ESA STUDY CONTRACT REPORT

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ABSTRACT

This document is the executive summary of the project under contract N° 4000112224/14/F/MOS between SATE and ESA regarding the "AUTOMATIC SPACECRAFT STATUS CHARACTERISATION BY DATA MINING MISSION HISTORY", which is issued in compliance with the updated schedule, agreed with ESA.

This document summarises the results achieved in the project, draws the conclusions of the study and identifies possible future applications.

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european space operations centre

AUTOMATIC SPACECRAFT STATUS CHARACTERISATION BY DATA MINING MISSION HISTORY

EXECUTIVE SUMMARY

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1 SCOPE

This document is the executive summary of the project under contract N° 4000112224/14/F/MOS between S.A.T.E. (briefly SATE) and ESA regarding the "AUTOMATIC SPACECRAFT STATUS CHARACTERISATION BY DATA MINING MISSION HISTORY".

This document represents Delivery 6.4, issued in compliance with the revised planning agreed with ESA-ESOC.

2 EXECUTIVE SUMMARY

2.1 Introduction

The main purpose of this project, as mentioned in the SoW, was *to analyse historical mission data and search for new features which would be useful in the telemetry checking, command verification and procedure writing process in the future*.

Features of a signal (or parameter in this context) are defined as characteristics that can be measured or calculated over a given time window (such as mean, standard deviation or minimum of a signal).

In the SoW, it is also defined that *useful features in this context are those that are predictable enough under known circumstances that a check could be constructed which would not result in too many false positives.*

It is also said that *each parameter is expected to have some features that are useful and some that are not. In addition, some features are expected to be only useful under certain conditions, e.g. orbital effects, commands, or when other parameters are in certain states.*

For this reason, the assessment of the *usefulness* of features was performed both over the entire time period (i.e. under no specific conditions) and over multiple time periods (i.e. under certain conditions). The data set used to extract the knowledge refers to one year of telemetry data of the VEX satellite (in the period 1 March 2013 - 28 February 2014). This analysis was conducted in WP1 and WP2 of the project.

Another goal of the project was to analyse global mission data, which have to be *pre-processed and enhanced to create new data sets called derived parameter time series*. These are intended to be used to identify the external factors that influence features checkability. The definition and extraction of derived parameters was performed in WP3.

The last step foreseen in the SoW was the identification of useful correlations between the derived parameters, the telemetry data and the various features.

This activity was originally meant to include two types of correlation analysis: linear correlation analysis and non-linear correlation analysis.

In agreement with ESA, the focus of the linear correlation analysis was generalized to find relationships between tele-commands, parameters and features, by identifying the simultaneous or correlated changes in their time series. This analysis was conducted in WP4.

In addition, ESA decided to replace the task of non-linear correlation analysis with a different activity, which consisted in the validation and enhancement of the methods to identify useful features and checks, with an additional data set of the VEX satellite, covering the period 1 March 2014 - 31 January 2015. This task was performed in WP5.

As part of WP5, an additional task was performed by SATE upon ESA request, to investigate, define and apply a method for the detection of *abrupt changes* in the modal behavior of the features, which represented an important aspect to be included in the study.

Finally, as foreseen in the contract, SATE applied the checkability analysis and defined checks to the XMM datasets that were used by SATE during the parallel project AUTOMATIC BEHAVIOUR DETECTION AND INTERPRETATION FROM LOW LEVEL DATASETS SUCH AS TELEMETRY, in order to further validate the methodologies and results obtained in the two projects.

Therefore, the activities performed during the project lead to:

- the definition of several methods to characterize the spacecraft behavior from different perspectives,
- the extraction of relevant knowledge about the expected spacecraft behavior,
- the verification of that knowledge against new datasets (of two different satellites).

2.2 Features checkability

The purpose of the features *checkability analysis* was to identify the set of features and checks to be applied to those features that are potentially useful to detect novelties in the behavior of the parameters of a spacecraft, over the entire time period (i.e. always) or over multiple time periods (i.e. under certain conditions).

As mentioned, a feature is a characteristic of the parameter time series that can be calculated over a given time window (e.g. mean, standard deviation, minimum, etc.).

One of the main results of this analysis is that all checks can be applied continuously, over the entire time period. The checks over multiple time periods differ from the others in the fact that multiple "reference behaviors" are identified and used to compare a new observation, i.e. new feature data. These multiple "reference behaviours" may be associated to (unknown) external factors that may influence the parameters behavior.

