

Weather forecast based satellite operations at ESA

Maria Montagna^{a*}, Jose Villalvilla^b, Klara Spieker^c, Marco Lanucara^c, Paolo Antonelli^c, Livio Bernardini^d, Paolo Scaccia^e, Saverio Di Fabio^d, Marianna Biscarini^f

^a *VisionSpace @ European Space Operations Centre/ESA, Darmstadt, Germany, maria.montagna@ext.esa.int*

^b *Telespazio Germany @ European Space Operations Centre/ESA, Darmstadt, Germany, jose.villalvilla@ext.esa.int*

^c *European Space Operations Centre/ESA, Darmstadt, Germany, klara.spieker@esa.int, marco.lanucara@esa.int*

^d *HIMET s.r.l., L'Aquila, Italy, livio.bernardini@himet.it, saverio.difabio@himet.it*

^e *AdaptiveMeteo s.r.l., Rome, Italy, paolo.antonelli@adaptivemeteo.com, paolo.scaccia@adaptivemeteo.com*

^f *Sapienza University of Rome, DIET, Rome, 00185, Italy, marianna.biscarini@uniroma1.it*

* Corresponding Author

Abstract

The paper reports about the on-going introduction of weather forecast based operations (WFBO) into the operations of ESA satellite missions. The strategic capability will ensure a leap step in data rate/volume performance from science and exploration missions, as well as an enhanced availability of missions' operations. After previous works focusing on the architecture definition and on the proof of concept, the present account describes in more detail the operational setup which has been adopted, to transit from the initial breadboard development to an operational capability.

Keywords: Spacelink operations, weather forecast, radio propagation.

Acronyms/Abbreviations

API	Application Programming Interface	JAXA	Japan Aerospace Exploration Agency
ATT	Attenuation	LB	Link Budget
BT	Brightness Temperature	LWP	Liquid Water Path
CDF	Cumulative Distribution Function	NASA	National Aeronautics and Space Administration
ECMWF	European Centre for Medium-range Weather Forecast	NCEP	National Centers for Environmental Prediction
ESA	European Space Agency	RF	Radio Frequency
ESOC	European Space Operations Centre	SFL	Spacelink Feedback Loop
ESTRACK	ESA Tracking Network	WFBO	Weather Forecast Based Operations
GFS	Global Forecast System	WS	Weather Station
ITU	International Telecommunication Union	WVR	Water Vapour Radiometer (also written as RAD)

1. Introduction

Weather forecast based operations have been investigated and further developed at ESA over the last decade. The basic concept concerns the use of weather forecast at the ground station sites to manage and optimize the spacelink configuration shortly before the planned start of track. This means that instead of relying on long term statistics of the atmosphere, such as ITU yearly statistics [1], the link budgets are calculated by using atmospheric data derived from the latest weather forecast available.

The idea was introduced by NASA during the preparation of the Mars Reconnaissance Orbiter mission, which was equipped with a Ka-band (~ 32GHz) downlink demonstrator [2]. The need of an accurate characterization of the atmosphere is higher when dealing with Ka-band signals, because even non precipitating clouds and moderate rainfall can significantly degrade the radio wave propagation at these frequencies. The knowledge of the atmospheric state a day or a few hours before the spacecraft pass allows to exploit the large channel availability in clear sky days or to reduce the transmission rate to mitigate expected atmospheric impairments. Differently, link budgets based on long-term statistics, aggregated over a month or a year, and on a required availability, could become quite conservative since the atmospheric data, by definition, span a large range of weather conditions.

Similarly to the NASA experience, at ESA the weather forecast projects started during the preparation of the BepiColombo mission, which is equipped with a Ka-band downlink transponder, at 32 GHz, for science data return.

BepiColombo is a joint mission to Mercury between ESA and JAXA [3], launched in October 2018 and currently in its cruise phase, with planned arrival into the planetary orbit in late 2025.

The first activities (2013-2017) consisted in feasibility studies to evaluate the benefits of using weather forecast for the link sizing in terms of data volume improvement [4]. The studies focused on the characterization of the ESA deep-space antenna sites of Cebreros (Spain) and Malargüe (Argentina) for radio propagation at Ka-band, later extended also to X-band (8 GHz). A preliminary architecture for weather and radio-propagation forecast was identified, to simulate approximately 4 years of BepiColombo operations based on weather forecast. Weather station, microwave radiometer, and radiosonde observations data collected at the ground station sites allowed to validate and, when needed, fine tune the weather and radio-propagation models. The studies estimated a data return increase of about 20% - 25 % in case of link configuration based on weather forecast.

After the promising results, the focus moved to the introduction of such forecast system into the mission operations concept and infrastructure. As discussed in [5], the following is required for routine operations:

- Timely reception of input data for the initialization of meteorological and radio-propagation forecast.
- Timely provision of the forecast output products.
- Automatic processing of the forecast products to generate optimized spacelink configurations.
- Automatic ingestion of updated configurations into mission operations shortly before the pass, with generation of commands to the spacecraft to be sent as soon as an uplink is available, and generation of instructions to the ground station for updated support.
- Continuous validation of the forecast products and of the link performance.

