

Improving satellites constellations monitoring and diagnostics with CASTeC

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Abstract

The assessment of the health status of satellites during operations is one of the major tasks of Satellites Controllers (SCs) who continuously check satellites telemetries to detect symptoms of potential anomalies. This continuous assessment requires knowledge of the monitored system and to be focussed on a subset of the hundreds of telemetries that can be practically monitored by a human operator.

This paper describes the CASTeC approach to increase constellations health status awareness during operations and end users' perspectives gathered during the product validation with flying missions.

CASTeC is a software tool performing:

- Automatic identification of anomalous behaviours and relevant events that require investigation by SCs.
- Early detection of anomalies in the behaviour of the satellites/constellation, at system, subsystem and parameter level.
- Automatic identification of correlated telemetries and events.

The CASTeC solution is based on an innovative Machine Learning based approach, applied to contextualised periods of satellites operations. The CASTeC methodology can be described as follows:

- CASTeC characterises the expected behaviour of satellites exploiting real historical (or simulated) data, based on the FETCH method developed by SATE that automatically learns the expected behaviour of each telemetry in each different context (i.e., specific mission phases and satellite working conditions or states). This approach allows to overcome the limitation of the fixed thresholds based methods.
- a set of “parameter-specific” and “context-specific” checks is applied to provide early detection of incipient anomalies.
- correlated events and telemetries are identified, to allow better understanding of anomalous events or, in general, of the satellite behaviour.

With respect to potential existing solutions, the benefits of the CASTeC approach are the following:

- CASTeC provides predictive alerts on the status of entire constellations of satellites, producing a priority list of anomaly events, thereby allowing fast reaction to unexpected behaviour and prompt implementation of the mitigation strategies;
- CASTeC supports events troubleshooting by guiding the SC in the identification of potential cause-effect relations between events;
- CASTeC implements Machine Learning methods developed by SATE that are fully interpretable.

The paper provides examples from in-orbit missions on the limitations of the current approaches to satellites diagnostics and how the methodologies implemented in CASTeC can overcome these limitations, also reporting end users' benefits from the operative use of these solutions.

This presentation also reports the main lessons learnt gained by SATE in almost twenty years experience in systems diagnostics, which drove the development of the CASTeC solution, that was implemented together with Planetek.

Keywords: Constellation, diagnostics, health monitoring, Artificial Intelligence, prognostics

Acronyms/Abbreviations

AI	Artificial Intelligence
AIT	Assembly, Integration and Test
DKM	Diagnostic Kernel Modules
I/O	Input/Output
NN	Neural Network
OBSW	On Board Software
R&D	Research and Development

1. Introduction

During operations, Satellites Controllers (SCs) are in charge of checking the behaviour of their assets (satellites of a constellation) aiming at detecting anomalous behaviours early enough to implement the right counteractions for mitigating the related risks and costs.

In this scenario, the typical methodologies to investigate the presence of anomalies in operational telemetry data are based on Out-Of-Limit thresholds [1]. These techniques are able to assess if the system remains within the allowed bounds, but do not allow detecting trends of incipient anomalies, which may result in unexpected system behaviour during operations.

The limits of the fixed threshold checking approach are highlighted with a real data example (Figure 1). This example reports a known failure of a thermostat of the XMM (X-ray Multi-Mirror) mission, which could not be detected in advance by applying fixed thresholds checking, because the temperature evolves in an anomalous way within the nominal bounds.

In this case, more advanced checking approaches could have allowed the detection of the incipient degradation more than one month before the failure, which is clearly visible from the plot.

