REMOTE LEOP AND IN-ORBIT SUPPORT WITH AUTOMATED HEALTH MONITORING APPLIED TO THE COSMO-SKYMED MISSION

F. Corallo[a]*, A. Nicito[b], M. Vanzulli[c], A. Croce[d], A. Ruscitti[e], C. Oddi[f], M. Virelli[g], F. Longo[h], G. Varacalli[i] , R. Lorusso[l] , C. Facchinetti[m], E. Tedeschi[n]

Thales Alenia Space Italia (TAS-I), Via Saccomuro 24, 00131, Rome, Italy,
{ [a]francesco.corallo, [b] annamaria.nicito, [c] matteo.vanzulli, [d] anna.croce } @thalesaleniaspace.com
T*elespazio, Fucino Space Centre, 67050, Ortucchio, Italy,* { [e] alessandro.ruscitti, [f] camillo.oddi } @telespazio.com
Agenzia Spaziale Italiana (ASI), Via del Politecnico, 00133, Rome, Italy, { [g] maria.virelli, [h] francesco.longo, [i] giancarlo.varacalli, [l] rino.lorusso, [m] claudia.facchinetti, } @asi.it
Italian Ministry of Defense, Via Venti Settembre, 8, 00187 Roma, Italy, [n] r4usacs.cs1@sgd.difesa.it
* Corresponding Author

Abstract

Thales Alenia Space (TAS) is prime contractor for many of the world's most advanced satellite systems and challenging space missions. For some of these satellite constellations, like Cosmo-SkyMed (CSK) and Cosmo-SkyMed Second Generation (CSG), designed and built for the customer *ASI (Agenzia Spaziale Italiana)* and the *Italian Ministry of Defence (It-MoD),* Thales Alenia Space Italia (TAS-I) provides also operational in-orbit engineering support, working jointly with Telespazio, which is the Ground Segment provider as well as Flight and Ground Operations responsible. This work details the evolution of the systems set-up by TAS-I in order to remotely support the Cosmo-SkyMed Second Generation FM2 Launch and Early Orbit Phase (LEOP), and also to improve the mission in-orbit engineering support, in particular the monitoring of the constellations' health through advanced data analysis applied to the downlinked telemetry, and the investigation and resolution of on-board anomalies. The telemetry archives downlinked from the spacecraft of the constellation are being automatically transferred from the Satellite Control Center to TAS-I premises, where they are automatically processed and analyzed with ad-hoc procedures. A number of Big data processing tools have been deployed in TAS-I premises in order to improve the telemetry monitoring and anomaly detection processes, exploiting a range of data processing techniques including Machine Learning algorithms, in order to support the anomaly investigations processes, and also provide constellation-wide trend analysis, finally allowing to extract valuable information from telemetry data. These newly introduced approach contributed to the successful execution of the Launch and Early Orbit Phase of the second CSG satellite, and is greatly improving the overall in-orbit support activity, health monitoring and constellation maintenance process.

Keywords: LEOP Remote Support, Telemetry Analysis, Health Monitoring, Big Data, Artificial Intelligence

Acronyms

Agenzia Spaziale Italiana (ASI)
COnstellation of small Satellites for Mediterranean basin Observation (Cosmo-SkyMed)
Cosmo-SkyMed (CSK)
Cosmo-SkyMed Second Generation (CSG)
Failure Detection Isolation & Recovery (FDIR)
Flight Module (FM)
Flight Operation Procedure (FOP)
Italian Ministry of Defense (It-MoD)
Launch & Early Orbit Phase (LEOP)
Project Support Room (PSR)
Syntethic Aperture Radar
Telespazio (TPZ)
Telemetry & Telecommand (TM&TC)
Thales Alenia Space Italia (TAS-I)

1. Introduction

Cosmo-SkyMed (COnstellation of small Satellites for Mediterranean basin Observation) is an Italian Dual-Use (Civilian and Defence) end-to-end Earth Observation System, commissioned and funded by Italian Space Agency (ASI) and Italian Ministry of Defense (MoD).

The first generation of the constellation (CSK) consists of four Low Earth Orbit mid-sized satellites, each equipped with a multi-mode high-resolution Synthetic Aperture Radar (SAR) operating at X-band, and with All weather and Day/Night acquisition capabilities. The COSMO-SkyMed Second Generation (CSG) is the follow-on mission to the first generation constellation, consisting of two radar satellites, already in flight and operational, expandable to a total of four satellite in the constellation. The mission has the twofold need of ensuring operational continuity to the currently operating “first generation” COSMO-SkyMed satellite constellation (CSK), while achieving a generational step ahead in terms of functionality and performance [1]. Table 1 summarizes the launch dates and current operational status of the six flying satellites.