A first implementation of weather forecast based operations system was achieved during the Ka-band ESTRACK support to JAXA mission Hayabusa-2 with Ka-band downlink, while the spacecraft was in the asteroid phase [6]. For the first time, between May and September 2019, weather forecast data provided 24 or 12 hours before the scheduled pass were sent regularly to the mission and ground operations team. Also, pass performance validation was performed with a flying spacecraft, instead of simulations. The system architecture was however completely detached from the operational one and the forecast products were not forwarded automatically to the link operations system, but used as information only.

The architecture developed for the test with Hayabusa-2 is the basis of the current activity, which aims at integrating the weather forecast concept into mission operations at the European Space Operations Centre, with direct interfaces to different operational sub-systems. The target mission is again BepiColombo: at present the forecast is provided for the sites of Cebreros and Malargüe, for Ka-band frequencies only, but the architecture and its interfaces have been defined with a multi-mission view and are easily scalable in terms of ground station sites and frequency bands of interest.

The paper is organized as follows: an overview of the system architecture is illustrated in section 2, while the following sections 3 to 5 describe in detail the implementation of the subsystems responsible of radio-meteorological forecast provision, link budget analysis, and system validation, respectively; the current status of the integration into the mission operations flow is provided in section 6 together with a discussion of the methods identified to evaluate the benefits of the proposed architecture for the spacelink management and for data return increase; concluding remarks are reported in section 7.

2. System architecture

The weather forecast based operations system (WFBO) architecture is shown in Fig. 1

The radio-meteorological forecast system is the core element of the architecture and it runs as a service provided by the consortium composed by HIMET s.r.l., AdaptiveMeteo s.r.l., and Sapienza University of Rome. It is composed by a numerical weather prediction model, configured for high resolution forecast in the region surrounding the considered ground stations [4] [6], that produces time series of the atmospheric parameters such as pressure, temperature, humidity, wind, etc. The forecast considers an area of 7x7 grid points, with a grid resolution of 6 km, centered at the ground antenna location. The weather outputs are ingested into the radio-propagation module, which determines the effects of the predicted atmosphere on the radio wave by means of a radiative transfer model and provides time series and statistics of atmospheric attenuation and brightness temperature at different elevation angles. The radio-propagation module is currently working at 32 GHz. In order to provide regional weather forecast, global data are needed for temporal and spatial initialization. The presented implementation relies on data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and from National Centers for Environmental Prediction (NCEP), United States. Details of the global input data, together with the operational configuration of the two modules, are reported in section 3.

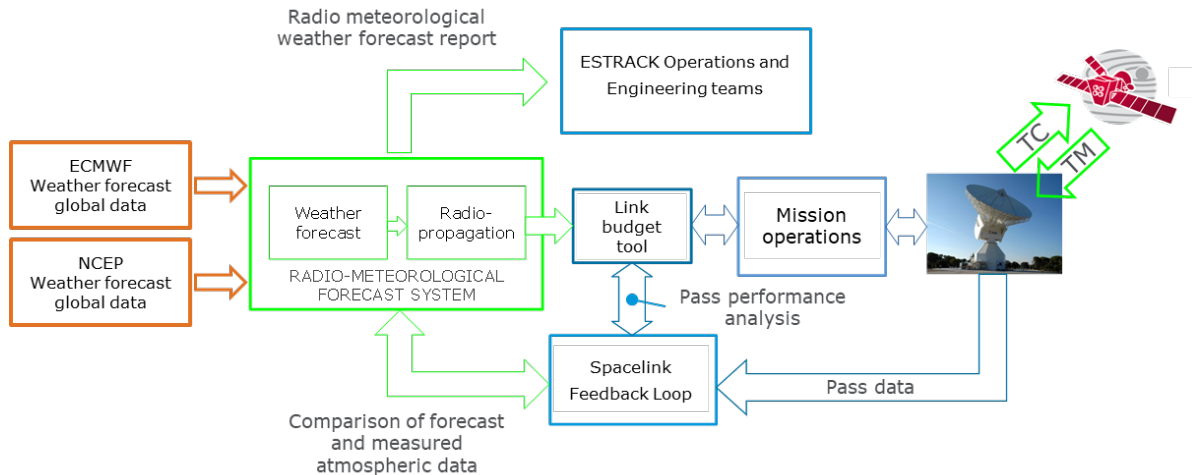


Fig. 1 WFBO system architecture. Orange: external inputs; green: radio-meteorological service provision; blue: ESOC sub-systems.