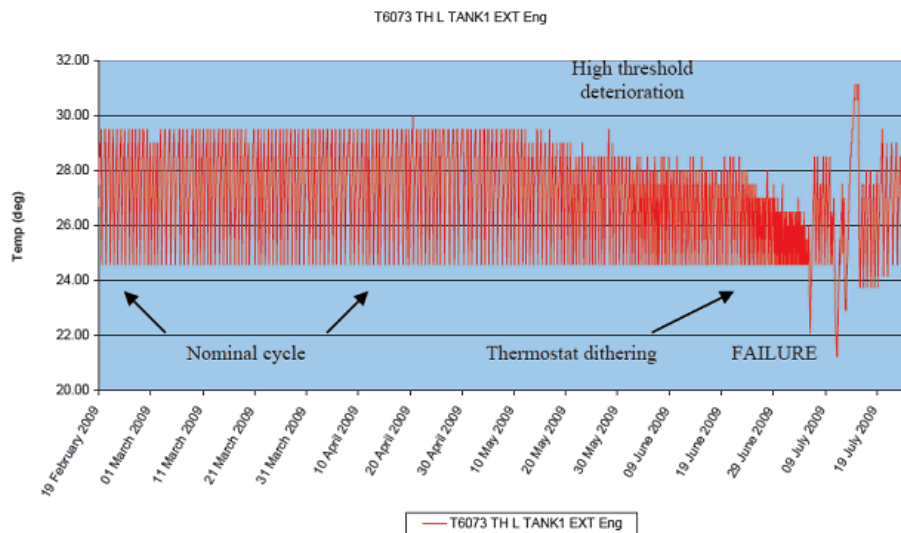


Figure 1. Behavior of a thermostat of the XMM mission [1]. The temperature exceeds boundaries on 9th of July but an incipient degradation could be detected more than one month before the failure

Another limitation of the traditional checking approaches is that these techniques do not allow detecting contextual anomalies, i.e. telemetries behaviour that are anomalous only under certain operational contexts.

Operational contexts definition is based on an ambient or operative conditions that occur several times during satellites missions. For instance, a context can be related to a positional information, e.g. the satellite eclipse condition, or to a functional condition, e.g. specific configuration imposed by the operators.

As a third key aspect, when dealing with satellites constellation, it is impracticable for the operators to monitor the high number of telemetries produced. In this case, the need is to lower the operators' workload by introducing automatic processes that support the monitoring operations (e.g., automatic extraction of the nominal behaviour of the telemetries based on the context information, automatic selection of the most anomalous telemetries/subsystem to be

investigated etc.). This allows the operators to improve the quality of their work and monitor a higher number of satellites with the same resources, with reduction of operational costs.

Finally, an additional point that is worth mentioning is related to the fault isolation process. Often the effects of an anomalous event can be observed in multiple parameters, also belonging to different subsystems, which makes the identification of the location and cause of a fault more difficult. In this regard, the solutions to be adopted to support satellites operators activity shall include advanced tools for fault isolation, i.e. the identification of the most likely root causes, obtained from the elaboration of the health status of the various systems.

In conclusion, new strategies shall be envisaged to address the need for improving anomaly detection and investigation during operations, which shall be characterized by:

- Predictive capabilities (to detect trends of degradation and anomalies well before these evolve into more severe events)
- Context-based reasoning
- Automatic processes for reducing operators workload
- Correlation analysis for supporting fault isolation

The following sections describe the main approaches and methods implemented in CASTeC that characterize the points listed above.

2. CASTeC approach

The predictive capabilities provided by CASTeC rely on an approach developed by SATE based on the analysis of each single telemetry and of a set of “features” extracted from the raw data, which are simple statistical features such as average, maximum, minimum of the parameters in certain time windows, and more innovative features.

From the analysis of these features, CASTeC first characterises the expected nominal behaviour (by means of FETCH algorithm) and then uses this characterisation to compute an index that measures the degree of anomaly at parameter level, subsystem level and satellite level (by means of the Check algorithm).

As can be seen from the scheme depicted in Figure 2, the historical data are exploited for characterizing the expected behaviour of the satellite with FETCH, which receives information by the user such as the periods of time and the context in which the behaviour shall be characterized. Once this characterization is performed, the output of the FETCH can be passed to the Check algorithm, which will provide the assessment of the health status of the satellite by comparing the new data downloaded from the satellites with the reference information built by FETCH.