Table 1. CSK and CSG missions status

	Launch Date	**Mission Phase**	**Curr. age (exp. age)**
CSK-1	08/06/2007	Operational	15 (5)
CSK-2	09/12/2007	Operational	14 (5)
CSK-3	25/10/2008	End of mission	13 (5)
CSK-4	06/11/2010	Operational	11 (5)
CSG-1	18/12/2019	Operational	3 (7)
CSG-2	31/01/2022	Operational	1 (7)

The Constellation has been designed and built for the customer *ASI (Agenzia Spaziale Italiana)* and the *Italian Ministry of Defence (It-MoD).* Thales Alenia Space Italia (TAS-I) is the prime contractor for both the CSK and CSG constellations, taking care of the Mission Phases from the mission requirements flow-down and early engineering design, up to the Launch Campaign. The Space Segment Operations unit of TAS-I gives crucial support throughout the whole Spacecraft development, taking care of all the Operational engineering aspects, including the LEOP & Deployments timeline design, Flight Operation Manuals, Simulator development and maintenance, System Validation Tests and Flight Dynamic and TM&TC Databases development. Moreover TAS-I provides crucial support also in the Operational Phase, providing post-launch in-flight engineering support via Maintenance Support Contracts with the customer, working jointly with Telespazio which is the Ground Segment provider as well as Flight and Ground Operations responsible.

The objective of this paper is to describe the systems deployed in TAS-I premises to remotely support the Launch and Early Operation Phase (LEOP) and the in-flight support through advanced data analysis tools.

This paper is structured as follows: after the introduction, Section 2 describes the LEOP activities and the in-orbit engineering support provided by TAS-I; Section 3 describes the Remote Project Support Room and the tools used during the LEOP of CSG FM-2; Section 4 describes the activities and ecosystem set-up in TAS-I premises to offer in-flight engineering support for the constellation.

2. Cosmo-SkyMed Second Generation LEOP & Mission Support

2.1 LEOP remote support activities

The Launch and Early Operation Phase starts with the launch and ends up after completion of the appendages deployment and acquisition of the nominal operational orbit. This is arguably the most delicate phase of the mission, as vital operations like the deployment of solar arrays and acquisition of a power-positive condition, initial health check and configuration of the satellite subsystems are carried out.

Fig. 1. Summary of Mission Phases after Launch

The execution of the LEOP for the Cosmo-SkyMed satellites is in charge of Telespazio and performed in Fucino Space Centre, which is the Mission Satellite Control Center (S-CCS). People from TAS-I Space Segment Operations (SSO) team, together with subsystems Engineering Specialists, actively participate in the LEOP as "Project Support team", with a dedicated Project Support Room (PSR) in the Satellite Control Center, where some of the Ground Segment workstations are made available to allow the monitoring of the relevant platform telemetry data and on-board events, to help confirming that the spacecraft behaves as expected, to monitor the behavior and performance of the on-board subsystems and units, and to provide recommendations and support during the critical activities like appendages deployments and the resolution of possible anomalies.

The second satellite (FM2) of the Cosmo-SkyMed Second Generation constellation was launched in the end of January 2022, during the worldwide pandemic crisis related to the diffusion of COVID-19. In this frame TAS-I proposed to Telespazio and the Customer to configure a Remote Project Support Room (R-PSR) located in TAS-I premises in Rome, to reduce the risk of a possible spread of the virus among the engineers involved in the LEOP, at the same time increasing the number of engineers who could support this critical phase, and giving also the chance to young industry engineers to be involved in a unique experience like the LEOP. More details are reported in Section 3.

2.2 In-orbit engineering support activities

After the Launch & Early Operation Phase, during the Commissioning Phase all the on-board subsystems and payloads are verified and calibrated if necessary. At this point the satellite is ready to enter the Routine Operational Phase. During the routine operations phase the Ground Segment (in this case *Telespazio*) manages the satellites of the constellations, downlinking platform and payload data, and uplinking the required Telecommands and Mission plan. In accordance with the Customer TAS-I provides post-launch in-orbit engineering support via Maintenance Support Contracts. This includes the analysis and investigations of on-board anomalies, the support to operations, the maintenance of the on-board software, design and simulation of reduced-operation modes (see [2] and [3]), the Preventive Maintenance based on the archived telemetry and other activities required to ensure the continuous and full operational capacity of the constellation.

3. Remote CSG FM-2 LEOP Support

3.1 Satellite Control Center – TAS-I link

A secure communication link is established between the Satellite Control Center (*Fucino Space Center*) and TAS-I premises in Rome. This link only interconnects the Fucino LEOP building and TAS-I facility in Rome, without invalidating and compromising the actual Routine operational activities, for obvious security reasons. The security is ensured by using secured Virtual Private Network service and encrypted protocols for data transfer. The VPN is also protected by Firewall devices dedicated to monitoring all packets to detect any threats, prevent attacks by viruses and malware and ensure greater security through an access policy.

