higher elevation angles. In contrast, the bit rate provided by DBT is used for all mini-passes of the pass. In addition, even when no visibility interruptions are present, LBT optimizes the elevation at which the transmission starts, also exploiting the link performance with respect to the elevation. DBT approach, instead, is always based on point-to-point link budgets performed at 20 degrees and cannot process the dynamic orbital conditions during the year.

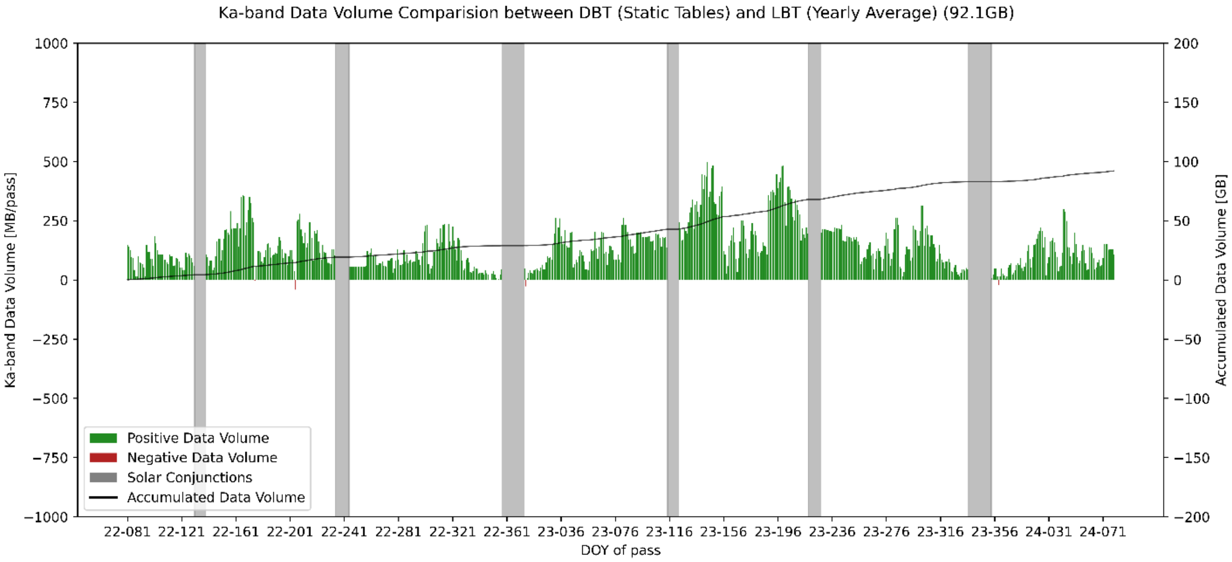

Figure 4: Daily Ka-band data volume comparison for MPO passes over the Cebreros station. Each bar represents the amount of data gained or lost during a pass, whereby a performance gain of the LBT driven optimization over the static DBT optimization is shown in green and a loss in red. The black line shows the accumulated difference in data volume. Superior solar conjunction phases are indicated by grey bars and are excluded from the evaluation.

Given the early execution of the optimization during the planning stage – well ahead of real-time spacecraft operations – the LBT approach is not time-critical and introduces only minimal operational complexity, making it a convenient choice for adoption into routine mission planning.

4.2 X-band performance evaluation

A similar analysis has been performed on the X-band link, in order to determine whether the introduction of the LBT driven bit rate optimization described in section 3 is also suitable for the lower frequency band. For this purpose, we deviate from the idea of robust and simple X-band communication with a single data rate used for the whole pass even if divided into mini-passes, by allowing the optimization to select a separate bit rate for each mini-pass. To keep operational complexity as low as possible, LBT optimization is not allowed to change the minimum pass elevation, which would shorten the mini-passes, and the minimum pass elevation is set to 10 degrees. LBT TM rate optimization based on link availability mode, with a target availability of 90%, is selected. The same availability target is used to prepare the lookup tables used in case of DBT planning, for which also a minimum elevation angle of 10 degrees for each pass is considered.