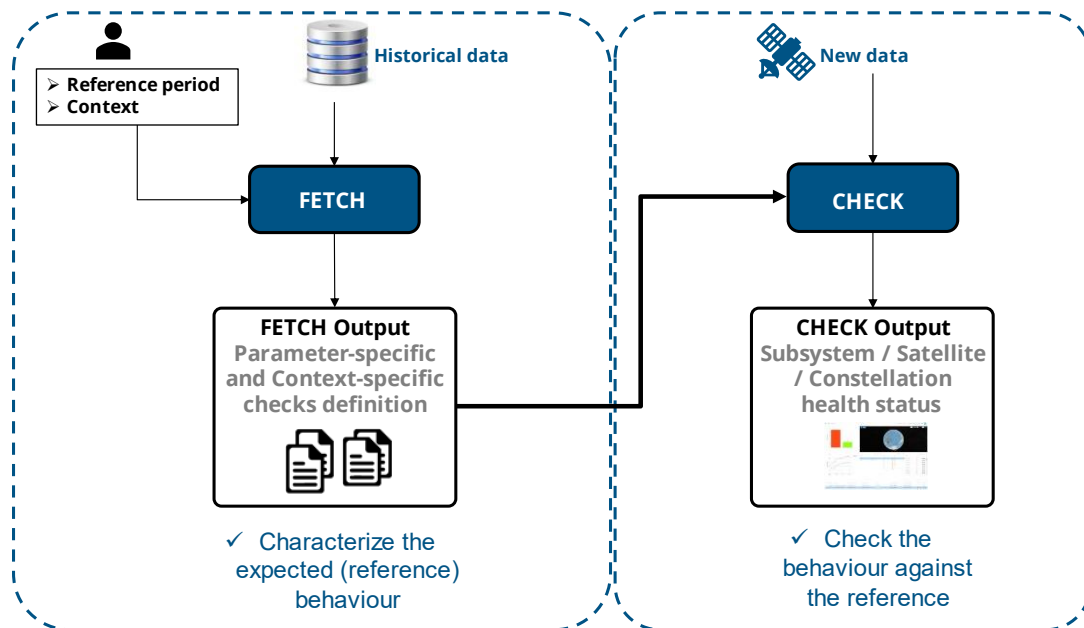


Figure 2. Workflow of the anomaly detection process in CASTeC

It is remarked that FETCH is launched only when it is needed to build a reference, whereas the Check algorithm is an automatic process that computes the health status of the satellite based on a schedule provided by the user (e.g., many times a day, once every day, etc.). A frequent and automatic update of the assessment of the health status of the satellites of the constellations allows the operators to be promptly notified of potential anomalous conditions.

In detail, the approach can be described as follows. Figure 3 shows a telemetry raw data (in green) with its traditional nominal bounds (in red). In the initial part of the plot, the signal is characterized by a nominal behaviour; then the range of the signal changes until the signal exceeds the nominal lower bound. This moment would correspond to a traditional alarm onset.

CASTeC, instead, would raise an alert well before the parameter exceeds its bounds, since the detection is based on the analysis of the features behaviour of this parameter. In particular, CASTeC provides an index called *CASTeC index (CI)* that measures the degree of anomaly (from 0 to 100) and raises when the parameter starts showing the drift behaviour (see Figure 4).

In fact, in this figure, when an anomalous decrease of the signal values is occurring, *CASTeC Index* starts to increase its value. This measure grows from 0 (that represents a condition of nominal behaviour) to 100 (that means a highly anomalous condition). In Figure 4, it is also shown the moment in which the first alert is raised by CASTeC, well before the alarm generated by a traditional anomaly detection method.

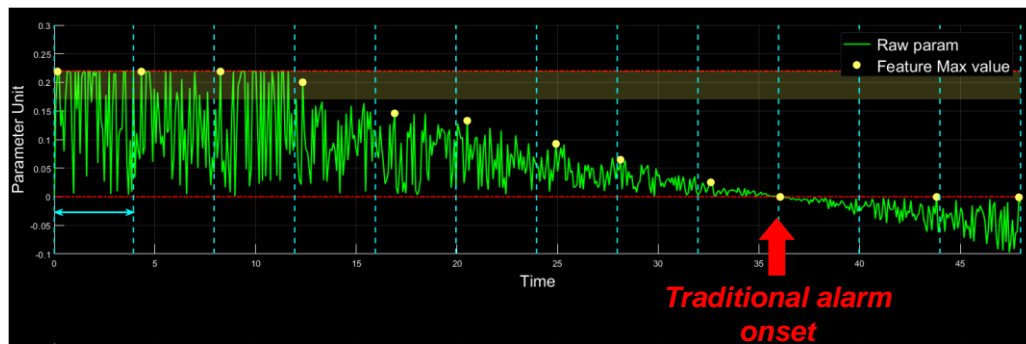


Figure 3. Time series of a parameter with its traditional nominal bounds. The arrow highlights the moment at which traditional anomaly detection methods raise an alarm: that is when the parameter takes a value lower than the nominal inferior threshold.