The objective of this link is twofold:

- Allow the remote usage of some of the Satellite Control Center workstations located in Fucino.
- Allow the instantaneous transfer of raw telemetry data archives.

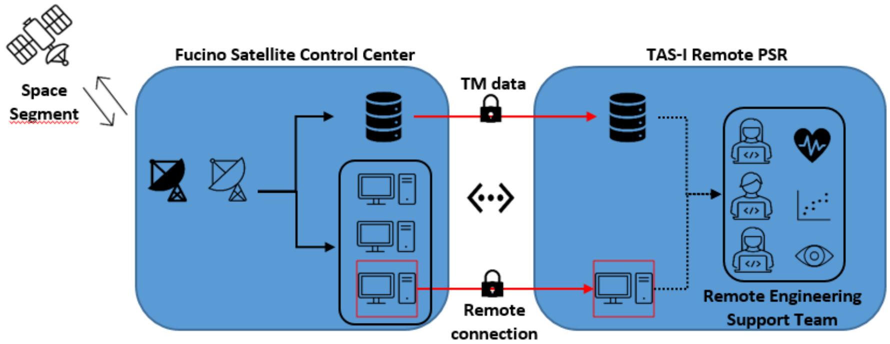

Fig. 1. *Telespazio – TAS-I* link architecture

3.2 Remote PSR Facility

Fig. 2. LEOP TAS-I remote PSR facility

The TAS-I Remote Project Support Room in Rome successfully allowed a second "Remote" Project Support Team during the CSG FM2 LEOP, while the main "Local" team was on-site in the Project Support Room of Fucino Space Centre. This doubled the engineering support offered by the Industry while reducing the risk of spreading the virus among Telespazio and Industry engineers, thus avoiding endangering the LEOP activities.

The Remote Project Support facility is equipped with workstations connected to the secured VPN between TAS-I and Telespazio, allowing the remote use of up to four Telespazio/Ground Segment workstations without limiting the functionality. The Remote Project Support facility is equipped also with large monitors and state-of-the-art hardware in order to make the process effective and safe.

The instantaneous transfer of telemetry raw data archives is guaranteed through a dedicated script that runs in parallel on the LEOP Control Center to detect the immediate availability of a TM raw file received from the Ground stations.

3.3 Automatic Telemetry Retrieval

The raw Telemetry archives downlinked from the spacecraft can be processed to extract the history of on-board events and the evolution of thousands of telemetry parameters, which are critical to assess the correct behavior of the satellite subsystems and to detect and solve possible anomalies. Consequently during the LEOP and the Operational life of the satellites of the constellation, the downlinked telemetry archives are shared with TAS-I (via the *Satellite Control Center – TAS-I* link, see section 3.1), which in turn processes them and provides feedback to Telespazio about the constellation health and correct behaviour.

The processed platform Telemetry data is securely stored in TAS-I premises in a dedicated Database which allows to process the data and feed large amounts of telemetry data to the Data processing Ecosystem (see section 4), allowing for example to produce long-term Trend Analysis about on-board units degradation, and to extract valuable information about the constellation health.

3.4 LEOP Support Tools

Several Software tools were developed to provide better engineering remote support during the critical LEOP activities.

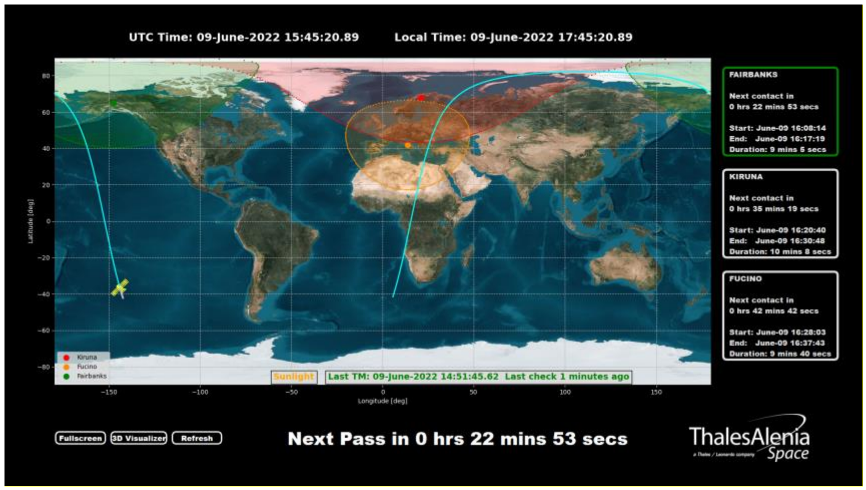

Fig. 3. TM-based orbit propagator and visualizer tool used in the remote PSR

The first software tool consists in an orbit propagator and ground contacts predictor, with the objective to allow the Remote Support Team to be prepared in time for the subsequent ground contacts, without interfering with the actual Satellite Control Center activities. This tool is written in Python and it’s connected to the Telemetry Database, in order to extract the last actual position and velocity values (PVT) from flight telemetry data and use them as input to the orbit propagation process, periodically updating the prediction as soon as newer telemetry data becomes available. Moreover a User Interface (Figure 3) provides visual information about spacecraft and ground stations locations and visibility regions. The tool was validated during the CSG FM2 LEOP, and it allowed to obtain very accurate predictions based on the actual orbit reached.

