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Spacelink configuration and mission operations with the new ESA link budget tool

Stefano Finocchiaro[a], Maria Montagna[b]*, Guillermo Lorenzo[c], Elena Garcia Tomas[d], Alessio Coppotelli[a], Stefano Milani[a], Massimiliano Mattioli[a], Alessandro Ardito[a]

[a] *Arpsoft SRL, Via della Stazione di San Pietro 65, Rome, Italy, finocchiaro@arpsoft.it, coppotelli@arpsoft.it, milani@arpsoft.it, mattioli@arpsoft.it, ardito@arpsoft.it*
[b] *VisionSpace @ European Space Operations Centre/ESA, Darmstadt, Germany, maria.montagna@ext.esa.int*
[c] *European Space Operations Centre/ESA, Darmstadt, Germany, guillermo.lorenzo@esa.int*
[d] *LSE Space @ European Space Operations Centre/ESA, Darmstadt, Germany, elena.garcia.tomas@ext.esa.int*
* Corresponding Author

Abstract

After many years of spreadsheet-based link budgets, a new centralised tool for spacelink analysis and operations is now available at the European Space Agency (ESA).
The new Link Budget Tool (LBT) is based on a core software application running on a centralised virtual environment in charge of the link budget calculations, which interacts with several databases for spacelink data exchange and for user management, among others. The tool provides a web-based graphical user interface as well as a REpresentational State Transfer Application Programming Interface (REST API) for remote interface. Due to the foreseen operational use, a redundancy mechanism and a queue management to handle priority requests have been implemented.
Thanks to the selected web-based interface, accessible via a standard web browser, the tool is reachable by all ESA engineers connected to the working network, with its rigorous collection of validated formulas and consolidated data of missions in operations and in preparation, ground stations, and propagation medium, together with orbital information. Owing to a flexible database management, the users can edit and create data structures and share their work with other colleagues as required. The software implementation is ready for tool scalability, with easy introduction of new software libraries for additional link budget methods. Finally, the remote interface allows for machine-to-machine interaction, key feature to enable automation, for instance for routine link budget calculations for mission planning and the weather forecast based mission operations.
The major challenges faced during the implementation of the new tool concern test and validation, user management, and associated queue management, being the tool a central repository for mission and ground station performance data. The described tool, online as of December 2021, is constantly evolving in terms of core computations and spacelink operations, as required by the missions under preparation and by future operations concepts developed in the Agency.
Keywords: Link Budget, Spacelink optimization, Operations software, performance data.

Acronyms/Abbreviations

ESA	European Space Agency	LEOP	Launch and Early Orbit Phase
TC	Telecommand	HTTP	Hypertext Transfer Protocol
TM	Telemetry	WF	Weather Forecast
MS	Microsoft	MPS	Mission Planning System
ESOC	European Space Operations Centre	BER	Bit Error Rate
GUI	Graphical User Interface	FER	Frame Error Rate
SDK	Software Development Kit	GS	Ground Station
CLI	Command Line Interface	CDF	Cumulative Distribution Function
LDCT	Link Design and Control Table	UL	Uplink
AMPQ	Advanced Message Queuing Protocol	DL	Downlink
JSON	JavaScript Object Notation	ECSS	European Cooperation for Space Standardization
FIFO	First Input First Output	RNG	Ranging

1. Introduction

During SpaceOps 2018, ESA presented the concept of a link budget analysis tool to be used as a support to the operations activities [1]. The tool is operative in ESOC since December 2021. This paper illustrates its structure and capabilities.

Link budget analyses are a key aspect of mission operations (Fig. 1).

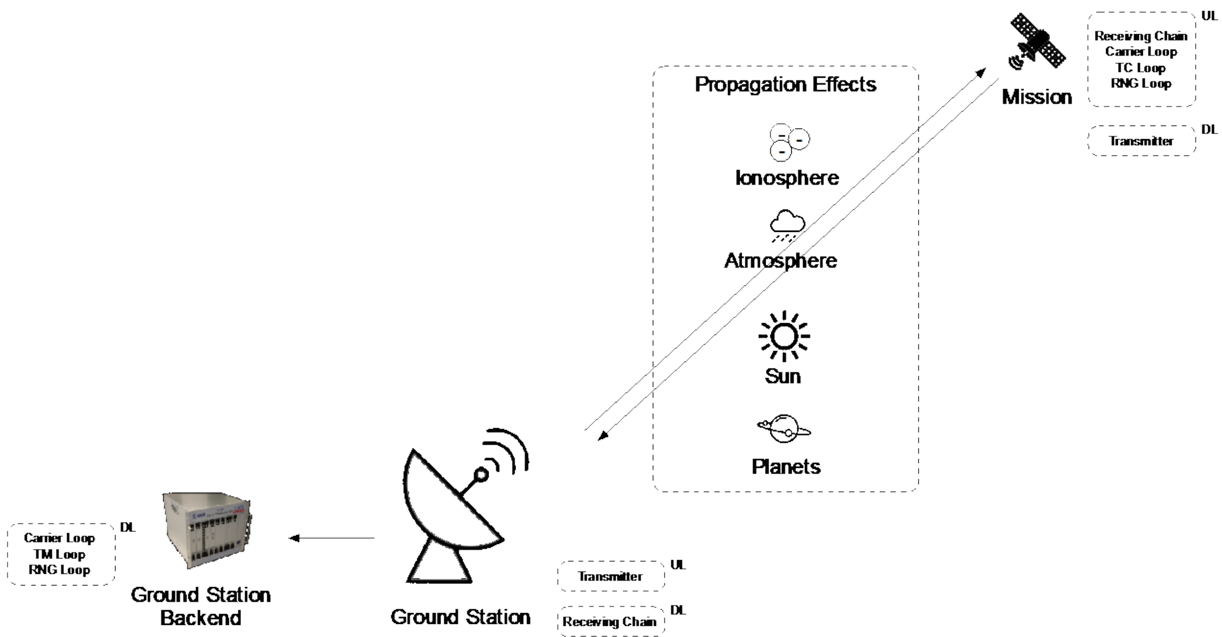

Fig. 1. Basic concept of a link budget analysis. The computation of the telecommunication margins must consider several hardware setup and signal propagation effects concerning both the ground and the spacecraft segment.

