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Telemetry Prediction within the Mission Planning System: Optimizing the Battery Unitization of the TerraSAR-X and TanDEM-X Satellites

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Abstract

A novel approach on the decision-making of the Mission Planning System is developed for the TerraSAR-X and TanDEM-X satellites. Combining the available data from the ground and the space segment, a continuous quantitative study is performed on the batteries of the TSX and TDX satellites. The first model developed as an outcome of this study is the chain model that groups the SAR acquisitions of the satellites depending on their time separation. Processing a long period of past data allowed us to estimate accurately the battery performance in upcoming periods, especially around the summer solstice of the following year, where the poorest battery performance is expected. Evolving on the estimation concept, we developed a new model that estimates the battery voltage telemetry for every SAR acquisition during the planning run. Depending on the level of the predicted telemetry parameters values, the Mission Planning System can decide if an activity should be planned or not. Once real telemetry is available on ground, the status of the batteries is compared to the estimated values. The inevitable ageing of the satellites is the main driver for a continuous study on their batteries. Our objective is a) to preserve the good performance of the batteries, supporting all the mission operations, while b) prevent any event on the batteries that might interrupt the operations. As a result in the last years, as long as the machine learning algorithms are running in the Mission Planning System, we filter all the on-board activities in which the battery-related telemetry would have exceeded the nominal limits, while we maintain the activities volume at the same levels as before, succeeding the optimization of the battery utilization. Applying this logic to the battery telemetry parameters is proving the concept of predicting accurately the telemetry during the planning run. This does not only lead to off-limits-violation prevention during the generation of the timeline, but also to the detection of unexpected onboard anomalies. This approach could potentially be applied on several other satellite units, in order to optimize their utilization via machine learning, regression, algorithms.

Keywords: lithium-ion battery, voltage control, supervised machine learning, regression, anomaly detection, out-of-limit violation prevention

Acronyms/Abbreviations

DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center)
GSOC	German Space Operations Center
MPS	Mission Planning System
PTS	Power and Thermal System
SAR	Synthetic Aperture Radar
TerraSAR-X	TerraSAR-X mission
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurements mission
TSX	TerraSAR-X satellite
TDX	TanDEM-X satellite

1. Introduction

The TSX and TDX satellites, flying in a bistatic close formation, form a single-pass space-born interferometer [1] [2] [3] [4] [5]. Launched in 2007 and 2010 respectively and operated in DLR/GSOC, both satellites have been delivering high-quality SAR products for over a decade. The ageing of the satellite equipment is one of the challenges that every operations team faces in almost any satellite mission. TSX and TDX satellites are not an exception. Focusing on the batteries of the two satellites, we describe the quantitative battery models that have been developed within the joint MPS for the TerraSAR-X and TanDEM-X missions [6]. The differences between the theoretical approach of the models and the operational implementation in the MPS are highlighted. Finally, we detail how the automated monitoring of the model performance can provide crucial information for the battery performance, within an automated telemetry processing tool.

2. Power Constraints within the Mission Planning System

After the launch of the TDX satellite, the joint TerraSAR-X and TanDEM-X Mission Planning System was deployed operationally [6] [7] [8] [9]. Several constraints on the satellite power consumption, related to every satellite activity, are considered while planning the mission [8] [10]. The sun-synchronous dusk-dawn orbit of the two satellites allows the solar panels to be continuously illuminated [11] [12] [13]. The energy provided by the solar panels covers the nominal satellite-bus energy consumption [14]. When the SAR instrument is operating, the additional requested energy is provided by the satellite's batteries. Below we describe the models of the MPS related to the battery power and thermal constraints, as they were developed in the beginning of the mission.

2.1 The Energy Consumption Model

A linear model of the battery discharge has been developed within the MPS. When the battery is fully charged, the level remains at zero (no negative values when overcharging). During the SAR instrument operations the discharge level increases linearly. Once the instrument operations are over, the battery charge is modelled via the solar panel input considered by the model [8]. This model has been proven accurate when cross-checked against the telemetry values.

2.2 The Gliding Windows

A gliding window is a continuously shifting time interval in which a limit on the accumulated consumed resources of the window can be set. The gliding windows concept has been implemented in MPS after a dedicated power and thermal analysis [8]. The smallest gliding window was defined with the length of an orbit (95min) allowing up to 400s of the SAR instrument operations. The longest gliding window has a length of 15*95min, allowing a maximum workload of 15*210s. This gliding windows concept was extended by additional windows and limits to apply the new battery constraints as described below within the MPS.

3. The Satellite Battery Voltage Models

A diffusion rate effect on the lithium-ion batteries was the main driver for a dedicated study on the behaviour of the satellite battery voltage [14] [15]. The outcome was concluded in a battery voltage model, named the "chain model" [16]. This concept was initially developed in 2017 for the eclipses phases, and in 2018 for the sun phases.

Evolving the concept of the chain model, a novel, supervised machine learning model was defined [17]. Below we describe both models, as well as their implementation within the Mission Planning System, highlighting the differences between the offline concepts and their operational implementation.