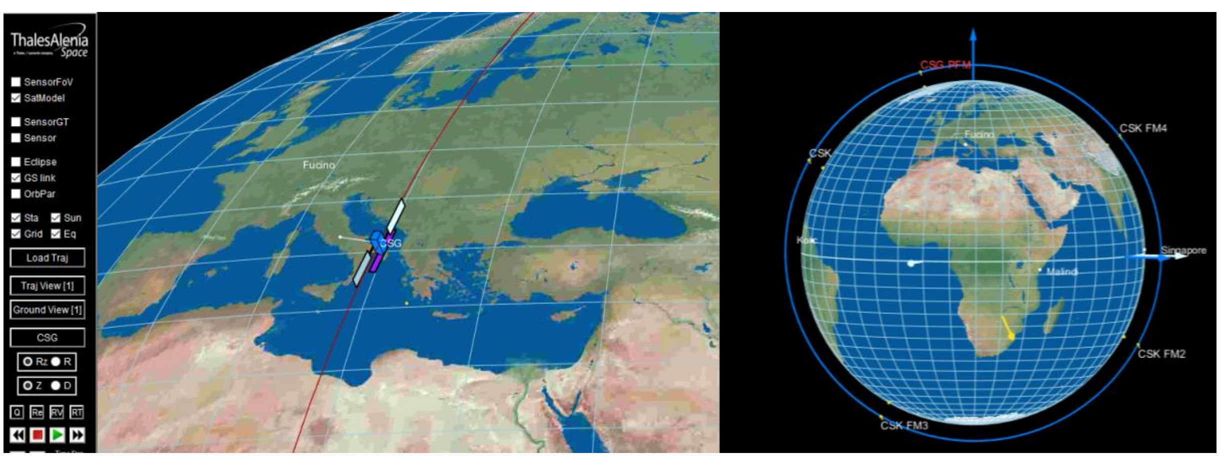

Fig. 4. Orbit and Attitude Visualizer UI

The same tool allows also to extract historic telemetry data about spacecraft position and attitude and pass them to an Orbit & Attitude Visualizer (Figure 4). The objective of this tool is to facilitate the visualization of attitude data and correlate it with the orbit position, allowing to evaluate the correct behaviour of the satellite. Moreover the orbit of several other spacecraft can be visualized in order to evaluate the relative position of the spacecraft of the constellation.

The communication between the local and remote Project Support Teams was granted by audio-video connection to synchronize the activities between the two groups. Moreover each group of local and remote operations or subsystem specialists could access a dedicated virtual space in order to exchange data, observations, and results.

4. Data Analysis & Telemetry Ecosystem

A telemetry data processing environment, named "DANTE" (Data ANalysis & Telemetry Ecosystem), has been setup in TAS-I premises with the objective to extract valuable information from the enormous amount of telemetry data downlinked every day from the constellation, to support the investigation and resolution of on-board anomalies, to automate the Trend analysis, finally allowing the customer to obtain a clear and detailed overview of the constellation health, and support the Ground Segment in the operations and monitoring. The objective is to automate as much as possible the telemetry monitoring of the constellations, specifically leveraging TAS-I decades of experience in designing, building and supporting them in-flight.

4.1 Data storage, processing and visualization

The DANTE Ecosystem includes several hardware and software components including the Telemetry Database, and a collection of dedicated applications and services running periodically or upon request. Applications run in dedicated virtual machines or Docker containers, or as services in the OS (Operating System). The Telemetry Database is routinely automatically populated with Telemetry Data as described in section 3.3, and a dedicated in-house developed application, *Shiva*, takes care to interface very quickly and effectively with the Database and extract the requested data for the chosen satellites and the selected time range, with all the requested options, including aggregation or combinations of the telemetry parameters. The data can be extracted and then visualized via the *Shiva* web application *Sight*, or through dedicated API (Application Programming Interface). The visualization and correlation of several telemetry parameters (i.e. timeseries, often years of data with sampling in the order of seconds) coming from different subsystems of the same spacecraft, and even the correlation of data from different satellites with similar on-board hardware, greatly improves the work of engineers in the evaluation of the performance of the on-board units, or in the early detection of anomalies or degradation.