Since the early stages of the mission design, reliable link budget analyses allow to size the communication systems both on board and on ground to achieve the desired data return, while at later stages they are used to check the foreseen TC and TM margins. The Link Budget Tool aims at serving the ESA community in

- Preliminary study phases computations.
- System design aid.
- Industry link budget verification.
- Data Return optimization and automatic telemetry mode selection for spacecraft operations.
- Definition of operational ground station configuration.
- Verification of actual performance data during operations (e.g. expected vs observed)
- Providing input for the definition of relevant mission documentation such as space-to-ground interface control documents.

Before LBT, a MS Excel spreadsheet was distributed to perform the analyses and to store relevant telecommunication data for space missions and ground station systems and for atmospheric impairments required by the computation. Even if extremely reliable in its formulation, the Excel spreadsheet did not guarantee that every user was using the most updated version concerning either the formulas or for the data. Even the parametric models, for example the one for the adaptation of the ground station system noise temperature at different elevation angles, were not uniform for the same antenna type. Moreover, the capability for enhancements was limited by the spreadsheet formulation, therefore Visual Basic macros were introduced for more complex analyses. Finally, such a tool runs on the user personal machine; thus, it was not possible to assure that the minimum requirements in terms of resources were always met.

The new Link Budget Tool has been developed to target these specific limitations while maintaining the core computation reliability. It is a web-based application, running on dedicated servers at the European Space Operations

Centre (ESOC) and accessible only within the ESA network. This approach guarantees that every logged in user interacts with the same version of the tool. The core computations have been translated to Python language, which easily allows code maintenance and accommodating new functionalities. Significant effort has been dedicated to the harmonization of the models. Moreover, all the computation is centralized on the ESA server, thus strongly reducing the minimum requirements for the tool usage to a standard broadband internet connectivity. The application hosts databases for mission, ground station antennas, ground station receivers, atmospheric and ionospheric models, sun and planets brightness temperature, solar scintillation effects, called data structures. Each user can create and share its own data structures or use the ones defined for operational purposes, which are managed under configuration control by a team of engineers at ESOC,

The paper is organized as follows: Section 2 describes the architecture of the tool, in terms of its main blocks and services; Section 3 contains an overview of the tool capabilities and interfaces, while Section 4 illustrates how LBT is integrated in the current ESA operations workflow.

2. System Architecture

2.1. High Level Architecture

The Link Budget Tool is architecturally composed by several different blocks (Fig. 2). LBT is deployed following the microservice architectural pattern that allows to distribute different functionalities in different services in a modular and scalable way.

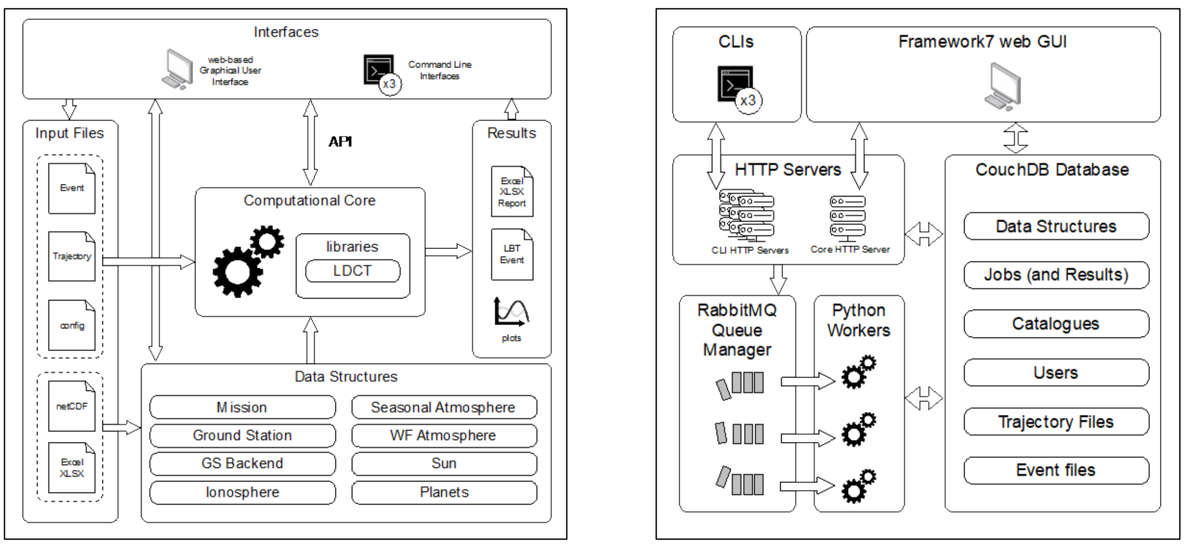

Fig. 2. Link Budget Tool high level architecture. The figure on the left illustrates the logical blocks of the tool while the figure on the right shows how the different tool services interact.

The user can communicate with the tool using multiple interfaces. The general-purpose interface is the web-based Graphical User Interface. Depending on the user type, different functions of the tool are accessible, e.g., upload of input files, communication with the computational core, data structures creation and examination, link budget analysis tasks, results retrieval.