The other subsystems composing the architecture are all developed and operated at the mission control centre. The link budget tool processes the forecast data to produce optimized spacelink configurations in terms of optimized data rate for Ka-band transmission and optimized transmission time inside the visibility window at the ground stations. The outputs of the analysis are used for short term planning by the mission operations functional block, which is in charge of updating spacecraft and ground stations configuration for the upcoming pass. Environmental and link performance data are collected regularly at the ground station and stored in databases for further processing. After each spacecraft pass, the spacelink feedback loop (SFL) retrieves the related data to validate the overall system performance in terms of predicted versus measured radio-propagation and link performance. In addition, the SFL routes atmospheric and radio propagation data back to the service provider consortium for validation of all forecast products.

The described architecture is designed to be operated as much as possible in an automated way, with very limited human intervention required only for supervision or to start specific processes. The automation, gradually introduced, is achieved by automatic file transfer and retrieval and tasks to run the analyses based on the pass schedule.

The current implemented blocks cover all tasks reported above, except for the final ingestion into the mission planning, which is still under discussion with the BepiColombo flight control team.

3. Radio-meteorological forecast provision

As mentioned in section 2, global weather data are required for the initialization of the forecast: ECMWF and NCEP data. ECMWF periodically delivers weather forecast products to an operational server located at ESOC, and in turn to the WFBO systems. Such provision, which is in operation since end of April 2022, covers the geographic areas where ESTRACK deep-space antennas are located. The global input data relevant to WFBO consist of the forecast data generated by the most recent ECMWF deterministic atmospheric model. Forecast data are delivered every 12 hours. The required fields are part of the ECMWF real-time products catalogue: Set I - Atmospheric Model high resolution 10-day forecast (HRES) [7], for sub-areas covering the sites of Malargüe, Cebreros and New Norcia (Australia), the latter not further processed at the moment. The products files are encoded in GRIB format [8]. Equivalent products as the ones received from ECMWF are obtained from the Global Forecast System of the National Centers for Environmental Prediction [9].

Both ECMWF and NCEP/GFS global atmospheric predictions are used for initial and/or boundary conditions for subsequent processing by the Radio-Meteorological Forecast System of Fig. 1. The operational products are delivered twice a day and cover 24 hours, starting at 00:00 and 12:00 UTC. In order to maintain an adequate service availability, the Radio-Meteorological Forecast System is replicated on three separate platforms, as illustrated in Fig. 2:

- A primary computing platform with ECMWF and NCEP initialization.
- A primary backup platform with ECMWF initialization.
- A secondary backup platform with NCEP initialization.

In nominal operations, the primary computing platform delivers to ESOC two sets of weather forecast products: one computed with ECMWF data and one with NCEP data.

All the platforms are set up with ad hoc procedures for automatic acquisition and consistency data-check of ECMWF and NCEP initialization data. This configuration allows a switch-over to redundant (backup) systems both in case of primary hardware failure and/or unavailability of initialization data.

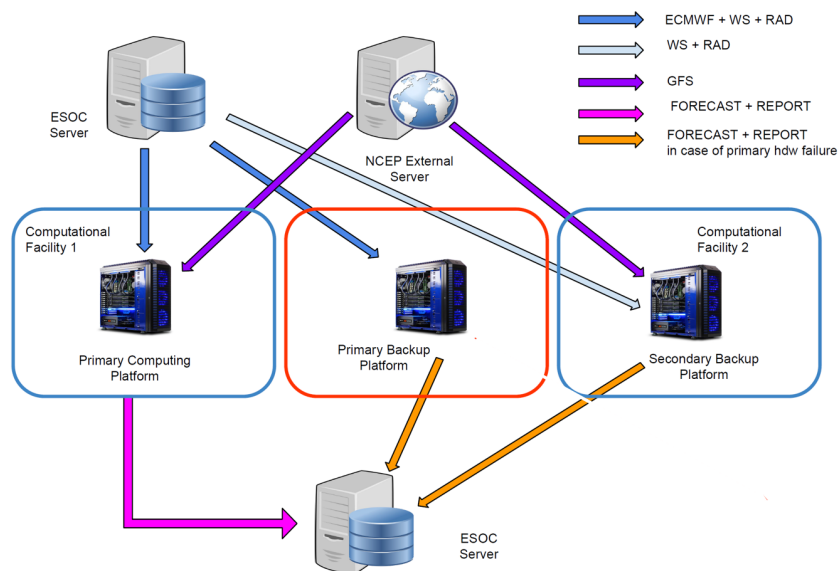


Fig. 2 Radio-Meteorological Forecast System architecture.