SATE defined and validated six different types of checks (see also Table 1):

1. *Domain check*: this check includes two types of check, named *Range check* and *Values check*. These verify if the range or values of the feature change over time with respect to the reference ones, computed from a nominal dataset.
2. *Variability check*: this check verifies if the trend of the feature changes over time with respect to the reference one computed from a nominal dataset.
3. *Distribution check*: this check verifies if the distribution of the feature changes over time with respect to the reference one, computed from a nominal dataset.
4. *Frequency check*: this check verifies if the frequency content of the feature changes over time with respect to the reference one, computed from a nominal dataset.
5. *Inter period check*: this check verifies if the modes of a feature (among those with modal behaviour) change over time with respect to the reference ones, computed from a nominal dataset.
6. *Few samples check*: this check applies to the parameters that do not have enough samples to compute feature. It consists in verifying if the parameter values change over time with respect to the reference ones, computed from a nominal dataset.

It is highlighted that *Range check* (of *Domain check*), *Trend check*, *Distribution check* and *Frequency check* consist in the comparison of a parameter or feature behaviour observed in the new dataset with a single reference (normal behaviour).

Instead, the *Inter period check* compares the feature behaviour observed in a new dataset to a set of possible (normal) behaviours (modes) identified in the reference dataset.

Similarly, the *Values check* (of *Domain check*) and the *Few samples* check compare the feature or parameter values observed in a new dataset with the set of (normal) values observed in the reference dataset, which may be more than one.

All checks, except the *Few samples* check, are applied to <u>features time series</u>, computed from the raw parameter time series. The *Few samples* check is applied to the raw parameter time series, due to the fact that it is applied only to parameters that do not have enough samples to be analysed by the other checks.

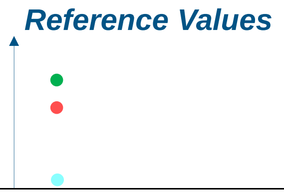
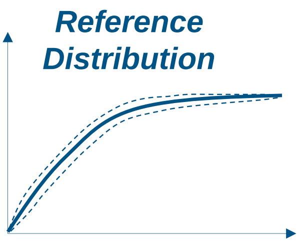
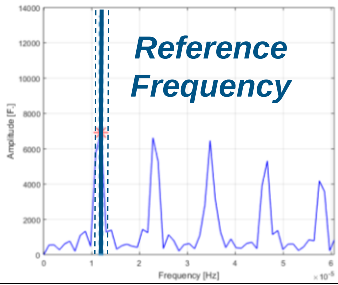
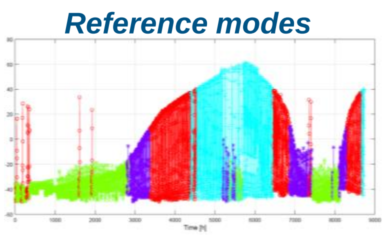
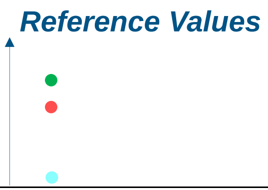
Checks	Single Reference	Multiple references
Domain check		
Trend check		None
Distribution check		None
Frequency check		None
Inter period check	None	
Few samples check	None, unless the parameter is constant (i.e. takes only one value in the reference dataset)	

Table 1 - Checks with single and multiple normal references.

SATE defined a set of 44 features for numerical parameters and 12 features for categorical parameters, which are potentially useful to check.

The reason for checking features instead of the raw parameters is that features characterise the parameter behaviour in a way that may allow identifying different novel behaviours in the parameter which may not be detected from the analysis of the raw parameter time series.

The *usefulness* of a feature is correlated to its checkability which must be:

- Significant: it provides valuable information on the behaviour of the feature (and related parameter) to which it is applied, allowing at least fault detection, i.e. the determination of the presence of a fault in a system.
- Reliable: it does not generate too many false positives.

An innovative method defined by SATE, called **Fe**a**t**ure **Ch**eckability (***FETCH***) allows identifying the shortest time window (and consequent warning delay, see Figure 1) beyond which *Domain check*, *Trend check*, *Distribution check* and *Frequency check* are useful (significant and reliable) for each feature, thereby identifying automatically the settings required to perform the check over the entire time period (e.g. *Time Window Duration* for feature computation, reference values, thresholds, etc.). The checkable features and the corresponding settings are provided in the *usefulness matrix*, generated for each check.