In addition to the web GUI, SDKs and CLIs have been developed to target specific needs for integration with ESA systems external to the Link Budget Tool. Both the SDKs and the CLIs exploit different set of APIs hosted in remote Servers to run link budgets from the command-line or to exchange input/output files with LBT. Such APIs allow to integrate the Link Budget Tool with the ESA Mission Planning System and the ESA Weather Forecast Based Operations System [2]. The command line interfaces allow users to efficiently automate some repetitive actions, such as computing many link budgets, each one differing by a few specific parameters, whose value can be set with a file or script instead of requiring manual update at the GUI. An example is the daemon that, exploiting the exposed APIs for the Weather Forecast Based Operation System, automatically:

- creates atmospheric data structures from daily received atmospheric forecasts at the ground station sites;
- runs cases using the latest weather forecast data;
- verifies the system performance by comparing data acquired at the stations with LBT predictions.

All these interfaces communicate the Computational Python Core that is responsible for creating, maintaining, and dispatching the processes that perform all the link budget computations and optimizations (jobs), and produces plots, output files and reports. The computational core includes ESA Link Design and Control Table (LDCT) Library, which carries the mathematical formulation of the link budget theory [3]. The LDCT Python library has been developed by ESA to provide the functions necessary to compute the link budget of the radio communication between a spacecraft and a Ground Station. The same set of functions can be used to compute the link budget for the communication between a spacecraft and a rover/lander on the surface of a celestial body. It is maintained by ESA independently from LBT which only includes the library for the core computation.

An AMQP Broker allows to distribute and perform the computation in background. A dedicated service is responsible to publish a task describing the job into the broker, and several services, depending on the type of the submitted job, retrieve such task, and perform the actual computations. Such approach allows to the user to close the browser and check the results on any available interface in a later moment. The chosen AMPQ Broker is RabbitMQ, one of the most used open-source production-grade solution [4].

The input parameters for the link budget analyses are retrieved from input files, data structures as well as user input. Examples of input files are trajectory information, spacecraft events timeline with start and end time of tracking, or link budget configuration file to load a predefined link set-up. Input files can be used also to define data structures to ease the import of specific parameters in a table format.

Every service in LBT share the same CouchDB database, to store and retrieve information such as user details, data structures, job configurations, input and output files, and computations' results. CouchDB is an open-source NoSQL Database Management Systems [5]. CouchDB organises data in different Databases, each of them composed of a collection of JSON document. It exploits the Mango Indexes to perform fast and reliable queries even over a large number of documents. It offers the built-in capabilities to create a cluster allowing certain degree of redundancies and fault tolerance.

The link budget results can be retrieved from the web GUI: a short and detailed report is available both online and in form of a downloadable MS Excel file. The latter can be downloaded also from the CLI. For specific analysis modes, the tool allows to create plots showing the evolution of the telecommunication margins with time.

2.2. System Configuration

LBT is deployed on a Kubernetes cluster, an open-source container orchestration system [6]. Kubernetes allows automating software deployment, managing and distributing the different services composing the software through several nodes and scaling both the replicas of the services and the number of nodes to accommodate performance requirements, increasing workload and hot redundancy.

The tool is deployed on two identical virtual machines in the ESA network called lbt1 and lbt2. A third machine, lbtdata, has been recently added to the pool to serve Weather Forecast Based Operation integration.

LBT exploits the automatic and manual scheduling methodologies to adapt to the needs of each service:

- The database instances are manually scheduled among the three available nodes, one per node, creating a robust and resilient cluster.
- The nodes lbt1 and lbt2 host several services: the GUI, the web interface server, the CLI servers, the workers (backend computational services) computing the available kind of processes. The RabbitMQ cluster is deployed to dispatch the process computation among the workers asynchronously.
- The lbtdata node hosts the services needed to perform the automatic tasks related to the Weather Forecast functionalities. It hosts the folder in which it is possible to upload new atmospheric data generated by the Weather Forecast system, the daemon that checks for new files and, if needed, runs link budget analyses with the updated atmosphere. An automatic clean-up task for expired data and link budget jobs executed by the daemon is periodically scheduled in the lbtdata node.

Other micro-services are managed automatically by Kubernetes. A reverse proxy dispatches the user's requests to the different services, then the service forward the request to an instance on one of the machines (Fig. 3).

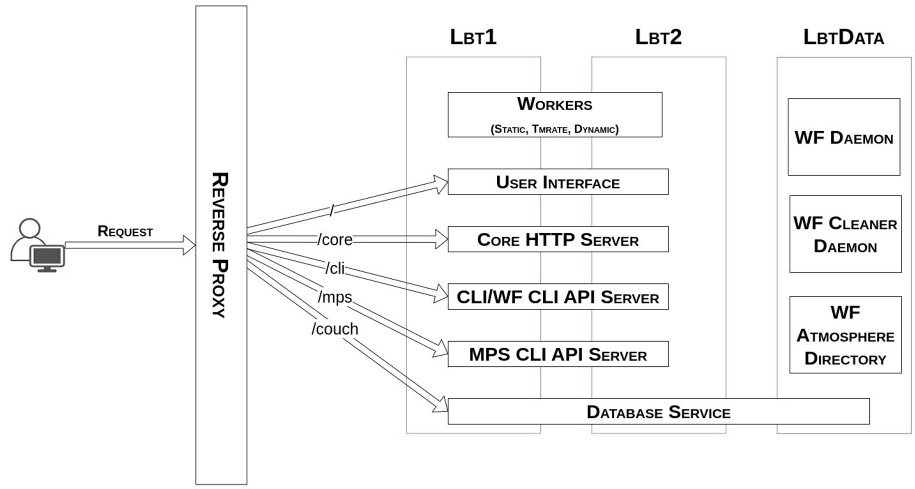

Fig. 3: Reverse proxy on each machine dispatching the user's requests to the different services.