The automatic generation and delivery of radio-meteorological operational data, for the ground station sites of Cebreros and Malargüe, are performed in terms of:

- Time series of atmospheric attenuation and brightness temperature at 32 GHz for each time instant (with time steps of 15 min), for antenna elevation angles from 5° to 50° with 5° steps (excluding 40°) and 90° for each considered grid point in the selected grid around the antenna location.
- Cumulative probability distribution functions of atmospheric attenuation and brightness temperature, built over a 24-hour time interval, for the above set of antenna elevation angles, at 32 GHz. This means that, for each antenna elevation step, a 24-h CDF is provided for the selected frequency and site, for the two radio-propagation variables.
- Time series of wind speed and direction at the altitude point in the forecast model that is closer to antenna center or anemometer height and for each considered grid point in the selected grid around the antenna location.
- Time series of rain rate, of the amount of snow precipitated between two time steps, of pressure, temperature and relative humidity, for each considered grid point in the selected grid around the antenna location.
- Warning and critical threshold values for atmospheric attenuation, wind speed, rain rate and amount of snow precipitated between two time steps. The warnings levels are selected considering expected impairments to the 32 GHz link propagation.

The schedule of the products delivery is as illustrated in Fig. 3, whereas the actual data content is outlined in Table 1. The data is provided in NetCDF format [10].

Together with the data provision, forecast and validation reports are provided for each data release. In addition, all forecast data and measured data collected at the ground station site, from weather station and microwave radiometer, are stored and available for visualization and analysis in a Grafana dashboard (Fig. 4). The evaluation of the forecast accuracy is performed in terms of different indicators, such as index of agreement, correlation factor and calculation of root-mean-square error.

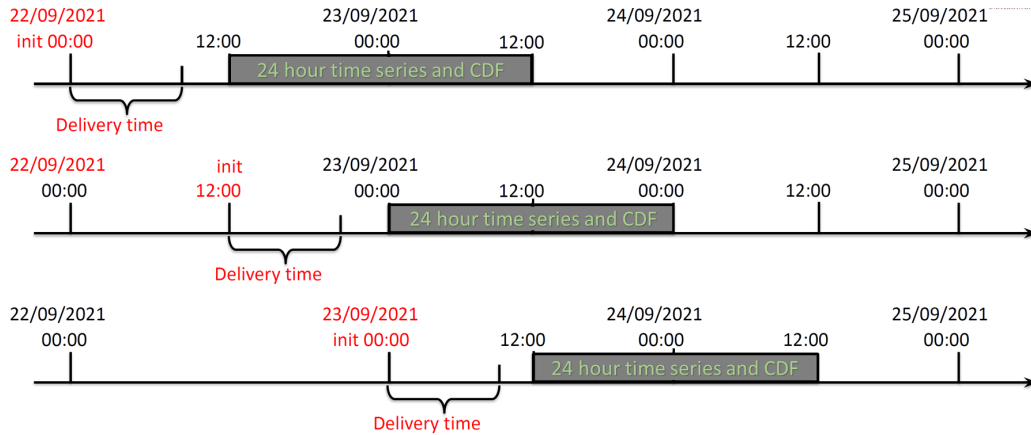


Fig. 3 Schedule of delivery of operations products by the Radio-Meteorological Forecast System.

Table 1 Operational data provided by the Radio-Meteorological Forecast System

Parameter	Description
<i>Weather Forecast Time series</i>	
wspeed	time series of wind speed [m/s] (array dimensions: 97 x 7 x 7)
wspeed warning_thr	wind speed warning threshold (dimension: 1)
wspeed_critical_thr	wind speed critical threshold (dimension: 1)
wdir	time series of wind direction [deg] (array dimensions: 97 x 7 x 7)
rainrate	time series of rain rate [mm/h] (array dimensions: 97 x 7 x 7)
rainrate warning_thr	rainfall intensity warning threshold (dimension: 1)
rainrate_critical_thr	rainfall intensity critical threshold (dimension: 1)
snow	time series of the amount of snow precipitated [mm] at model temporal resolution (15 min.) (array dimensions: 97 x 7 x 7)
snow_warning_thr	the amount of snow precipitated [mm] at model temporal resolution (15 min.) warning threshold (dim: 1)
snow_critical_thr	the amount of snow precipitated [mm] at model temporal resolution (15 min.) critical threshold (dim: 1)
pressure	time series of pressure [hPa] (array dimensions: 97 x 7 x 7)
temperature	time series of temperature [K] (array dimensions: 97 x 7 x 7)
relative_humidity	time series of relative humidity [%] (array dimensions: 97 x 7 x 7)
<i>Radiative Transfer Forecast Time series at 32 GHz</i>	
elev	antenna elevation angles from 5° to 50° with 5° steps (excluding 40°) and 90° (array dimension: 10)
freq	frequency of 32 GHz
att	time series of atmospheric attenuation [dB] (array dimensions: 10 x 97 x 7 x 7)
att_warning_thr	attenuation warning threshold (dimension: 1)
att_critical_thr	attenuation critical threshold (dimension: 1)
bt	time series of brightness temperature [K] (array dimensions: 10 x 97 x 7 x 7)
<i>Radiative Transfer Forecast statistical at 32 GHz</i>	
cdf_att_support_db	CDF attenuation values (array dimensions: 10 x 97)
cdf_att_probability	CDF probability values (array dimensions: 10 x 97)
cdf_bt_support_k	CDF brightness temperature values (array dimensions: 10 x 97)
cdf_bt_probability	CDF of brightness temperature probability values (array dimensions: 10 x 97)