One of the main results found by this analysis is that features checkability over the entire time period is strongly related to the duration of the time window used for the computation of the feature or its characteristics (e.g. distribution, frequency).

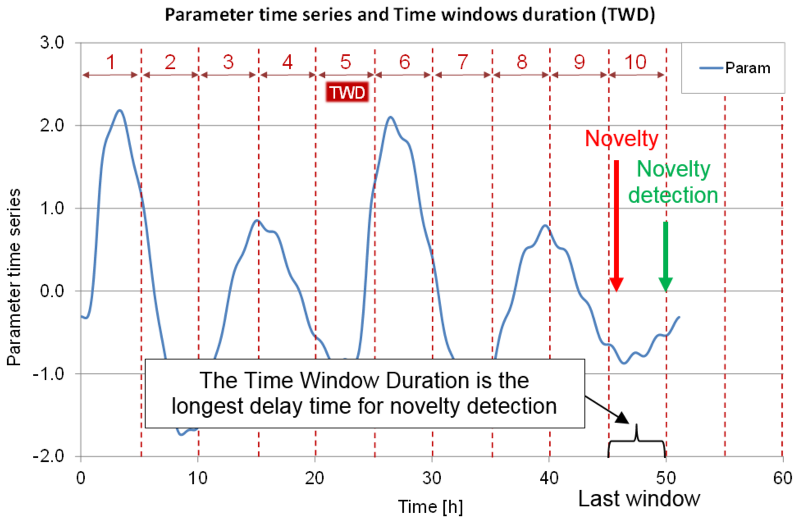


Figure 1 - Illustration of time delay for novelty detection.

A second method defined by SATE, called ***Inter period analysis***, allows assessing the checkability of the features over multiple time periods by identifying the features with modal behavior and characterizing their modes, thereby identifying automatically the settings required to perform the *Inter period check* (e.g. reference values, thresholds). The checkable features and the associated settings are stored in the *usefulness matrix* of this check.

The time windows used for the evaluation of the feature behavior by the ***Inter period analysis*** is the same for all the features and may be determined on the basis of the output of the *Frequency checkability* analysis, as the most recurrent frequency.

As mentioned, although it was intended to be a check over multiple time periods, the *Inter period check* can be applied over the entire time period, once the different references (associated to the different modes) have been extracted to check the feature.

The results proved that both the ***FETCH*** and the ***Inter period analysis*** are consistent in selecting the appropriate checks to be applied to each feature of each parameter, i.e. they allow defining useful checks on features.

In addition, the *checkability analysis* applied to the VEX and XMM satellites proved that all the parameters of the VEX satellite (except one numerical parameter, characterized by a very discontinuous behavior and a low number of samples) and of the XMM satellite are checkable by at least one of the six checks defined.

Few samples check is applied to the parameters that are not checkable by the other five checks because they have a low number of samples.

For the VEX satellite, 42% and 74% of the numerical and categorical parameters, respectively, are checked by *Few samples check* (2329 numerical parameters out of 5565 and 3845 categorical parameters out of 5203).

For the XMM satellite, only 4% of the numerical and categorical parameters are checked by *Few samples check* (183 numerical parameters out of 4816 and 109 categorical parameters out of 2706).

For both satellites, it is observed that *Domain check, Distribution check* and *Inter period check* are the most recurrent ones, which can be applied to the majority of the checkable parameters (see the distribution related to the VEX satellite in Figure 2 and Figure 3).