RabbitMQ makes use of FIFO and Priority queues to distribute tasks among the workers: two Priority Queues are reserved for jobs execution (to respect the privileges of the different type of users) and a FIFO one is dedicated to database updates. The Core HTTP Server publishes the task on the respective queue, and the workers consume the task and execute the respective function.

The LBT infrastructure is easily scalable both horizontally and vertically. This kind of flexibility will allow to respond quickly to an increase of the tool usage demand or in case new computational modules should require additional resources.

2.3. Data Structures

All the different elements of a link budget computation are represented in LBT as data structures (see Fig. 1).

There are 8 different kinds of data structures. Three of them are dedicated to describing the two ends of the communication link:

- Mission: contains the description of the spacecraft characteristics in terms of spacecraft transmitter and receiving system, frequency bands, ranging capabilities, coding schemes, list of available TC and TM rates and corresponding modulation schemes and modulation indices, TC and TM BER and FER targets, as well as the definition of the uplink carrier, telecommand, and ranging loops.
- Ground Station: contains the characteristics of the GS antenna transmitter and receiving chains. This data structure also reports the definition of the models for system noise temperature adaptation with elevation, antenna patterns for pointing losses, and coefficients for Sun and celestial bodies contribution to the overall system temperature.
- Ground Station Backend: describes the capabilities and performance of the GS modems.

The remaining data structures concern the inclusion of the propagation effects:

- Ionosphere: losses due to ionospheric effects.
- Seasonal atmosphere: attenuation and sky brightness temperature CDFs, with yearly or monthly average statistics.
- Weather Forecast atmosphere: attenuation and sky brightness temperature CDF from weather forecast performed at the ground station site. Differently from seasonal atmosphere, they are characterized by a validity time span, e.g., 24 hours from release time.
- Sun: Sun brightness temperature and scintillation effects.
- Planets: celestial bodies brightness temperature.

In addition to data structures, LBT defines Catalogues to share common data among the different kind of data structures or different versions of the same data structure. The Mission catalogue contains the basic definition of the Spacecraft (name, ID, etc.), the Location catalogue contains the coordinates of Earth Stations sites, the Coding Scheme catalogue contains the definitions and the bit-error-rate performances of the coding schemes. Catalogues can only be maintained and modified by the LBT team in ESA.

The same team provides and maintain operational versions of the data structures. Even a beginner user can start computing link budgets using the operational data without spending effort on defining a huge variety of parameters. The expert user can customize the data content of the data structures by creating its own private versions. To facilitate teamwork, the tool allows the sharing of private data structures.

2.4. Users and Permissions

LBT users can have three different levels of authorization:

- Standard: it is the basic authorization level. This kind of user can compute link budgets, create data structures, share his work but has no access to user management.
- Operational: the operational user shares the same authorization level of a Standard user, but his computations will have a higher priority in the queue management with respect to the other users (even Administrators).
- Administrator: this user can be parent of a group of users belonging to lower levels (standard and operational). It can create new users, manage their parentship, and access all the data structure and cases of its child-users (even the private ones).

2.5. Graphical User Interface

After the signing-in at the login web page, the users are presented with their job management page (Fig. 4). From here it is possible to check the status of the jobs and edit them, to retrieve the results of complete ones, and to share the work with other users and let them have access to the job results.

From the navigation panel on the left, the user can reach all the different areas of the tool:

- the data structure databases.
- the Catalogues for missions, locations, and coding schemes.
- input/output file databases.
- Users database.
- LBT Documentation.

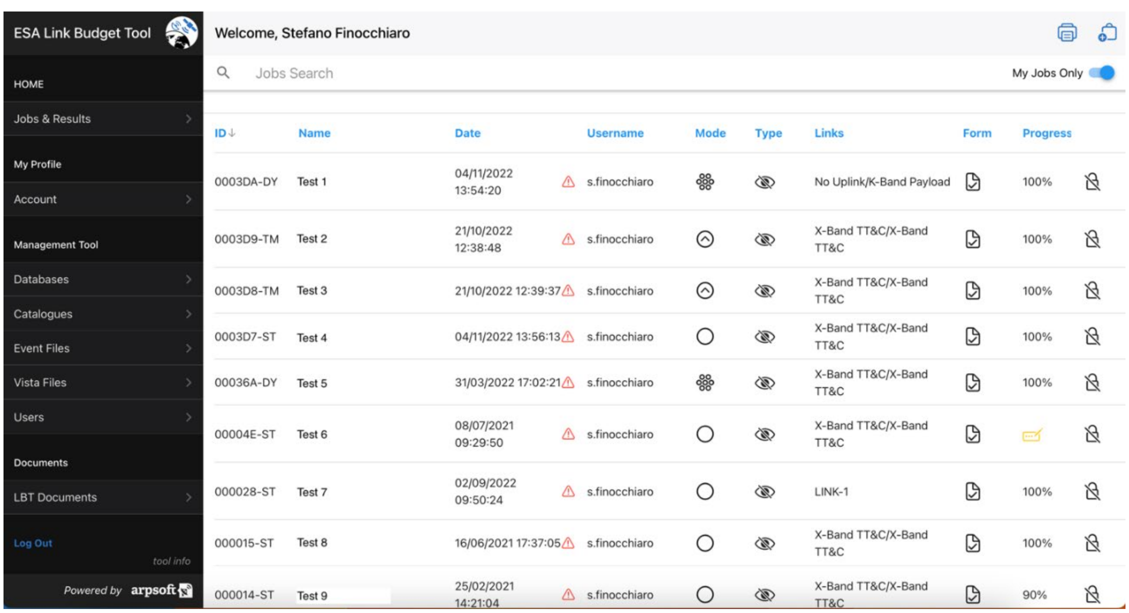

Fig. 4. LBT landing page. The navigation panel on the left allows the users to access the different areas of the tool.