4. Link budget analysis

The ESA Link budget tool is the reference tool for link budget calculation at the mission control centre. It is a web-based application, accessible to all engineers within the working network [11]. The tool includes databases with up-to-date spacecraft and ground stations parameters, which can be retrieved for routine link budget calculations. Also parameters to model the propagation media, including atmospheric statistics and celestial body noise temperature are available. In the frame of WFBO, a REpresentational State Transfer Application Programming Interface (REST API) has been developed as machine-to-machine interface for the other subsystems.



Fig. 4 Grafana: example of comparison of forecast (in green and violet) and measured (yellow) radio-propagation products, Cebreros, November 2022.

The main tasks assigned to the link budget tool in this project are:

- Import daily received atmospheric forecasts as netCDF files and automatically generate a database entry, with associated validity start and end time.
- Execute link budget optimization analyses for the upcoming scheduled passes, by using the latest weather forecast data, automatically selected by the tool; mission and ground station main parameters can be recalled by using stored link set-up information, e.g., BepiColombo, high gain antenna for uplink and downlink, ranging active, Cebreros, X/Ka link.
- Execute link budget analysis as requested by the spacelink feedback loop, for the evaluation of the link performance after the pass.

At present, the tool imports and processes only the CDFs of the propagation variables. Therefore, the same link budget methods already available with long-term atmospheric statistics can be selected for weather forecast analyses. The use of weather forecast time series is at present not included, because it is considered subject to the space-time double penalty of a model forecast: the error of the forecast could arise from predicting an atmospheric phenomenon correctly in time, but in the incorrect place or, vice versa, correctly in space but at the incorrect time. A preliminary investigation in the use of time series has been addressed during the weather forecast operations test with the Hayabusa-2 mission [6].

The link budget tool can ingest mission event files, which list events of start/end of tracking, pass interruptions due to blockages, spacecraft configurations relevant to the link budget analysis and orbital information for the calculation of elevation and slant range profile during the ground station support. Once the link optimization is performed, an updated event file is produced as output, to be used directly by the mission operations systems to update the configuration for the upcoming pass.

From the software architecture point of view, the link budget tool has been designed to guarantee redundancy and robustness. From the calculation side, the tool is subject to extensive validation, concerning the basic formulas, the subsystem models, and the interaction with its databases.

5. Spacelink feedback loop

The objectives of evaluating the pass performance and comparing it with the predicted one are twofold: determination of the benefits achieved with the introduction of weather forecast based operations, and constant monitoring of the whole system architecture.

Daily, the spacelink feedback loop initiates the validation process. Ground station data collected the day before are retrieved by the SFL from the archiving database: weather station data as temperature, humidity, rainfall intensity, etc.; microwave radiometer data as brightness temperature and atmospheric attenuation measured or extrapolated at different frequencies; ground station system data, as parameters recorded at the modem or by the antenna positioning system, collected only in case of satellite passes.

The first type of SFL analysis aims at comparing the expected propagation variables with the radiometer measurement, in terms of cumulative distribution functions for the 24 hours under evaluation. CDFs are selected because they represent the data used for the link budget calculations: a large discrepancy between radiometer and

forecast is very likely reflected also in the link performance comparison. An example of very good predictions is shown in Fig. 5, for a rainy day in Cebreros.

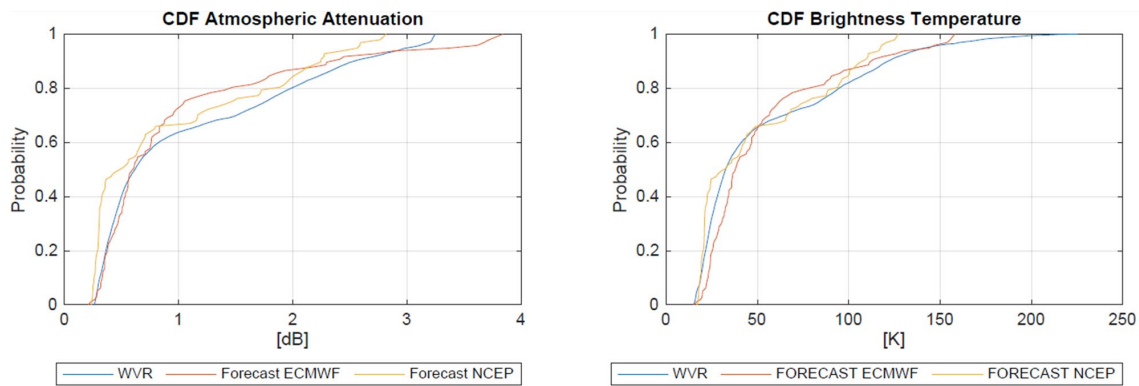


Fig. 5 Example of SFL analysis: comparison of Zenith atmospheric attenuation and brightness temperature CDFs at Ka-band (32 GHz), Cebreros (Spain), 13 December 2022. ECMWF and NCEP forecast start: 00:00 UTC.