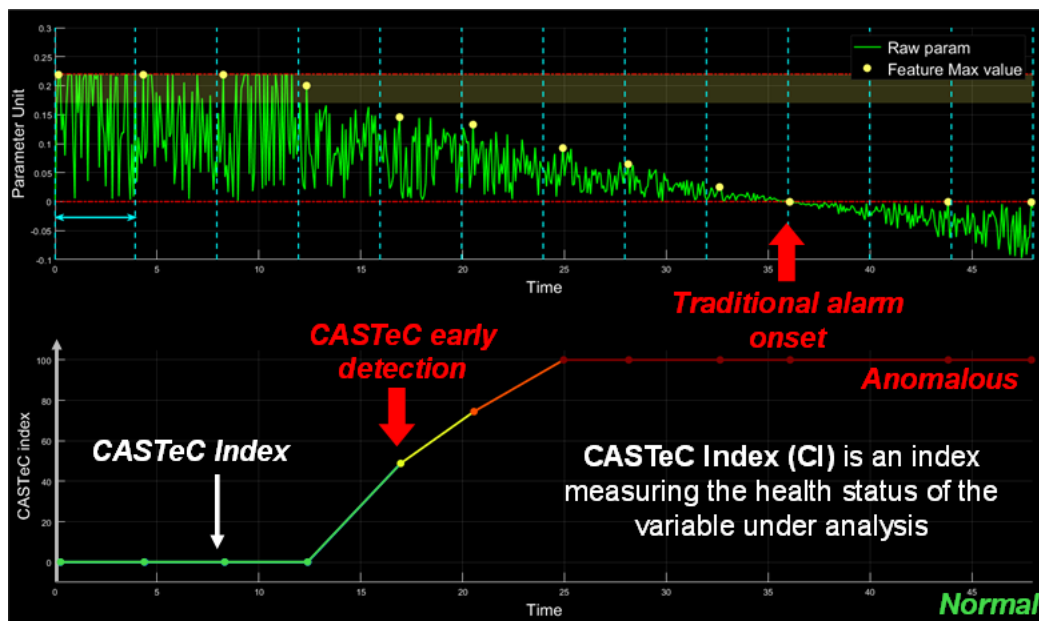


Figure 4. Evolution of CASTeC Index as a result of parameter behaviour.

CASTeC produces an index for all telemetries and provides a sorted list of relevant events that may need further investigation by spacecraft controller. This list contains all the analyzed parameters and can be sorted by *CASTeC*

Index in decreasing order, so that the most critical telemetries are on the top of the list. This list allows operators executing further investigation: they can filter the parameters and access details of the reasons for the detected anomalies.

CASTeC Index values of each analysed parameter are in fact visualized through a heatmap panel that shows all telemetries grouped by subsystems in a topological representation and easily explorable. An example is shown in Figure 5; in this example the parameters illustrated belong to four different subsystems: EPS (Electric Power Subsystem), OBC (On Board Computer), SDR (Software Defined Radios) and ADCS (Attitude Determination and Control System).

Each pixel or cell of the image represents one telemetry and the colour of the cell corresponds to the *CASTeC Index*, i.e. the degree of anomaly (green means nominal behaviour and red means highly anomalous behaviour). Grey cells mean that the parameter was not checked, because no data were present or because the parameter does not satisfy the criteria set by the algorithm (i.e., check on the parameter cannot be considered reliable). The position of each parameter in the heatmap is automatically set based on the parameter-subsystem membership but it can be customised by the user, if necessary.

The column on the left (“Values Analysis”) shows the results obtained by investigating the values of the timeseries of the parameters, whereas the column on the right (“Data Gap Analysis”) shows the results obtained by considering the timestamps of the parameters. Since the position of the parameters is the same in both the columns of this heatmap, having this separate analysis helps in understanding if an anomaly at parameter level is due to a modification of the parameter behaviour or a lack of data in the period observed.