Two types of user input form for the definition of the link budget parameters are available: a standard form and a detailed form, called Engineering form.

The Standard form (Fig. 5) is the default way to setup a complete link budget. The computation inputs are for the largest part retrieved from the selected data structures and only a few additional parameters need to be manually configured by the user. By adding browser tabs to the form, the user can process more than one link at the same time (multi-link functionality). Depending on the analysis mode, a selection of output parameters is available on the right of the standard form page, to help the user with a real-time update of the calculations depending on the selected inputs.

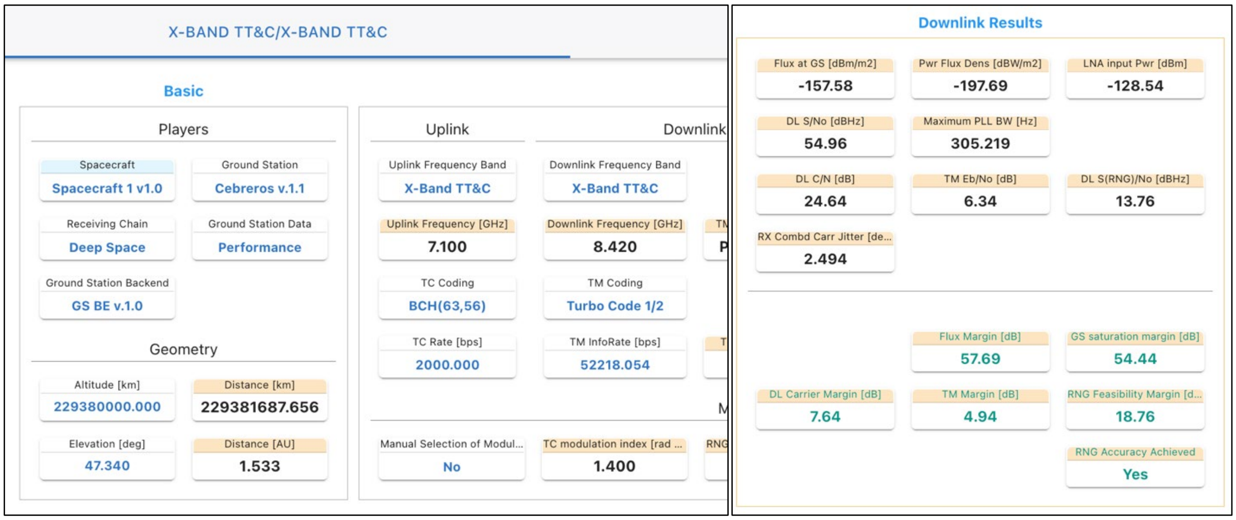

Fig. 5. Details of the Standard form. On the left, input section: orange header cells correspond to parameters computed or retrieved from the data structures; blue text cells correspond to user inputs. On the right, results preview for the uplink and downlink segments: margins are reported in green if larger than 3 dB, in red otherwise.

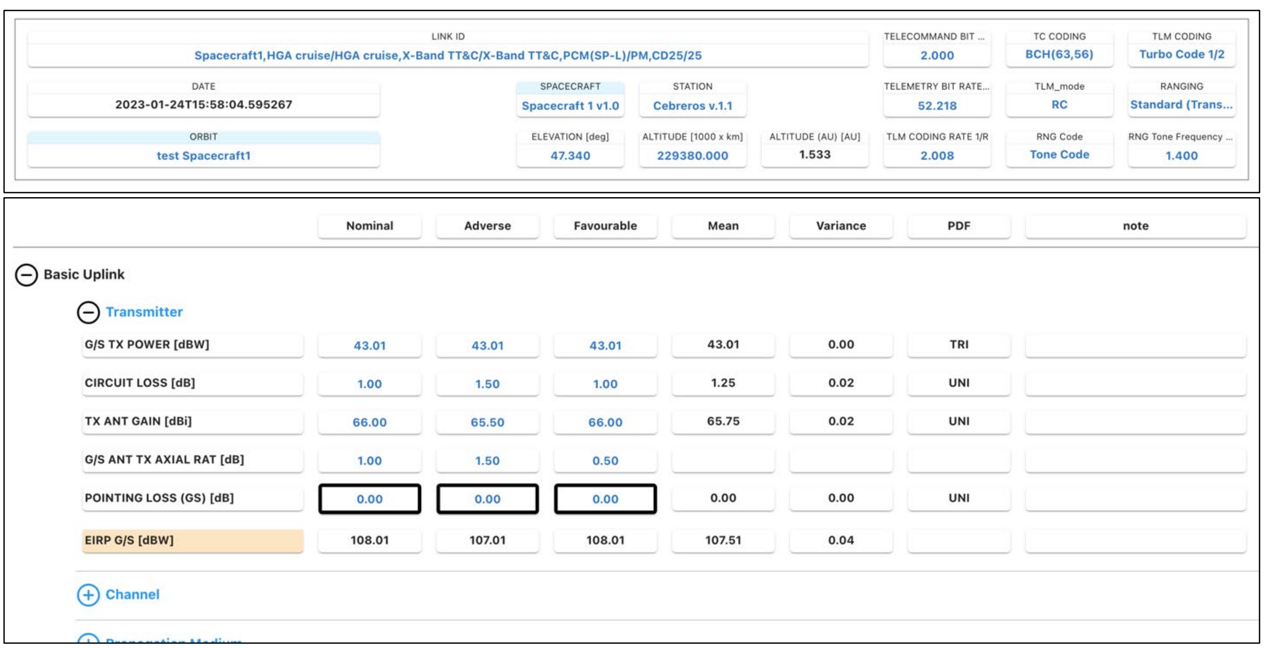

Fig. 6. Details of the Engineering form: form header (top), form body (bottom). Orange header cells correspond to computated parameters, white header cells correspond to intermediate computations, and blue text cells correspond to user inputs. Margins are reported in green if larger than 3 dB, in red otherwise.