The WFBO concept focuses on the propagation effects; however, when evaluating the spacelink performance the whole communication system, on board and on ground, also needs to be considered.

An example of performance analysis of BepiColombo Ka-band downlink is shown in Fig. 6. In the top panel, the most relevant parameters for the evaluation of the signal to noise ratio are reported. The left plot (a) shows the two different components of the signal-to-noise ratio: the carrier level (blue, left axis) indicates the evolution of the signal power, while the red dots correspond to the total power recorded at the input of the wideband receiver (right axis). In the case of BepiColombo, the downlink signal occupies a small bandwidth compared to the receiver bandwidth (hundreds of MHz) and is weak due to the large distance, so the total power is in fact representing the total noise that is received by the antenna at Ka-band, whose variation is dominated by the sky noise, in turn related to the atmospheric brightness temperature. The plot on the right (b) shows the energy-per-symbol-to-noise-power-spectral-density ratio, E_s/N_0 , measured at the demodulator (green dots), versus different link budget estimates of E_s/N_0 (green dashed line, red and blue cross, left axis). The E_s/N_0 (the ratio between the energy of a coded binary symbol and the noise spectral density) is the core parameter of the pass performance, because it is impacted by the evolution and possible degradation of any other parameter of the analysis, and ultimately can cause frame loss, here shown as a cumulative number on the right axis (yellow dots). Ideally, data loss should be avoided; yet, thanks to the implementation of file transfer mechanism with related retransmission functionality, frame gaps can be recovered by the mission operations system. The plot in the middle panel, left (c), shows the pointing elevation (blue, left axis) and azimuth (red, left axis) angle of the ground station during the pass, with the corresponding error registered by the antenna positioning system (right axis). Atmospheric impairments are larger the longer the path through the atmosphere; therefore, it is essential to relate the evolution of the signal to noise ratio to the ground station elevation angle. For example, in clear sky conditions, the total noise decreases when the elevation angle increases, because the volume of atmosphere observed by the antenna is smaller. Finally, parameters related to the atmospheric and weather conditions measured during the pass are reported. In the middle panel, right (d), the atmospheric attenuation (blue, left axis) and the brightness temperature (green, right axis) measured by the radiometer at Ka-band, at the same azimuth and elevation angle at which the ground station is pointed to, are shown. It should be possible to relate any disturbance observed in the attenuation to a decrease of the carrier level, in the same way as any increase of the brightness temperature should correspond to an increase of total input noise. The bottom panel, left (e), reports the wind characteristics: direction (blue, left axis) and speed (red, right axis). At Ka-band, the beamwidth of the antenna is significantly narrower than at lower frequencies (for example 4 times smaller than at X-band), so high wind conditions can degrade the pointing performance; this effect is visible as signal level decrease. The effect of the wind depends also on the relation between antenna pointing position and wind direction. To conclude, the bottom right plot (f) shows liquid water path measured by the radiometer in the direction of the spacecraft (blue, left axis) and the rain intensity at the ground station site (violet, right axis). This information helps in the interpretation of the radiometer measurement, because the measured value of attenuation and brightness temperature can saturate in case of heavy or continuous rain.

In the considered pass, the weather conditions were good, corresponding to clear sky until about 15:00 UTC. After that, it is possible to notice a degradation of the signal to noise ratio, possibly caused by higher liquid content

along the spacelink path (clouds) and by the increase of the wind speed, therefore of the pointing error. For the weather forecast project, the most important comparison is shown in Fig. 6(b), where the measured performance is compared with the expected one, defined by the link budget analyses computed before the pass with the weather forecast system products. In the selected example, atmospheric attenuation and brightness temperature valid from 00:00 UTC of the day of the pass are used for the link budget predictions. The graph shows that the forecast E_s/N_0 is mostly lower than the measured one, but the difference reduces in the last two hours of the pass, during the weather impairments. The use of the weather forecast products would lead in this pass to a slightly conservative link configuration, which would reduce the transmitted data but at the same time mitigate the weather impairments and, in case of lower link margins, avoid data loss.