In Figure 5, it can be seen that there are only few parameters of the EPS and ADCS that were detected as highly anomalous (red cells) for the Values Analysis on the left, whereas the Data Gap Analysis indicates that data are correctly retrieved for all the parameters (green cells), except for a group of parameter of the OBC, which are characterized by red cells. Users can investigate the results obtained through additional panels that provide information on the distribution of parameters and their features, along with their plots.

On the left part of Figure 5, the list of all the analysed parameters is provided. In this specific example, the list is ranked from the highest value observed for the Values Analysis to the lowest.



Figure 5. Example of heatmap showing the health status of the parameters analysed

In addition, it is highlighted that the *CASTeC Index* is computed not only at parameter level but also at subsystem and satellite level, producing both detailed and global indications of the health status of the subsystems and satellites of a constellation, for example, which are provided to the user in a dedicated dashboard.

As already anticipated, another crucial aspect of the *CASTeC* approach that is worth mentioning is the context based reasoning.

An example of this can be found in Figure 2, in which a parameter timeseries of a flying mission is reported in a period of time in which the satellite behaviour is considered nominal (for confidentiality reasons, the parameter name and the unit of measurement are not disclosed). This figure shows that the parameter time series has different ranges depending on the operative conditions considered. When all the operative conditions are considered, it can be observed that the parameter values range from -2 and 2 [P Unit] (upper part of the figure). In the lower part of the figure, instead, the data are considered only when the automatic attitude control is deactivated. In this latter case, the bounds in which the parameter values range are reduced, i.e., between -0.5 and 0.5 [P Unit].

This leads to the consideration that an approach based on the operational context helps in defining with higher accuracy the bounds within which the parameters can range, according to operative conditions that are defined by the user. Thanks to this approach, an accurate definition of the expected behaviour of the parameters can be performed, thus improving the diagnostics and monitoring operations.



Figure 6. Parameter time series with two different nominal ranges depending on the context considered

The influence of a context could be impacting a large set of telemetries: for instance, in the mentioned example the influence of the context may be important also for parameters that may not directly belong to the same subsystem. This makes *context-based approach* even more powerful.

Another crucial need of the satellite operators is the identification of the causes of the anomalies. Usually this is a time-consuming process for the operators, who often shall investigate hundreds of plots and investigating different components datasheets in order to be aware of what triggered the anomalous behaviour observed.

In order to address this need, CASTeC implements a methodology developed by SATE that is capable of detecting both linear and nonlinear correlations by analysing the dynamic of the signal over short and long time scales. This correlation analysis can identify potential cause-effect relationships, which are useful for the interpretation of the behaviour detected.

In greater detail, considering two sets of parameters, the first called “base parameters” and the other called “target parameters”, the correlation analysis aims at answering to the following questions:

- which of the target parameters are correlated to the base parameters?
- what is the level of correlation (i.e., strong, weak, none)?
- what is the time scale over which this correlation exists? e.g., parameters can be poorly correlated in short time ranges, but highly correlated over larger time scales.

Once these answers are provided, the user can investigate the plots of the most relevant correlated parameters in order to understand which behaviours are linked to or triggered by a specific event among the different subsystems, accelerating the process of interpretation of the satellite behaviour.

An example of two parameters for which a high level of correlation has been detected is provided in Figure 7. In this figure, the parameter in the upper part represents a status (indication provided by the OBSW), whereas the parameter on the lower part is a temperature measured by a component of the EPS. The capability of intercepting this kind of linked behaviour is a strong support and improvement to the monitoring and diagnostic of satellites.