To increase the level of control on the link budget inputs, the user can access the Engineering form Fig. 6, which is structured as a classical link control design table, where all the link budget parameters can be checked and all input parameters can be edited. When working on a Standard form, the Engineering form is filled in by LBT while retrieving the information from the data structures.

The link budget table is computed in Nominal, Adverse and Favourable conditions. Depending on the parameter type, the tool automatically computes mean and variance whenever required. The computation is updated in real time every time an input value is updated.

Once the jobs are completed, it is possible to open the relative results page. Each analysis mode has its own specific result page, with a summary of the output parameters and a downloadable MS Excel formatted report file.

Finally, a GUI page is available to the user as data structures management page, to create, edit, share, and delete data structures. The user can edit its own data structures or see and duplicate shared data structures.

3. Link Budget analysis modes

The tool aims at fulfilling the needs of different kinds of users at ESA. The system engineers designing the telecommunication space and ground systems, the ground operation managers or flight control teams in the mission operations phase are all interested in having the possibility to compute, with different levels of detail, a correct link budget.

The Link Budget Tool can be used in three different operational modes. All the operational modes can be run in multi-link mode: the user can define more than one link setup and run all the cases at once in the same run, for example a dual frequency downlink case.

3.1. Static mode

The Static (or Single) mode is used to verify link budgets in predetermined geometrical conditions defined by one elevation and slant range. The results of the computation are presented in the form of a link budget table (Fig. 7) modelling the uplink and downlink communication between the spacecraft and the ground station according to ECSS standards [7]. The relevant outputs are:

- UL and DL overall S/N_0
- UL and DL C/N
- UL and DL E_b/N_0
- UL and DL $S(RNG)/N_0$
- UL received power margin
- UL and DL carrier margin
- TC and TM margin
- UL and DL ranging margin
- DL flux at the ground station, power flux density, and flux margin
- amplifiers input power and saturation margin

	B	C	D	E	F	G	H	I
2	LINK ID							
3	Spacecraft1,HGA cruise/HGA cruise,X-Band TT&C/X-Band TT&C,PCM(SP-L)/PM,CD25/25							
5	DATE	2023-01-24T16:05:29.425805						
6	ORBIT	test Spacecraft1			ALTITUDE	(1000 x km)	229380.00	
7					ALTITUDE	(AU)	1.53	
8	SPACECRAFT	Spacecraft 1 v1.0			ELEVATION	(deg)	47.34	
9	GROUND STATION	Cebreros v.1.1						
11	REGENERATIVE RANGING		TLM COD RATE					
12	No		2.01					
13	TM CODING	TM RATE [kbps]	TM MOD SCHEME		RANGING			
14	Turbo Code 1/2	52.22	RC		Standard (Transparent)			
15	TC CODING	TC RATE [kbps]			CODE	TONE FREQ.	(MHz)	
16	BCH(63,56)	2.00			Tone Code	1.40		
19	BASIC UPLINK							

21	Transmitter	NOM	ADV	FAV	MEAN	VAR	PDF	UNITS
22	G/S TX POWER	43.01	43.01	43.01	43.01	0.00	TRI	dBW
23	CIRCUIT LOSS	1.00	1.50	1.00	1.25	0.02	UNI	dB
24	TX ANT GAIN	66.00	65.50	66.00	65.75	0.02	UNI	dBi
25	G/S ANT TX AXIAL RAT	1.00	1.50	0.50				dB
26	POINTING LOSS (GS)	0.00	0.00	0.00	0.00	0.00	UNI	dB
27	EIRP G/S	108.01	107.01	108.01	107.51	0.04		dBW

32	Channel	NOM	ADV	FAV	MEAN	VAR	PDF	UNITS
33	FREQUENCY	7.10	7.10	7.10	7.10			GHz
34	SLANT RANGE	229381.69	229381.69	229381.69	229381.69			1000 x km
35	PATH LOSS	276.68	276.68	276.68	276.68			dB
36	COPOLAR ANT GAINS	Yes						
37	POLARISATION MISMATCH	0.04	0.06	0.02	0.04	0.00	UNI	dB
38	TOTAL PROPAGATION LOSS	276.77	276.79	276.75	276.77	0.00		dB
39	POW.-FLUX at S/C	-100.19	-101.19	-100.19	-100.69			dBm/m2

link 1 X-Band X-Band

Fig. 7. Static mode MS Excel report. On the web GUI the result page of a Static mode analysis presents as a non-editable version of the Engineering form shown in Fig. 6.

Static jobs are computed in real-time as the user completes the form. A few seconds after the job is run, the results are available.

3.2. Dynamic mode

The dynamic mode allows to determine the time evolution of the telecommunication margins. The user shall provide an input file as trajectory information, with time series of elevation angles at the ground station, slant range, range rate and off-pointing angles of the spacecraft antennas. Along with the output quantities of the Static mode, the UL and DL Doppler shift and Doppler rate are computed, to help the engineers with the dimensioning of the ground receiver loop bandwidths for carrier acquisition and tracking. The results are available as a time series of link budget tables (one for each time epoch) and plots of the evolution of the output quantities with time (Fig. 8). This link budget mode is very useful in case the link geometry changes rapidly during the ground station pass, for instance during the LEOP [8].