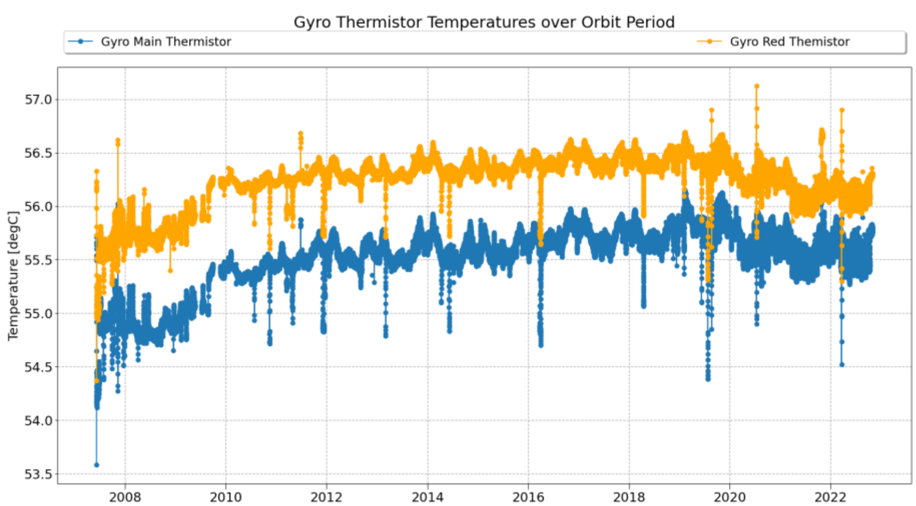

Fig. 5: Long-term visualization of the temperature data for the on-board gyroscope units

4.2 Automated Trend Analysis & Reporting

The growing number of satellites and constellations to monitor pushed TAS-I to increasingly invest in the development of automated routines to support the constellations telemetry analysis, at the same time improving the detail and accuracy of the periodic reports provided to the Customer. In the context of health monitoring, an important periodic activity is the Trend Analysis, consisting in the systematic data-driven analysis of every unit and subsystem of each satellite of the constellation. The analysis and visualization of thousands of parameters describing the life-long behavior of each satellite allows to have a detailed overall overview of the health status and early signs of possible degradations or malfunctioning, and can also be used to cross-correlate the behavior of each satellite of the constellation. Fig. 6 reports an example of Trend Analysis.

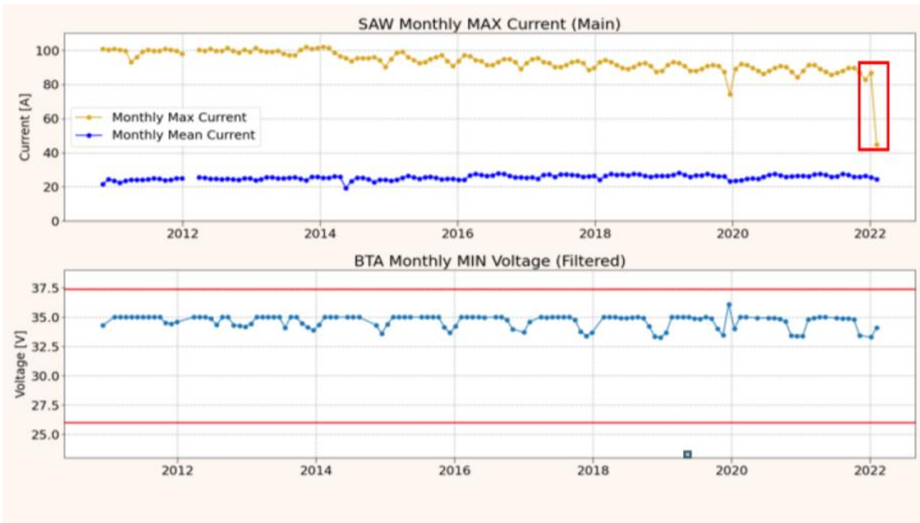

Fig. 6: Evolution of the current provided by the Solar Arrays, anomaly highlighted

At S-CCS in Fucino, Telespazio Flight Operations Team takes advantage of the MUST software (Mission Utility & Support Tools) in order to perform trend analysis, assess satellites health status as well as to promptly detect possible on board subsystems degradations or malfunctioning. MUST is a framework supplied by ESA and is a collection of client tools that support the analysis, visualization, exploration and exportation of telemetry and ancillary mission data designed to complement the Satellite Control Center. The architecture includes a server and a suite of client applications. The server takes care of the import, processing and storage of all the required data, in order to provide the clients with fast access to calibrated data. It supports the management of up to 50000 TM parameters and allows up to 50 simultaneous connections from application clients.