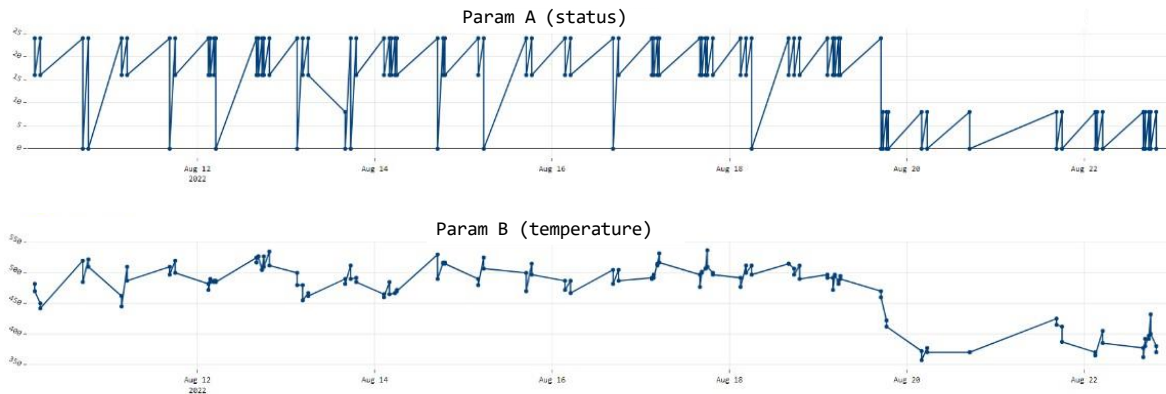


Figure 7. Example of a strong correlation identified by the Correlation Module.

In addition, it is remarked that the context based approach is applied to the correlation analysis, therefore CASTeC is able to identify correlations that occur only in specific operative conditions defined by the user.

The correlation analysis is part of the CASTeC workflow as represented in Figure 8.

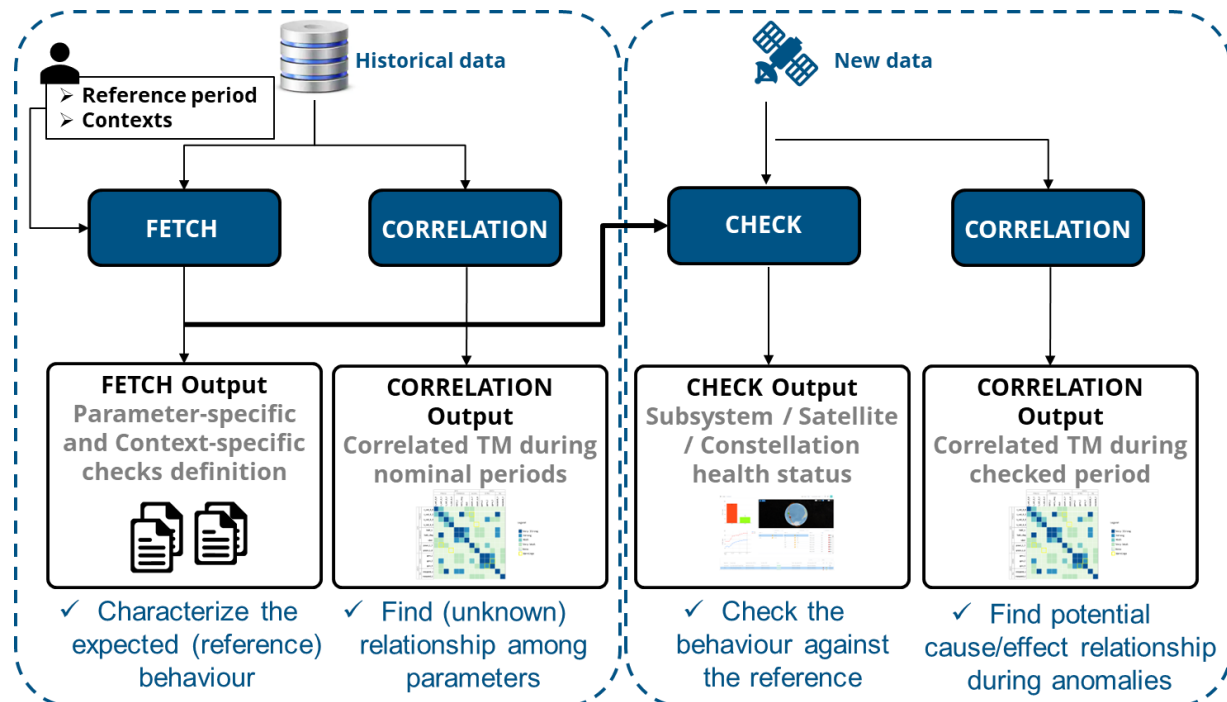


Figure 8. Workflow of the anomaly detection and correlation analysis processes in CASTeC

3. Anomaly detection example

In this section, a use case from a flying mission is presented that demonstrates how the proposed methodology can improve the early detection of anomalies.

Real historical data of a flying satellite were investigated for the example reported in Figure 9.