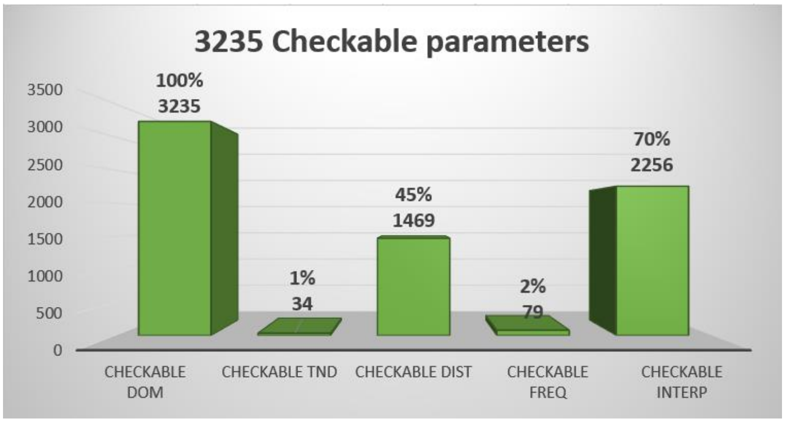


Figure 2 – Number of checkable numerical parameters among the 3235 numerical parameters of the VEX satellite with at least one check among *Domain*, *Trend*, *Distribution*, *Frequency* and *Inter period check*.

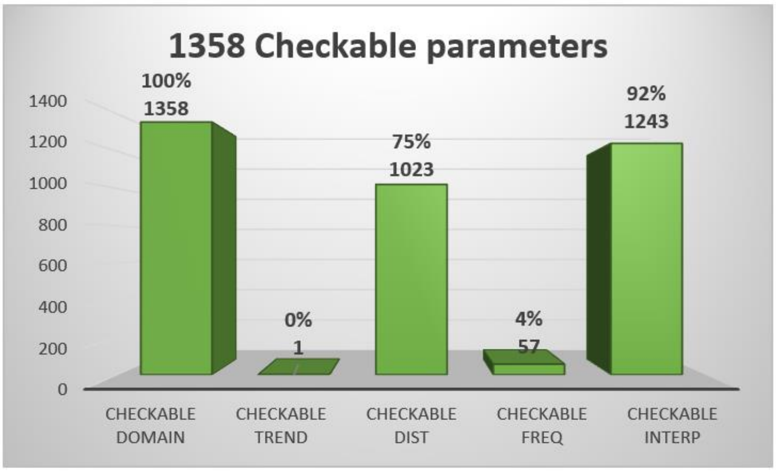


Figure 3 – Number of checkable categorical parameters among the 1358 categorical parameters of the VEX satellite with at least one check among *Domain*, *Trend*, *Distribution*, *Frequency* and *Inter period check*.

As output of this activity, in addition to the report describing the methods and results, SATE delivered to ESA the *usefulness matrixes*, the time series of all features and the time series of the modes observed for the features with modal behaviour.

2.3 Checks application to new datasets

The checks defined in the previous section were applied to two new datasets (named *comparison datasets*), of the VEX and of the XMM satellites, which are different from the ones (*reference datasets*) used for the checkability analysis.

The purpose of this activity was to validate and enhance the check methods defined and to evaluate the novelties detected by the checks, for the two satellites.

The output generated by the checks is the ***symptomatic variable***, which is a quantity that measures the degree of novelty in the time series analysed. For all the checks, except the *Few samples check*, novelties are detected for each pair (parameter, feature). Therefore, the *symptomatic variable* is computed for each of these pairs. The distribution of the *symptomatic variable* represents a synthesis of the overall status of the spacecraft over time and allows identifying the days which are likely to be characterised by critical events. Figure 4 shows an example of the distribution of the symptomatic variable of *Domain check*, computed for all the features of numerical parameters of the VEX satellite. It can be noticed that in the first 90 days of the new dataset almost all the novelties have low values of the *symptomatic variable* (<5%). Instead, the second and third quarter are characterised by novelties with high *symptomatic variable*, i.e. a high degree of novelty.

This information allows identifying relevant novelties and generate priority lists according to the degree of novelty, which may represent extremely valuable information for the Flight Control Engineers.