Figure 5 shows the amount of data returned per pass and the cumulative amount of data over time for the baseline bit rate selection based on static distance-bit-rate lookup tables (green) and LBT driven (yellow) optimization, using yearly averaged atmospheric statistics. The same orbital scenario as in the Ka-band analysis has been considered; therefore, the same considerations about distance, elevation angles, and solar conjunction periods discussed in section 4.1 apply. For the X-band scenario, LBT driven bit rate optimization yields 16.7% of increased returned data, compared to the DBT driven approach. Figure 6 shows the daily comparison between the two spacelink operations planning methods: it can be seen that the improvement shrinks in phases of short spacecraft-Earth distance, below 0.7 AU. This is because in those passes the maximum data rate available on the spacecraft is selected by both methods and no additional performance gain can be achieved from using LBT. In the graph, more negative data volume days for LBT optimization are visible than in the Ka-band case. These cases occur mainly close to solar conjunctions, to which X-band is more sensitive, therefore the link starts to be impaired at Sun-Earth-Spacecraft angles larger than 5 degrees, included in the data volume comparison. However, since the solar effects are correctly modeled by LBT driven optimization and are not included in the DBT approach, the spacelink setting provided by LBT is more adequate and DBT overestimates the available data return for these passes. As final remark, the outlier on DOY 308 of 2022, with large negative data volume for LBT optimization is due to an inferior solar conjunction pass that was not filtered out, during which the Sun is behind the spacecraft and increases the noise received at the ground station antenna, correctly modelled by LBT.