The Check algorithm detects an anomalous behaviour (in correspondence of the red dashed line) for the two parameters represented in the upper part of Figure 9, one representing a payload parameter, the other representing a current signal linked to the payload utilization. Through discussion with the satellite operators, it was found that this anomaly was due to a flight plan that froze, resulting in an interruption of data collection for one of the payload of the satellites. Then, this anomaly propagated, causing the interruption of another payload activity (third signal of Figure 9, in correspondence of the green dashed line).

At this point, the satellite was only performing a basic set of actions to keep the system alive; no payload activities were ongoing and this resulted in a lower power use, as shown by the battery voltage that decreases its range in correspondence of the green dashed line (bottom part of Figure 9). The only time operators were aware that flight plan failed was when all the payload data were not delivered (in correspondence of the green dashed line). This means that the Check module was able to anticipate the operators detection by almost two days.

It is remarked that the anomaly on the current signal would not have been detected by checking the bounds of the parameter values against fixed threshold. In fact, as can be seen in the second plot of Figure 9, the behaviour of the signal changed in an anomalous way (in correspondence of the red dashed line) although the telemetry values did not exceed parameter nominal bounds. This is a key point of the diagnostic approach exploited, helping the operators in the identification of incipient anomalies.

In addition, from the result here reported, the operators acknowledged that they discovered new knowledge and they understood that battery voltage level could be used to detect when a flight plan failed.