WebMUST is a web client developed for the MUST system. It allows users to browse and visualize mission data available in the MUST repository, such as telemetry, telecommand history, event packets and the MCS event log. Here it is possible to explore the data existing in the database, and plot it with a graphical way in real-time or historical mode.

WebMUST client also offers an easy and convenient mechanism to create reports from mission data. The reporting component can automatically generate and include data such as plots, tables or statistics into pre-defined placeholders in a Word document, which can then be downloaded by the user. Figure 7 reports an example of Web Must Tool.

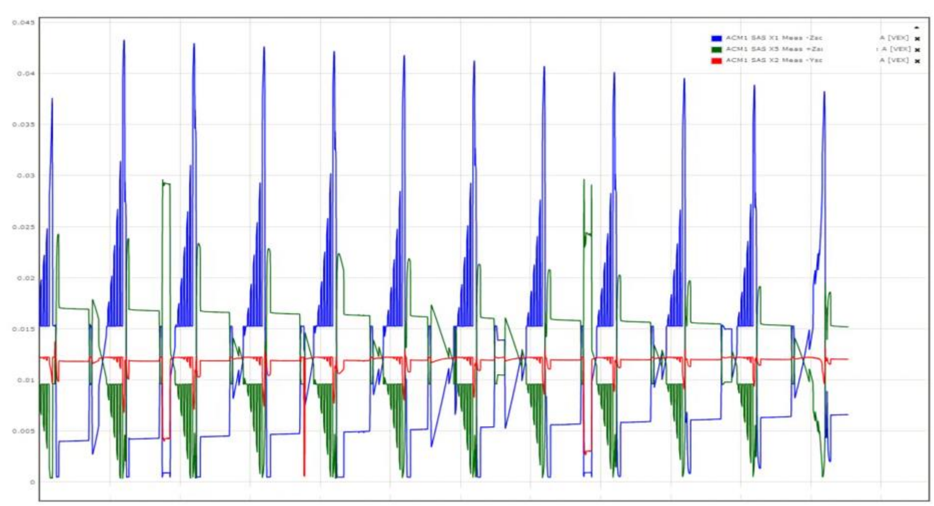

Fig. 7: Plot example - Web Must tool

4.3 Data science Ecosystem

In the frame of TAS-I in-orbit engineering support activities during LEOP and Operational Phase (see section 2), a number of data science tools and libraries, mainly written in Python, have been developed and used to analyze, correlate, visualize and extract useful insights from the large amount of platform telemetry data downlinked from the constellation, through statistical analysis, data mining and Machine Learning techniques.

The libraries features include for example functions to manipulate and correlate telemetry data (i.e. timeseries), calculate relevant statistical quantities and metrics, correlate orbit events with space weather data, count the occurrence of a specific event or pattern, or calculate additional physical parameters in order to better characterize the status of a subsystem/unit.

Ad-hoc data analysis scripts are developed when a specific analysis is needed, for example in case of investigation of an on-board anomaly. In this case the on-board event log is analyzed and correlated with the evolution of the telemetry data for the involved subsystem, and correlated with the domain-knowledge of the spacecraft operations engineer/data scientist. The scripting engine allows to extract data from the database with an API, and then manipulate it in the script, allowing the data scientist to try different paths to solve the problem, keeping a record of the results and of all the previous trials. If the analysis is successful and validated, then the script is integrated in the shared library to allow re-use in the future.

As in many data science applications, particular attention is here devoted to the re-use of the code, and in this context the usage of data “pipelines” has proved to be an optimal way to standardize all sorts of “transformations” applied to the data, allowing to create the desired stack of “transformers” and apply that sequentially on the data at hand.

The data analysis libraries are developed in collaboration between the users of the DANTE Ecosystem: the usage of a repository management tool allows the source code version control and the coordination of development efforts (using *Gitflow* branching model), automated tests and periodic releases of new versions of the libraries packages.

The usage of isolated python environments allows to safely install and use different versions of the libraries and provide isolations between the projects.

4.4 Automated Telemetry Monitoring (Artificial Intelligence-assisted)

As soon as new telemetry data is available in TAS-I SSO Database (as described in section 3.3), sanity checks are performed to verify the data consistency, and automated monitoring routines are triggered, which scan the new data in order to early detect the occurrence of non-nominal behaviour, or highlight desired events or user-defined conditions. Finally a summary report with the relevant findings is automatically assembled, and loaded it in the shared repository or sent it via e-mail to the interested people. The automated monitoring allow engineers to be warned if some spacecraft subsystem or unit behaviour is deviating from the nominal condition, moreover eliminating the need to manually inspect hundreds of telemetry data looking for pattern deviations. Moreover it’s often the case that deviations from the nominal behaviour are difficult to be detected also by the human operator’s eye, and Machine Learning can be of great help here.