The execution time of a Dynamic mode job depends on the length of the trajectory file and on the time step. As a reference, a 6 days analysis with a time step of 5 minutes is completed in 8 seconds.

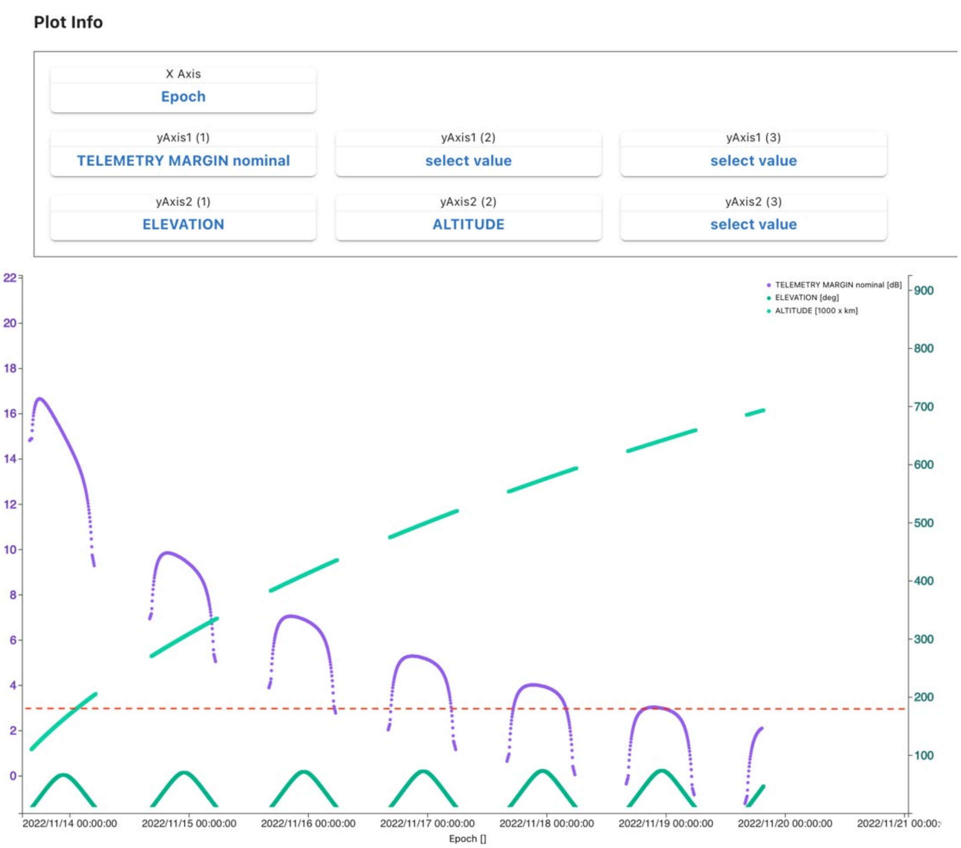

Fig. 8. Dynamic mode results page: plotting tool. TM margin are plotted on the main axis, elevation and slant range on the secondary axis. The plotting tool allows to plot 3 quantities on the main vertical axis and 3 quantities on the secondary vertical axis. The red dashed line marks the 3 dB threshold. The x-axis might be a time reference (epoch or seconds) or any quantity of the summary.

3.3. TM rate optimization

In the link budget analysis modes described in the previous sections, the transmission data rate is an input parameter. The third mode available with LBT is used instead to determine the optimum downlink rate depending on the link configuration and constraints set as input. If required, also the time window to actually transmit the downlink signal during the ground visibility slot can be optimized, by defining a minimum elevation angle at the ground station. The optimization targets only the downlink budget, because most science missions are striving to download as much data as possible from space, in an asymmetric channel capacity configuration where the uplink is used only for a limited number of commands.

The tool can perform either Link Availability or Data Return optimization.

In the first case the optimized TM rate and visibility time guarantee that the carrier and TM margins are satisfied throughout the pass for a required atmospheric availability, for example 95% of the time.

In the second case the selected TM rate and visibility time maximize the pass data return. The data return is computed as an average function (statistical expected value) considering the atmospheric conditions and the elevation angle profile at the ground station [9]. The computation requires the probability distribution function of the local atmospheric attenuation and sky brightness temperature, information that is derived at runtime by LBT from the atmospheric data structure stored as cumulative distribution function.

Orbital information is provided in the input file, in the form of an event file. The optimization can be performed for any period of uninterrupted visibility, called subpass. In case of link interruptions due to planet occultations or spacecraft antenna blockages provided in the input file, different data rates and optimized transmission time can be selected as outputs for each subpass.

The results of the optimization are provided in tabular form available both online and in downloadable MS Excel file format (Fig. 9). The tool also computes the expected transmitted, received, and lost data frames. In addition, the input event file is modified as a result of the analysis with the inclusion of the optimized output parameters, and saved as output event file.

The TM rate optimization mode is particularly suitable for integration and automation with other ESA systems, such as the Mission Planning System, for routine mission operations. Thanks to the command line interfaces of LBT, it is possible to upload input event files for upcoming mission passes from the MPS server and then retrieve the corresponding output event file containing optimization data to be used to update the spacecraft downlink configuration.

This analysis mode can also be used during the mission design phases for overall data return analysis.