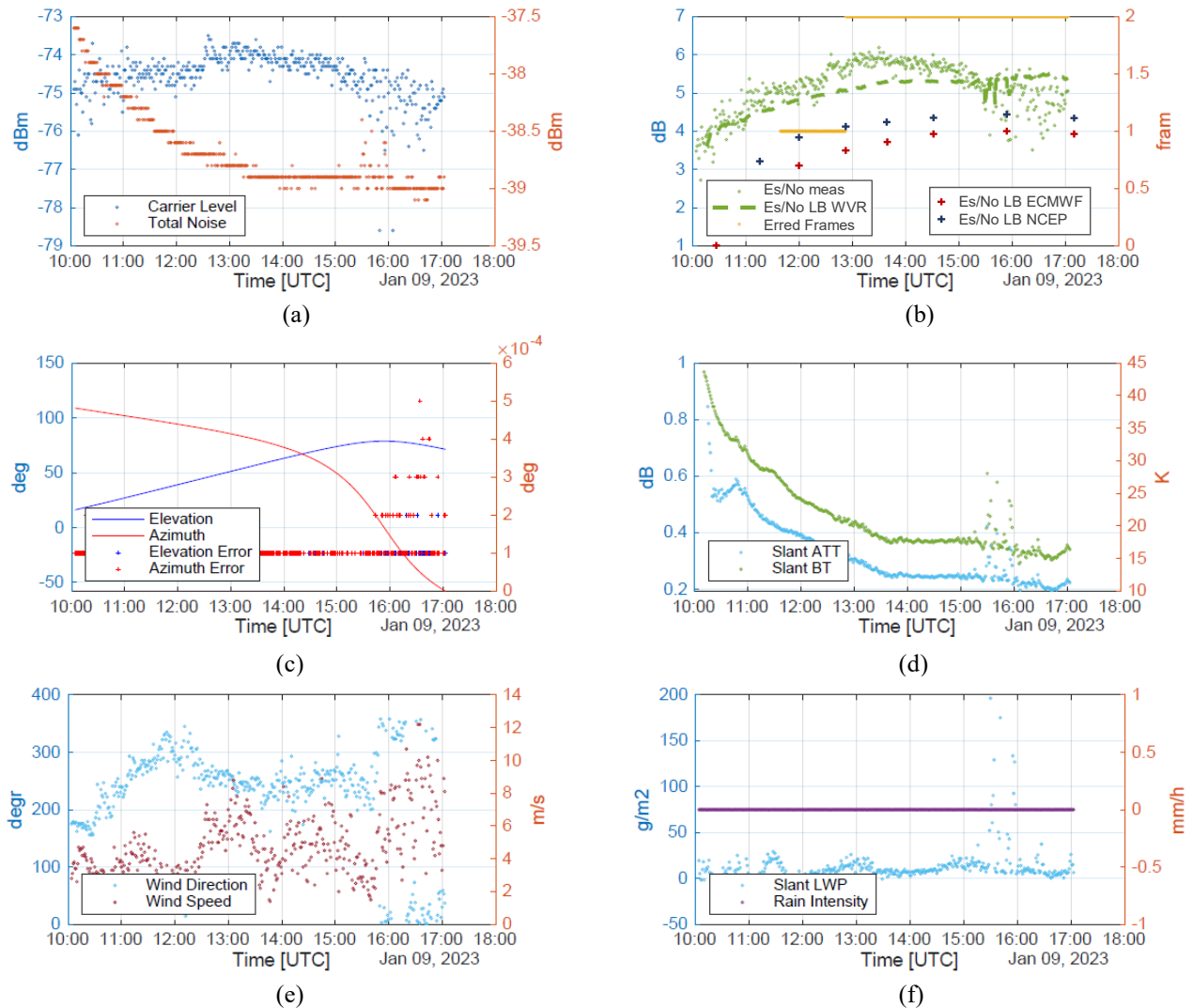


Fig. 6 Example of SFL analysis: pass performance analysis, BepiColombo Ka-band downlink (32 GHz), Malargüe (Argentina), 9 January 2023.

6. Integration into mission operations and expected benefits

The WFBO is meant to be a capability available for spacecraft operations, starting from BepiColombo Ka-Band downlink and later extended to all interested missions in a broader context of frequency bands and involved ground stations, with a long term objective of covering optical communication as well. The transition from a breadboard capability into an operational capability is a challenging on-going task, focused on integrating the distributed architecture shown in Fig. 1 into the existing operational software infrastructure of ESOC. Such integration must bring the newly developed subsystems into the operations workflow, with fully documented processes, long term

maintenance, and sustaining plan, to cope with anomaly resolution and system evolution. The current status of the system integration is as follows:

- The data interfaces with ECMWF (via ESOC server infrastructure) and NCEP are fully operational.
- The provision of weather forecast products by the consortium is fully operational since May 2022. Such capability includes the delivery of operational data and report, the provision of monitoring services via the Grafana tool as well as the delivery of operational weather alerts to operations and engineering teams. The products provision is structured as a service, with maintenance/sustaining/configuration control under the responsibility of the service provider. Since start of operations, the deliveries have been regular and on schedule.
- The link budget tool, including the capability developed for WFBO, is fully operational.
- The SFL capability is under development; it is currently available as a breadboard of the various functions described in section 5;
- The adaptation of the mission operations systems has yet to take place, being BepiColombo, the target mission, currently fully focused on cruise operations. At present, the optimized link configurations are not used for actual operations, though they can be used for validation purposes as described in section 5.