In particular three types of automated monitoring can be set:

- Condition-based
- Pattern search
- AI-based Anomaly Detection

Condition-based monitoring scan the data looking for telemetry signals to overcome pre-defined thresholds (similar to the so-called “out-of-limits” of the on-board *Failure Detection Isolation & Recovery* FDIR function) or to assume a specific value. Moreover custom monitoring on complex combinations of telemetry signals can be set, allowing to detect very specific conditions or events of interest happened on the spacecraft.

Pattern search monitoring looks for the occurrence of specific patterns in the data, for example a known pattern associated with a specific evolution of a telemetry signal (e.g. the evolution of the attitude of the satellite while performing a specific orbital manoeuvre, associating this pattern with a dedicated class). This can be useful to search for occurrences of similar patterns in the past, in order to understand in which circumstances a certain pattern shows up.

Artificial Intelligence (AI)-based Anomaly Detection aims to identify early warning signs of degradation or malfunctioning of the on-board units, which could lead to expensive failures in terms of reduced constellation operational capacity, time to restore the nominal constellation operability and at worst to the end of the mission for the spacecraft affected (see figure 8).

The Anomaly Detection (also called *outlier* or *novelty* detection) problem in the context of spacecraft telemetry data is often dealt with *unsupervised* Machine Learning techniques, i.e. techniques not requiring labelled datasets. This means that it is not required to define what an anomaly is, while it is sufficient to train the algorithm on what it is considered "normal" data, with the aim to identify "deviations" from the nominal expected behaviour. The use of unsupervised learning is motivated by the assumption, confirmed by TAS-I SSO experience, that anomalies on-board spacecraft are generally rare, and the available data associated with "nominal" behaviour far exceeds the data associated with anomalies.

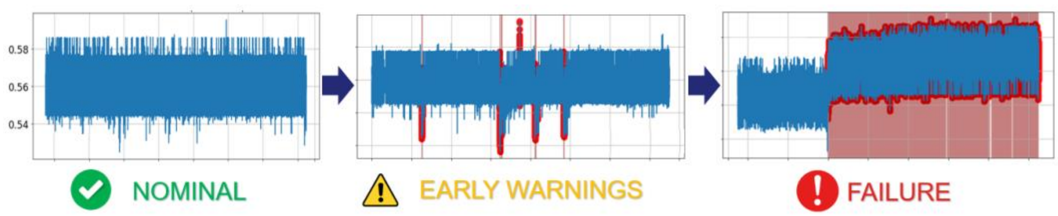

Fig. 8: Automated A.I. monitoring highlighting early anomalies, which anticipate subsequent hardware failure

Through extensive TAS-I Research & Development activity and through the collaboration with academic institutions, a number of techniques and algorithms have been developed and tested to face the Anomaly Detection problem [4,5,6,7,8,9,10].

The feature extraction techniques explored by TAS-I in the pre-processing step include classic statistical features (e.g. minimum, maximum, mean value, standard deviation), Fourier transform, discrete wavelet transform (DWT) and discrete cosine transform (DCT) [4]. Moreover principal component analysis (PCA) or Encoder-Decoder Neural Networks architectures have also been employed to automatically extract a low dimensional representation of the input signals [8]. Several Machine Learning algorithms have been tested in TAS-I against real flight telemetry data, including Hierarchical Clustering with mini-clusters approach [4], Local Outlier Factor (LOF) and One-Class Support Vector Machines (OCSVM) [8,9], Recurrent Neural Networks (RNN) [6], Generative Adversarial Networks (GANs) [7], Principal Component Analysis (PCA) and Autoencoders (AE) [8,9,10]. Refer to [8,9,10] for current TAS-I efforts in bringing these techniques on-board the spacecraft and adapting them to space hardware in order to improve the on-board FDIR capabilities.

Telemetry timeseries data often require an initial pre-processing step including data segmentation, cleaning, resampling, feature extraction, finally reaching the modelling and inference step. The sequence of transformations sequentially applied to the input telemetry data can be organized efficiently through the use of data *pipelines* (as already described in section 4.3). This is especially important when such pipelines are put in production (i.e. when they are deployed on production hardware and used by engineers in their daily work). Our experience confirms that the involvement of Machine Learning in the infrastructure introduces new challenges like pipelines orchestration, models versioning and deployment, monitoring of the model performance and re-train triggering, large dataset processing and parallelization, experiments and prototypes versioning, and in this context an *ML-Ops* approach can be greatly helpful.

Finally, research is in progress towards the automation of the *Root Cause Analysis*, i.e. the process which leads to the identification of the root causes of the detected anomaly, which is usually performed by the engineer exploiting specific domain knowledge.