Pass Count []	Optimised Pass Start Time []	Optimised Pass End Time []	Pass ID []	Pass Duration [s]	Elevation Threshold [deg]	Optimised TM Rate [bps]
2	2020-286T09:21:21.000Z	2020-286T18:51:21.000Z	A84T	34200	10.000	995980.348
5	2020-287T09:19:59.000Z	2020-287T18:51:59.000Z	A84T	34320	10.000	995980.348
8	2020-288T09:18:36.000Z	2020-288T18:53:36.000Z	A84T	34500	10.000	995980.348
11	2020-289T09:17:12.000Z	2020-289T18:54:12.000Z	A84T	34620	10.000	995980.348
14	2020-290T09:15:53.000Z	2020-290T18:54:53.000Z	A84T	34740	10.000	995980.348

Fig. 9. TM rate optimization mode results page: Optimization table.

The execution time of an optimization job depends on the number of passes or subpasses listed in the input event file and on the selected optimization level (i.e. Link Availability or Data Return, TM rate only optimization or TM rate and minimum elevation optimization). As a reference, the TM rate only Data Return optimization of an input file with 20 passes is computed in 40 seconds.

4. Integration into ESA Space Operations

LBT has been engineered not only as a design tool, but also as an application to be used in support to mission operations activities. Keywords for such usage are: reliability, robustness, availability, configuration control, automation. This means that ESA engineers must be able to compute, at any time, correct link budgets with input parameters as accurate as possible.

As described in section 2, the system architecture has been designed to guarantee redundancy and robustness. For instance, in case one of the two VMs is not available or communications issues among the cluster nodes appear, LBT remains online on a single machine and on a single node. The performance in terms of computational time and user experience can be degraded, but a minimum quality of service is provided. In addition, the operational users have priority in the queue management for the jobs' execution.

Reliability and correctness are addressed by extensive tool validation, concerning both the formulas and the data retrieval from different data structures. Dedicated tools and test instances of LBT are available for these campaigns, that are mandatory before any software release and before any update to the layout of the data structures. Nonregression test cases and procedures have been defined and are continuously updated during the project to follow the evolution of LBT capabilities.

The collection of up-to-date link budget parameters is also an important task. The data structures of LBT are available as up-to-date repository for the performance data of ESA's ground stations and of the telecommunication subsystems of ESA's spacecraft. In case of systems upgrades on ground, for instance the deployment of cryogenically cooled amplifiers, or in case of on-board characterisation campaigns, for instance of the antenna radiation pattern, the correspondent data structures are updated based on the latest measurements available. The new version of the data structure is tracked with a new configuration number and a change log, and is marked as operational, to let the users know that the data content represents the actual performance of the system. Previous versions of the data structures remain available to the users for tests as historical data.

The use of LBT as data repository and as operational tool for spacelink configuration requires adequate data protection, especially for what concerns spacecraft information. This is addressed by a strict password policy, firewall rules to block access from external networks and additional measures that prevent storing and processing of user data, including logs, outside the LBT architecture.

The first integration of LBT in mission operations at ESA is foreseen with the BepiColombo mission [10]. The tool will be used for weekly mission planning thanks to the interface developed for the MPS. For every planning cycle, a new mission event file will be submitted to the link budget tool. The file reports the up-to-date visibility time with the ground stations network and includes spacecraft configuration information to be used as link budget input parameter, as the on-board antenna selection. A TM rate optimization analysis command, with job definition based on the selected configuration file, will be sent to the tool, which in return will provide the output event file with the optimized weekly planning. The MPS will fetch the output file and used it to automatically generate the new planning in terms of telecommands to the spacecraft for uplink to the mission timeline and instructions for the ground station operations. Link optimization and planning can be performed from the same system, the MPS, without manual intervention of flight engineers for the update of the configurations. BepiColombo link operations based on LBT will be tested at ESA in the first months of 2023. Once the validation phase is successful, a new era of link budget analysis and link operations will start. From the tool side, all interfaces are ready to extend the described planning process to other science missions.

The inclusion of LBT in the weather forecast based operations system will be the next milestone [2]. Also for this project, BepiColombo is the target mission. The required link budget tool interfaces have been developed and it is already possible to compute link analyses by using atmospheric data corresponding to the weather conditions forecasted every 12 hours at two deep-space antenna sites of the ESA network: Cebreros in Spain and Malargüe in Argentina. The inclusion into the mission operations will imply that the weekly planning above discussed will be overwritten daily by link budget optimizations made available to the operations system shortly before the pass.

5. Conclusions

In the paper we have presented the new ESA Link Budget Tool, which is online for all ESA engineers since December 2021. The system architecture detailed in section 2 has proven to be reliable. The number of users connecting to the tool increased during the last months, and so did the number of operational data structures, currently available for most science missions currently operated or preparing for launch, and for the ground antennas of the ESA tracking network.

The LBT project continues: the next developments will include enhancements in the layout of the data structures, to improve the modelling of the on-board communication sub-system and of the ground station modems, and a change in the GUI software for a better user experience and response time. In the future, the core computation will be extended to include additional modulation schemes, adopted by missions in preparation that are also able to operate the link with variable transmission rates during the same visibility pass. Thanks to the flexible and scalable architecture, the new developments will affect only specific areas of the tool, allowing to optimize implementation and validation effort.

From the mission operations point of view, the use of LBT for the weekly planning of BepiColombo, with direct interface to the operational systems, is a turning point for link operations at ESA. The end-to-end validation phase with the mission team is about to start, with the aim of successfully approve the concept for baseline operations in the first half of 2023. In the meantime, the link budget tool is getting ready for the next step: weather forecast based link operations. The link budget tool is a crucial subsystem of the proposed architecture because it is responsible of providing the optimized link configuration based on the predicted atmospheric conditions, and it is used extensively for the validation of such predictions with measured link performance.

The link budget tool implementation, supported operation modes and the selected interfaces are not mission specific, so the introduction of LBT in the design and operations baseline for any ESA mission is straightforward and beneficial.

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