The adoption of WFBO by the missions as operations baseline depends on the benefits achieved by implementing the approach. For this reason, a careful analysis for quantifying such benefits is ongoing. The validation data collected and processed by the radio-meteorological forecast system and by the spacelink feedback loop are the main source of information.

The first question to be answered is related to the forecast accuracy, for both steps of weather forecast and atmospheric propagation forecast. This is the main task of the validation performed by the consortium, with the definition of statistical figures, like index of agreement or correlation factors, to help summarizing the day-to-day performance. In case discrepancies are regularly observed, an update of the physical models and parameterization might be required. The validation is in progress. Qualitatively, the forecast data is in general very good also in predicting rainy conditions, for which however it can be difficult to estimate the amount of rain intensity, especially in case of very quick events.

Intuitively, if weather forecast data are accurate, also the predicted link performance based on them is accurate. Nevertheless, additional factors on the link management based on the forecast can be considered. For example, a point under examination concerns the best practice in the use of the forecast CDFs depending upon the predicted conditions. More in detail, the idea would be to exploit the clear sky forecast, which turns out to be typically pretty accurate in terms of predicted weather and propagation effects, in order to obtain the largest improvement in data return. Instead, for forecast of very cloudy/rainy conditions, which also reveal more discrepancies between predicted and actual conditions, it could be wise to act more conservatively to avoid severe disruptions. A more conservative use of the forecast CDFs could also be applied for missions which focus on high spacelink availability and low latency rather than data volume, like for example the VIGIL Space Weather mission [12], designed with an availability target in excess of 99% and with a latency of few minutes on top of the one-way light time to receive the data from a distance of 1 astronomical unit. In the frame of the link performance analyses, different methods for link budgets and CDFs use are being compared.

Not only the use, also the definition of the CDFs on the forecast area is being assessed. As illustrated in Table 1, the products to be used as input to the link budget are CDFs of the quantities of interest, at given elevations, associated to given forecast periods. One important issue is how to form the statistical ensemble from which such CDFs are derived. At the moment, the ensemble is built by computing the median value for each grid point delivered at a given time: the sequence of median values for all time tags within the forecast period is then defined as the ensembles from which the CDF is derived and associated to the same forecast period. From initial evaluations, such approach, while being adequate for clear sky conditions, proved to be somehow optimistic in presence of strong weather effects, due to the action of the median function removing the situations of extremely bad weather from the grid. Alternative approaches are currently being evaluated.

7. Conclusions and future works

The presented operations concept, its implementation and the thorough undergoing validation demonstrates that WFBO has reached the required maturity for ingress into day-to-day satellite operations. The full processing chain transforming ECMWF and NCEP weather forecasts into usable radio propagation products available through fully fledged and reliable service provision, and in turn into optimized link configurations, has been completed. The validation is on-going. The results available so far are very promising and only minor discrepancies, amendable by means of model fine tuning, have been observed. In addition, different link management approaches have been

identified to exploit the weather forecast concept as much as possible under different atmospheric conditions. The WFBO capability has been exposed to ESOC operations teams with good feedback on the products currently made available.

The residual step to be implemented is the application of the optimized configurations to the satellite operations, by commanding the appropriate configuration to on-board and on-ground systems. This step will complete the operations architecture and it is planned to start with BepiColombo, with gradual subsequent infusion into the operations systems of other science and exploration missions. Further on, it is planned to extend such operations to different applications, like Earth Observation or Space Weather, typically requiring very high communications link availability, in excess of 99%. In the long term, WFBO could be a crucial ingredient for optical communications, not only for presenting the user with optimised link configurations for a give site, but also to help the dynamic site selection process for missions relying on site diversity to reach the required link availability.

Whereas the current focus for WFBO engineering and operations teams is to finalise the transition of the capability to full operations, its further evolution has already started, to incorporate new frequency bands (or wavelength within the optical domain), new sites (within or beyond ESA), and new operations concepts (use of nowcast for clouds coverage mitigation in optical communications). From the point of view of radio-frequency and optical wave propagation, WFBO has motivated the quest for improved modelling of the atmospheric effects and associated impairments, like in the case of the attenuation from cloud formations, which is crucial for optical communications and will be the subject of future studies.

When recollecting the history of this journey, from the initial intuitive understanding of the benefits which can be obtained from the a-priori knowledge of the propagation channel more than a decade ago, until the current quasi-operational status of the overall system architecture of Fig. 1, the large time-scale involved in radically changing operations habits can be appreciated. However the effort is worth, as demanded by the large set of future challenging missions.

Acknowledgements

Professor Frank Silvio Marzano was, among many other remarkable academic and research roles, one of the founders of the presented approach since the very start, and made the current status possible by means of his in-depth knowledge and strategic vision. We deeply regret his loss and acknowledge his immense contribution.

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