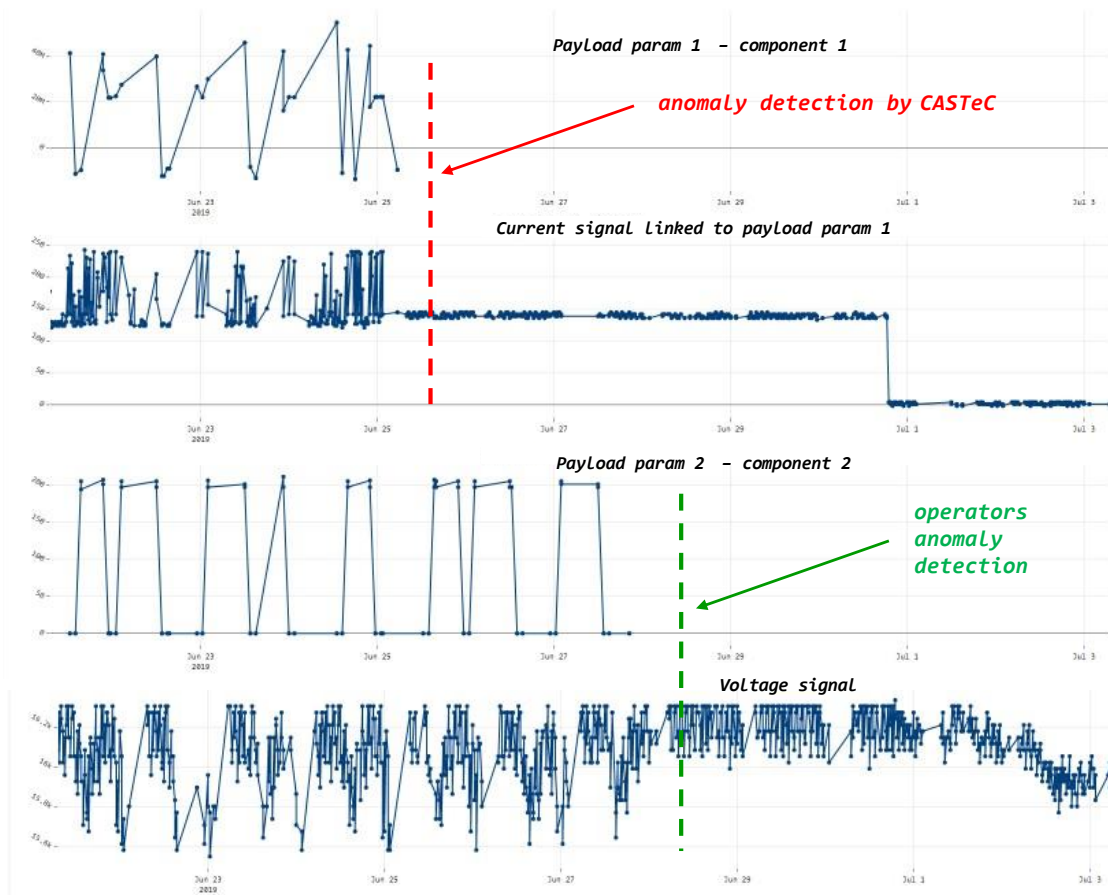


Figure 9 - Anomaly detection use case

4. Correlation analysis example

A significant advantage of the correlation analysis is that it also allows extracting new knowledge. In Figure 10, two parameters from a real satellite mission are shown. These parameters present some anomalies in the periods highlighted in red. These anomalies were identified by the Correlation module as correlated, which was of unexpected relevance and interest for engineers to whom these results were reported, as no correlation was expected among those parameters from a pure engineering knowledge. The detection of this correlated behaviour between parameters of different subsystems allowed the operators to increase their knowledge on how the monitored asset responds in specific anomalous conditions.

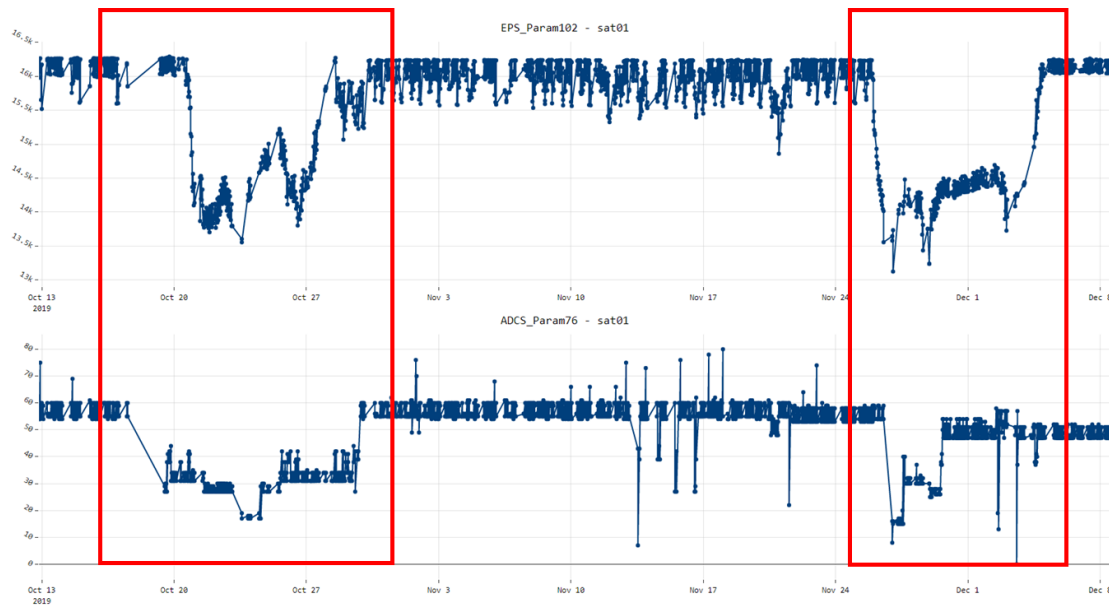


Figure 10. Example of two correlated parameters from a flying mission (correlation was confirmed by operators, yet was unknown before).

5. Conclusions

This paper briefly discussed the methods implemented in CASTeC and the benefits of using this tool for the monitoring and diagnostics of satellites constellations. The methods encapsulated in CASTeC cover different aspects and meet different needs expressed by the operators that are in charge of monitoring such complex systems.

CASTeC can provide predictive alerts on the status of a spacecraft and its subsystems, producing a health index associated to each of them, providing both detailed and high-level indications.

In addition, the correlation analysis allows the operator to reduce the time and effort spent in finding the causes of anomalous behaviour and it can be exploited for extracting new knowledge on how the satellite works, both during nominal or anomalous period.

Finally, CASTeC is fully context sensitive and it is based on an interpretable data-driven approach combining statistics, Machine Learning and experts' knowledge, that allow the operator to understand the reasons of a detected anomaly. This interpretability is a feature that is hardly covered by State-of-the-Art Deep Learning or, more generally, by Artificial Intelligence techniques typically exploited in the diagnostic field.

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