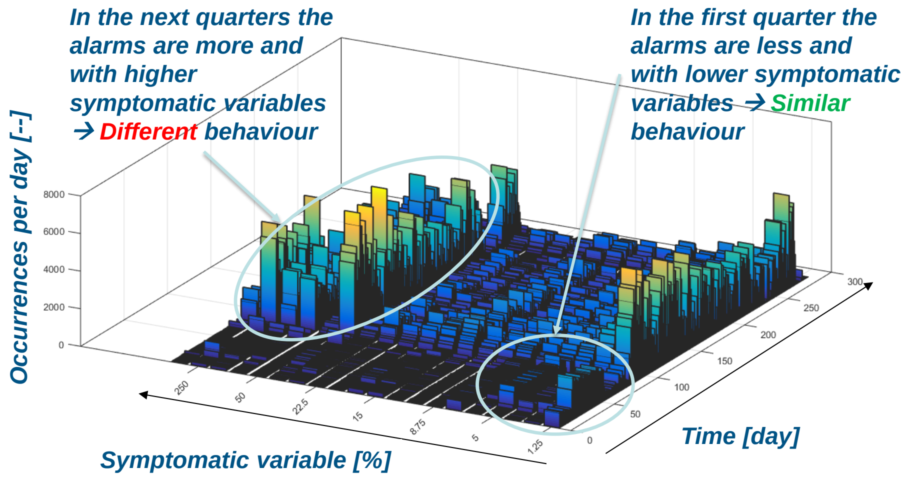


Figure 4 - Number of features with novelties, detected by *Domain check* for numerical parameters of the VEX satelite, distributed according to the *symtpomatic variable* (degree of novelty) and to the time period analysed.

In general, the results of the checks application to the two new (*comparison*) datasets of the VEX and XMM satellites show that in both cases novelties are detected in the expected time periods.

As regards the VEX satellite, the results show that, as expected, most of the checks detect a significant number of novelties in the second and third quarters of the comparison dataset, in which a series of aero-braking manoeuvers were performed (in the period May - July 2014) and a *reduced scientific phase* was started, lasting until the end of the available dataset.

Figure 5 shows for example the number of numerical parameters of the VEX satellite with at least one feature with novel behavior detected by *Domain check* in the *comparison dataset*.

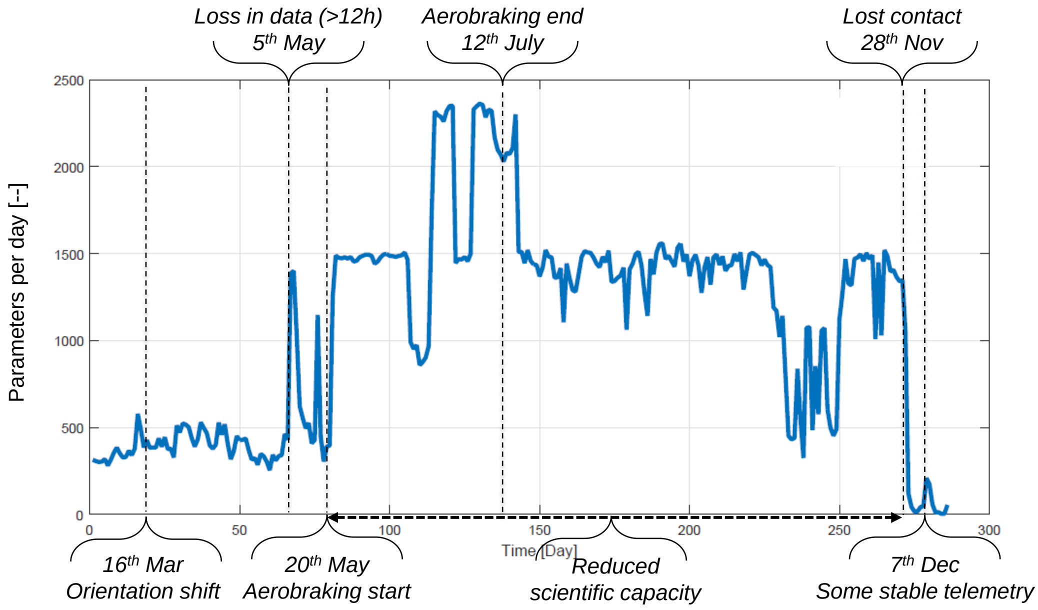


Figure 5 - *Domain check* - Number of numerical parameters of the VEX satellite that have novelties in the *comparison dataset*, in each day.

As regards the XMM satellite, the results of the checks are in line with the results obtained by one of the novelty detection methods (named *short-term time based static analysis*) implemented in the software prototype ***KETTY***, developed and validated by SATE under the parallel project AUTOMATIC BEHAVIOUR DETECTION AND INTERPRETATION FROM LOW LEVEL DATASETS SUCH AS TELEMETRY.

For both satellites it was observed that among all the checks defined (excluding *Few sample check,* which applies to a specific set of parameters), *Inter period check, Domain check* and *Distribution check* detect almost all the novelties in the *comparison periods*. This is mainly due to the fact that these checks have a higher number of checkable features compared to *Trend check* and *Frequency check*. However, the validation performed on these latter checks proved that they allow detecting different types of novelties that the other checks are not be able to detect.