4.5 Predictive Maintenance

The systematic analysis and monitoring of the telemetry performed by engineers or automated as described in the previous sections falls within the concept of *preventive* maintenance. i.e. the periodic assessment of the spacecraft equipment health status, looking for potential malfunctions and scheduling regular routine maintenance activities in order to *prevent* any equipment failure, which could lead to expensive costs and unplanned downtime.

In the context of *predictive* maintenance the focus is instead on the estimation of the equipment health status using the available historic operating data (pure data-driven techniques) and/or physics models, and try to estimate the so-called *Remaining Useful Life* (RUL, also called TTF i.e. *Time-To-Failure*). This allows to be notified of equipment degradation, to prevent unexpected failures and to schedule convenient maintenance activities, reducing downtime and costs.

TAS-I is developing and testing multiple strategies to obtain an estimation of the RUL for spacecraft equipment, using both *data-driven* techniques and integrating the physical model (*hybrid* approach). Data-driven strategies involve the extraction of relevant features from the data, for example using Autoencoders, the identification of a score associated with the "health" or "damage" condition, and the extrapolation of this score out to a given threshold. Another possibility is to learn to estimate the RUL directly from the data, but the major issue here is often the lack of enough Time-To-Failure data. Finally, the RUL estimation is being addressed also using a mix of data-driven and model-based approaches, the so-called *hybrid* approach, for example using *Physics Informed Neural Networks* (PiNN).

5. Conclusions

This work described the systems set-up in *TAS-I* premises to remotely support the CSG FM2 Launch & Early Operation Phase and the health monitoring applications deployed in order to allow the monitoring of the entire constellation health and to improve the overall in-orbit support activity and constellation maintenance quality.

A description of the link between *Telespazio* and *TAS-I* is provided, and the *Remote Project Support Room* facility with its support applications is presented. Then the *Data analysis and Telemetry Ecosystem* is introduced, including the *Big Data* processing tools and libraries, the *Automated Trend Analysis,* and the applications dedicated to the spacecraft equipment *Health Monitoring* and *Predictive Maintenance* based on Artificial Intelligence techniques. These systems are in constant evolution and will be adapted to monitor even larger constellations, in order to enhance future missions autonomy and reliability.

List of references

[1] D. Calabrese, F. Carnevale, A. Croce et al., "New concepts and innovative solutions of the COSMO-SkyMed 'Seconda Generazione' ", 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2015, pp. 223-226, doi: 10.1109/IGARSS.2015.7325740.

[2] G. F. De Luca, L. Fasano, M. Cardone et al., "Pseudo and Full-Gyroless Operative Modes on Board of COSMO-SkyMed Mission", 2016 SpaceOps Conference, 2016, doi:10.2514/6.2016-2469.

[3] G. F. De Luca, L. Fasano, F. Nirchio et al., "COSMO-SkyMed full gyroless operative modes: verification results", 2018 SpaceOps Conference, 2018, doi:10.2514/6.2018-2307.

[4] C. Ciancarelli, A. Intelisano, F. Corallo et al., "Spacecraft Telemetries Analysis for Anomaly Detection functions", Proceedings of the 2021 conference on Big Data from Space, 2021, pp. 85-88, doi:10.2760/125905.

[5] C. Ciancarelli, A. Nicito, A. Intelisano et al., "Analysis of Automated Techniques for Anomaly Detection in Spacecraft Telemetries", Proceedings of the 16th International Conference on Space Operations, 2021.

[6] C. Napoli, G. De Magistris, C. Ciancarelli et al., "Exploiting Wavelet Recurrent Neural Networks for satellite telemetry data modeling, prediction and control", Expert Systems with Applications, 2022, doi:10.1016/j.eswa.2022.117831.

[7] C. Ciancarelli, G. De Magistris, S. Cognetta et al., "A GAN Approach for Anomaly Detection in Spacecraft Telemetries", 17th International Conference on Soft Computing Models in Industrial and Environmental Applications (SOCO 2022). SOCO 2022. Lecture Notes in Networks and Systems, vol 531. Springer, Cham. , 2022, doi:10.1007/978-3-031-18050-7_38.

[8] C. Ciancarelli, F. Corallo, S. Cognetta et al., "New Concepts Of Automated Anomaly Detection In Space Operations Through ML-Based Techniques", 73rd International Astronautical Congress, 2022.

[9] C. Ciancarelli, E. Mariotti, F. Corallo et al., "Innovative ML-based Methods for Automated on-board Spacecraft Anomaly Detection", 2nd International Conference on Applied Intelligence and Informatics, 2022.

[10] S. Cognetta, C. Ciancarelli, F. Corallo, et al. "Spacecraft On-board Anomaly Detection: computational constrained Machine Learning approaches", 2023 SpaceOps Conference, 2023