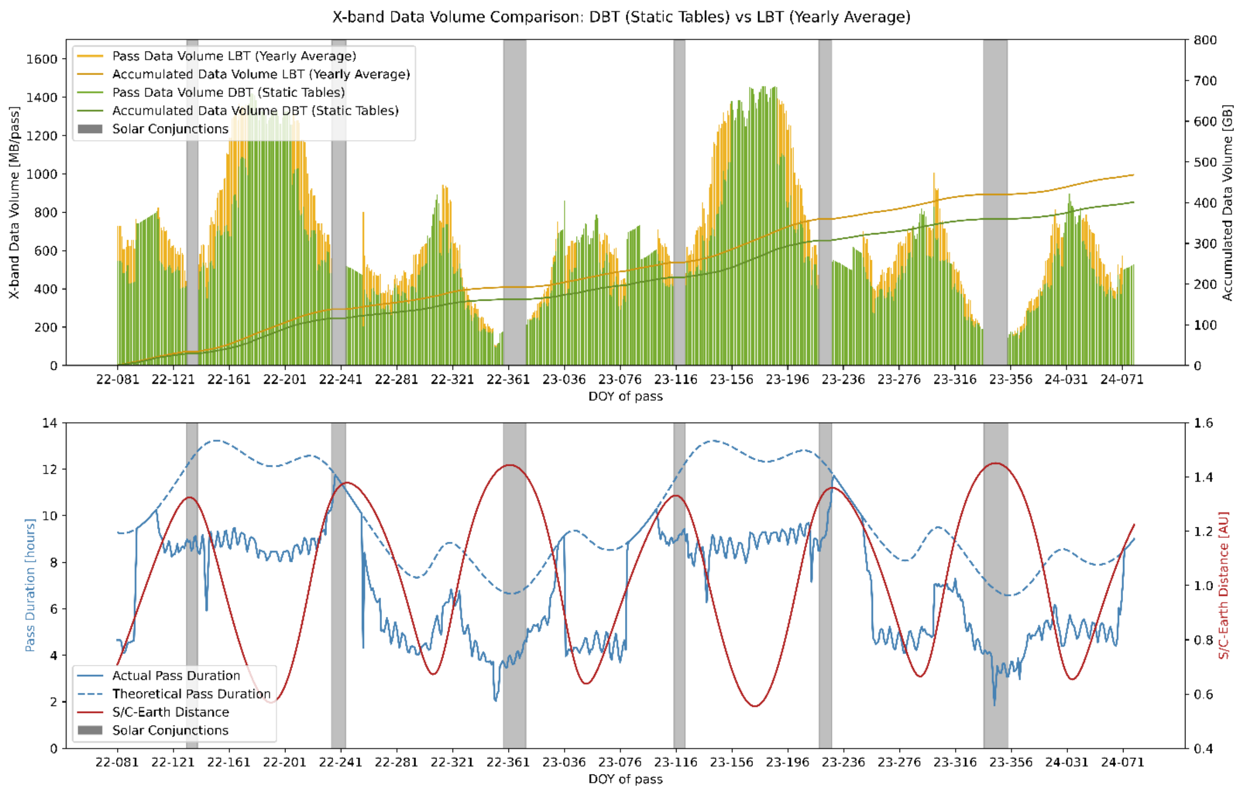

Figure 5: X-band data volume comparison for MPO passes over the Cebreros station. The upper part shows the amount of data returned per pass and the cumulative amount of data over time for the bit rate selection based on static DBT (green) and LBT driven (yellow) optimization, using yearly averaged atmospheric statistics. Each bar represents one pass. The lower part of the figure depicts the spacecraft-Earth distance (red) and the pass duration (blue). The dashed line indicates the theoretical maximum pass duration and the solid line the actual pass duration, which takes the antenna body blockages and planetary occultations into account.

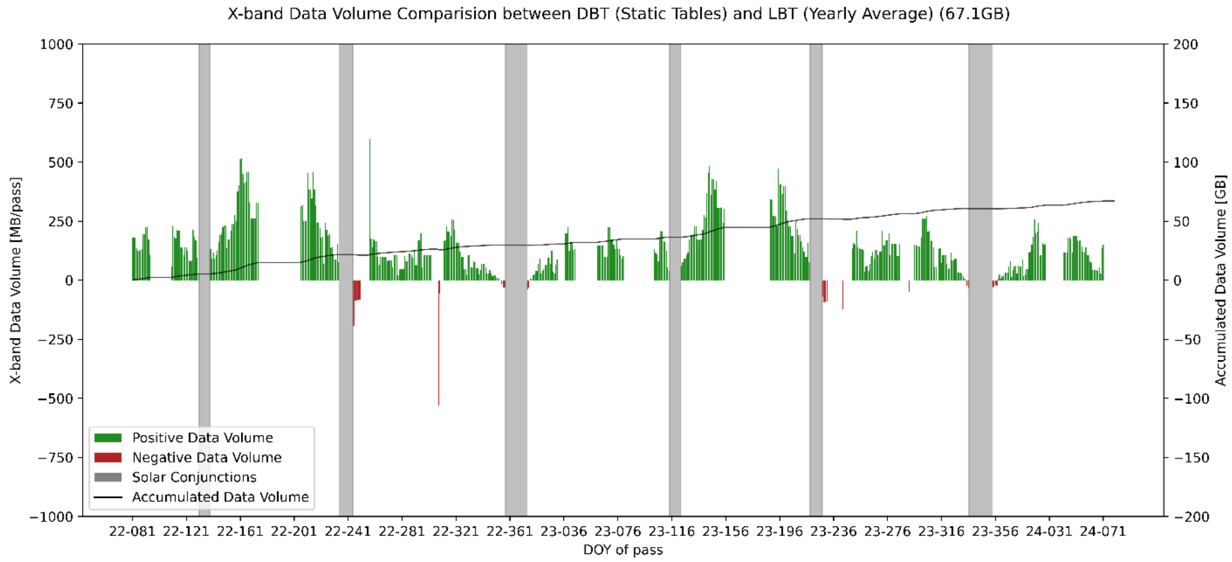

Figure 6: Daily X-band data volume comparison for MPO passes over the Cebreros station. Each bar represents the amount of data gained or lost during a pass, whereby a performance gain of the LBT driven optimization over the static DBT optimization is shown in green and a loss in red. The black line shows the accumulated difference in data volume. Superior solar conjunction phases are indicated by grey bars and are excluded from the evaluation.

The improvement achieved through LBT driven optimization is less pronounced compared to the Ka-band case. Nevertheless, the benefit of utilizing enhanced link performance at higher elevation angles remains evident. This is particularly relevant given that the ESTRACK deep-space antennas are equipped with cryogenically cooled receiving systems including the feed antennas, that are fully exploited at higher elevations, where the otherwise dominant sky brightness temperature significantly decreases [10]. In addition, from the operational perspective, the use of LBT allows to automatically adapt the link configuration to the dynamic orbital conditions during the year, including solar conjunction periods that are very critical for TT&C operations.