In general, the different checks may detect different types of novelty or detect the same novelties but within different times.

In order to limit false positives and to improve novelty detection, it may be useful exploiting the redundancy of some of the checks, e.g. *Domain check*, *Inter period check* and *Distribution check*, which analyse similar characteristics of the features by different approaches.

As output of this activity, in addition to the report describing the methods and results, SATE delivered to ESA the time series of the novelties detected by each check in the *comparison datasets* of the two satellites.

2.4 Derived parameters

Derived parameters are defined as the parameters time series that are extracted from the log files and database files such as telemetry data, global mission data, orbit information data and other log files. The derived parameters are mainly used to identify the occurrence of events on board the Spacecraft, the status of the spacecraft and occurrence of faults or errors during its operation.

To create the derived parameters, the log files containing the global mission data were converted into time series that are suitable to be processed as the telemetry data. As output of this activity, in addition to the report describing the methods and results, SATE delivered to ESA the time series of the derived parameters defined.

The extracted derived parameters are associated to the major different log files of the VEX Spacecraft based on its mission planning. The various sets of extracted derived parameters are summarized in Table 2.

S.No	Sets	Input Files / Information	Examples of Derived Parameter
1.	**Spacecraft Events Set (SES)**	− SC Events files − Orbit Information	− SES event time series − SES event group time series − SES event group orbit distance time series − SES severity flag time series
2.	**Tele-Commands Set (TCS)**	− TC History files − Orbit Information	− TCS command time series − TCS sequence time series − TCS sequence group time series − TCS sequence orbit distance time series
3.	**Communication and DMS Set (CDS)**	− SCOS Events files − Orbit Information	− CDS TM time series − CDS TC time series − CDS Missing Source data time series − CDS Missing transfer frames time series − CDS Anomalies time series − CDS FARC server time series
4.	**Auxiliary Set**	− Orbit Information	− Distance SC-Venus time series − Distance SC-Sun time series − Linear Velocity SC time series − Sun Shadow time series − SC Conjunction time series − Sun-SC-Earth angle time series − Sun-SC angle time series − Sun-SC-Venus angle time series

Table 2 - Overview of the different types of derived parameters that can be extracted from the given log files and orbit data of the VEX satellite.

2.5 Correlation analysis

SATE defined and implemented two methods to search for cause-effect relations between time series, named **Method 2** and **Method 3**.[1]

In general, the methods share the idea that if a cause/effect relation exists between two signals, then a change in one signal (i.e. the *cause*) should produce a change in the correlated signal (i.e. the *effect*). A *change* is defined as the variation of the signal to a different numeric value or state.

The methods investigate the presence of correlations between signals on the basis of different statistical analyses of the time lags between changes of the signals and by different characterisations of the changes, in some cases taking into account the values taken by the signals.

These were applied to identify correlations between tele-commands and parameters/features time series. Two different approaches are defined, named *Parameter Time Series* approach and *Feature Time Series* approach, according to the type of *effect* analysed, either raw parameters or features.

The results proved that both methods and approaches are capable of detecting potential cause-effect relations by complementary capabilities. For example, Figure 6 and Figure 7 illustrate the number of correlated pairs found by **Method 2** and **Method 3**, respectively, with the two different

[1] Method 1 was also defined but was not further analysed in this project, in agreement with ESA.

approaches. The figures show that there is a negligible intersection between the set of pairs identified by both the Parameters approach and the Features approach, for each method (see the small share "Common to both" in the figures).

Similarly, it was found that the sets of correlated pairs found by **Method 2** and **Method 3** with a specific approach (e.g. *Parameters Time Series* approach or *Feature Time Series* approach) have a small intersection.

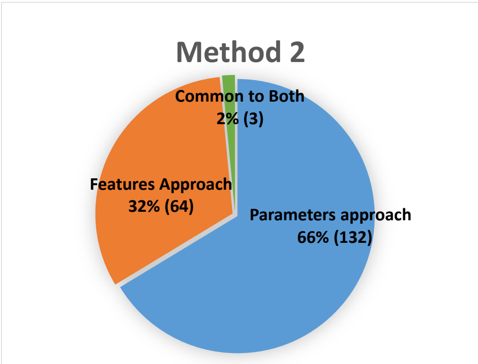


Figure 6 - Distribution of the correlated pairs (Tele-command, parameter) identified by **Method 2**.

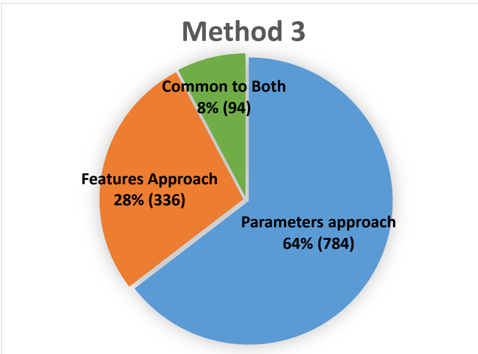


Figure 7 - Distribution of the correlated pairs (Tele-command, parameter) identified by **Method 3**.

Furthermore, the results obtained by both Method 2 and Method 3 indicate the presence of correlations between Tele-commands and parameters/features belonging to the same subsystem, as well as between Tele-commands and parameters/features belonging to different subsystems. This fact is considered a relevant result of this analysis, as it may provide some more insight into the spacecraft dynamics, identifying relationships that may not be always expected.

As output of this activity, in addition to the report describing the methods and results, SATE delivered to ESA *correlation matrixes* computed from the *reference dataset* of the VEX satellite.

2.6 Conclusions

The results achieved during the project suggest that the extracted knowledge may be useful mainly to the understanding of the S/C dependencies and/or dynamics and to monitoring the S/C behaviour during operation.

This is true, in particular, for the knowledge represented by the *usefulness matrix*, generated by the checkability analysis, and the *correlation matrix*, generated by the correlation analysis.

The set of *usefulness matrixes* available for each of the six checks defined allows characterising the expected S/C behaviour. The knowledge of the expected behaviour of all the thousands parameters monitored on the spacecraft is deemed a relevant information for the Flight Control Engineer, for two reasons:

1. The expected parameter behaviour can be used as reference to check the parameter behaviour in a different time period;
2. The statistics of the expected behaviour of all the S/C telemetry data allows evaluating the overall S/C expected behaviour. Indeed, the checkability analysis identified also the expected number of:
    - Parameters with few samples,
    - Features with few different values,
    - Features with almost constant behaviour,
    - Features with stationary distribution,
    - Features with stationary frequency,
    - Features with modal behaviour.

    This information may also be exploited to better understand the S/C dynamics.

The S/C dependencies may be investigated by the analysis of the *correlation matrix*, which characterises the cause-effect relationships identified among tele-commands and parameters/features. This knowledge may also be useful to help engineers in the preparation of operations.

The availability of the definitions of the methods allows further expanding the knowledge through different analysis of the data available or of new datasets.

Novelties or changes in the dynamics of the spacecraft can be detected by applying the checks defined with the settings determined automatically and available in the *usefulness matrix*, to a new dataset.

It is stressed that the settings are automatically derived for each feature and each type of check, with the purpose of improving check reliability. Therefore, the knowledge of the check settings that "best fit" a given feature is deemed an extremely valuable information for novelty detection.

The checks defined allow the generation of *symptomatic variables*, which are associated to the difference in the behaviors of the parameters in the two different time periods. Indeed these *symptomatic variables* are associated to the violation of the detected knowledge which is extracted in the form of *usefulness matrix* from the *reference dataset* and proved to be indications of possible anomalies in the way to develop.

Finally, the analysis of the *correlation matrixes*, which summarise the cause-effect relationships of tele-commands and telemetry data of the VEX satellite, may support the preparation of operations, because it may help the engineers considering also possible unexpected (or not a priori known) relationships that may characterise the S/C behaviour.

2.7 Suggested future developments

Given the results of the study, SATE has been thinking about possible future developments of the methodologies identified in this project ad in the parallel project ABDI, which are summarised as follows:

1. Further validation with additional datasets and with feedback from the Flight Control Engineers;
2. Implementation of a prototype or integration into ***KETTY*** of the solutions defined in this project;
3. Expansion of the correlation analysis to identify relationships between the modal behaviour of the features and the occurrence of events and commands, exploiting the derived parameters, or to identify relationships among all the parameters of the S/C.
4. Apply the correlation analysis to find cause-effect relationships among anomalies, in order to help identifying the possible causes of an anomaly, if any.