The LBT driven optimization workflow described in section 3.3 is also used at X-band by MPO since November 2024, with the following settings: TM rate optimization with 90% link availability target; minimum elevation angle of 10 degrees or of the booked visibility slot, with no elevation optimization; single bit rate used for all mini-passes of the pass. The X-band link performance is being monitored during this last phase of the cruise to Mercury. If deemed robust and necessary the LBT configuration job for the analysis could be modified to include the bit rate optimization at mini-pass level, therefore providing a data return increase as reported here. Alternatively, the approach could be selected by other missions that require an increase of X-band science downlink.

5 Conclusions

The paper discussed the automated spacelink operations workflow implemented by BepiColombo MPO, fully integrated within the mission planning routine, incorporating the ESA link budget tool into the day-to-day operations. The approach allows to automatically include different constraints in the spacelink setting procedure, including dynamic orbit conditions and spacecraft to Earth visibility conditions, mission science planning and operations constraints, and actual performance of the on-board and ground station antennas. If any of these aspects change from one mission planning to the next, the workflow automatically ingests such changes, with very limited user interaction, normally restricted to simple monitoring.

The advantages of the presented approach consist first of all in an increase of scientific data return, i.e. final objective of space science and exploration, and concurrently allow to fully exploit the spacelink and the visibility passes assigned to each mission. The paper focused on the pioneer work performed for BepiColombo, however the process uses multi-mission subsystems, including the ESA link budget tool; therefore, the application to other ESA missions is straightforward and would primarily require a proper definition of the mission operations constraints to correctly drive the optimization. Once the process is extended to most of the missions supported by the ESTRACK deep-space antennas, the tracking network itself can also benefit by the optimized spacelink exploitation, to increase the number of daily supported spacecraft.

Seeking further improvements, weather forecast based spacelink operations can be implemented [7]. The ESA link budget tool is ready to ingest atmospheric statistics computed based on the predicted weather at the ground station site at the time of the pass. The spacelink workflow would need to run shortly before the pass starts to profit from the latest available forecast, with an increase of complexity due to the time-critical execution and related reconfiguration of spacecraft and ground station. The implementation on the mission side, with BepiColombo again as pioneer, is currently under assessment, given that such approach not only enhances data return but also mitigates data loss during unfavourable weather conditions, in turns reducing spacelink operations complexity.

Acknowledgements

The authors would like to thank you the BepiColombo flight control team, in particular Nicholas Soubirous and Jessica Hopkins; the ESA Link Budget Tool team, with Elena Garcia Tomas, Guillaume Autret, and Donato Lospalluto; and the team who developed the spacelink performance monitoring tool: Klara Spieker and Jose Villalvilla, all based at the ESA European Space Operations Centre (ESOC).

References

[1] A. Cardesin-Moinelo, et al., Mars express: 20 Years of mission, science operations and data archiving., Space Science Reviews 220.2 (2024): 25.
[2] J. Benkhoff, et al., BepiColombo-mission overview and science goals., Space Science Reviews 217.8 (2021): 90.
[3] J. Helbert, et al., The VenSpec suite on the ESA EnVision mission to Venus., Infrared remote sensing and instrumentation XXVII. Vol. 11128. SPIE, 2019.
[4] S. Finocchiaro, et al., Spacelink configuration and mission operations with the new ESA link budget tool, SpaceOps Conference 2023, 6-10 March 2023, Dubai, United Arab Emirates.
[5] CCSDS Radio Frequency and modulation systems – Part 1, Earth stations and spacecraft, CCSDS 401.0-B-32, October 2021.
[6] ITU-R P recommendations: http://www.itu.int/rec/R-REC-P/en (accessed 05.04.25)

[7] M. Montagna, et al., Weather Forecast Based Satellite Operations at ESA: Architecture Implementation and Validation, In: Lee, Y.H., Schmidt, A., Trollope, E. (eds) Space Operations. SPACEOPS 2023. Springer Aerospace Technology. Springer, Cham.
[8] M. Montagna, et al, Maximization of data return at Ka-band for interplanetary missions, 18th Ka and Broadband Communications, Navigation and Earth Observation Conference, Ottawa, Canada, 2012, 24-27 September.
[9] G. Brussaard, and P. A. Watson, Atmospheric Modelling and Millimetre Wave Propagation, Chapman & Hall, London, UK, 1995.
[10] C. Chambon, et al., X-band cryogenically-cooled feed: high power validation and on-site integration, TT&C Workshop 2022, ESA/ESTEC, The Netherlands, 2022, 28 November - 01 December.