3.1 The Chain Model

Since 2015 it has been noticed that the existing battery model in the MPS was incompatible with some high power SAR acquisitions on the TSX satellite. This was particularly noticeable in eclipses when the battery had to supply all the needed power and energy. In order to restrict the planning of such SAR acquisitions, we performed a correlation analysis on the satellite telemetry data to similar data available in the MPS. The idea was to apply a limit on the total duration of acquisitions within chains of acquisitions instead of considering every SAR acquisition individually [16]. Consecutive SAR acquisitions are considered to belong in the same chain when their time separation is shorter than a defined threshold [14] [16], as displayed in Fig.1.

Fig.1 Defining chains of SAR acquisitions based on the time separation between them.

Based on past data, via a regression model, we projected the performance of several SAR acquisitions (based on their duration) in the future. For the first time, we forecasted the battery performance in a future timeframe and made a decision based on this result. Since 2018, prior to the yearly eclipses season, we estimate the threshold for the chain model that will be applied for the following year in MPS, covering the whole year and mainly the local minimum around the summer solstice. This limit is later communicated to the mission partners. The analysis performed for the TSX satellite in 2020 is depicted in Fig.2 [16].

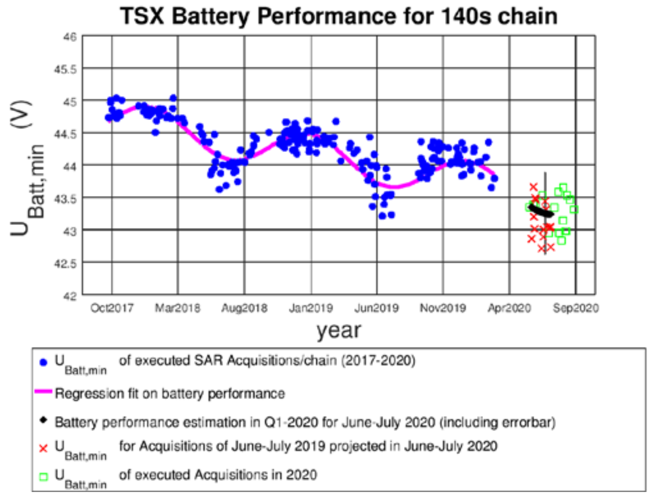

Fig.2 The TSX battery performance for chains of SAR acquisitions in the sun with a total duration of 140s over the last three years. Blue bullets show the minimum battery voltage according to satellite telemetry, while the magenta line is the regression fit. The estimated fit is plotted by the black rhombus, while with red points (x) are estimated minimum voltage values for the critical period of 2020 around the summer solstice derived according to the model in the first quarter of 2020. The measured minimum voltage of those SAR acquisitions/chains executed around the summer solstice of 2020 on TSX satellite is depicted by the green 'square' boxes. The performance of the battery has been estimated quite closely to the actual telemetry [16].

Within the MPS there are two different implementations of the chain model. For the eclipses the full chain model has been developed in 2017. The benefit of implementing it also for the sun phases was considered insufficient to justify the required effort of development and testing. Instead, it was proposed to adapt the gliding windows concept mentioned earlier in paragraph 2.2. In 2018 it was calculated for the chain model on the TSX satellite that we can allow up to 200s on SAR acquisitions. Per computations, another chain could start after 60s. As a substitute of the full chain model development, a new gliding window was defined, with length same as the limit of the 1-orbit gliding window, i.e. 400s.

In other words, we tried to manage the distribution of the 400s allowed to be executed in an orbit, via the threshold of 200s in the 400s gliding window. This ensured that the maximum acquisition duration would not exceed the chain model limit. It also ensured that the battery would charge for 200s, rather than the 60s established by the study. This model version is still operational and active in MPS. The limit is being adapted yearly, on both satellites.

3.2 The Supervised Machine Learning Model

The long term analysis based on the chain model demonstrated that we can forecast the battery performance in the future with reasonable accuracy. The chain model can be considered as a single-parameter regression. This was expanded into a multi-variable linear regression considering several parameters available in the MPS database, in order to estimate the battery voltage at the end of every SAR acquisition during planning the timeline. Based on the voltage estimation, a new planning rule is defined to filter the SAR acquisition candidates. The current model function in the operational implementation of MPS is (1), where E_{DT} is the total energy consumed by the SAR acquisition, P_{DT} is the power consumption during the SAR acquisition, E_0 is the energy level in the beginning of the SAR acquisition, and $T_{mission}$ refers to the mission elapsed time in the beginning of the SAR acquisition [17]. The values of the parameters: E_{DT}, P_{DT} and E_0, are provided by the energy consumption model, described in 2.1.

$$U_{Batt,est} = \alpha_0 + \alpha_1 \cdot E_{DT} + \alpha_2 \cdot P_{DT} + \alpha_3 \cdot E_0 + \alpha_4 \cdot T_{mission} \tag{1}$$

The same machine learning concept has been applied as for the chain model, depicted in Fig.3 [16] [17]. This regression algorithm running in the MPS is a beta version, developed as a technology demonstration. Nevertheless, the results are already quite promising. An update of the model function that improves the estimation accuracy is under evaluation, see also in [17].

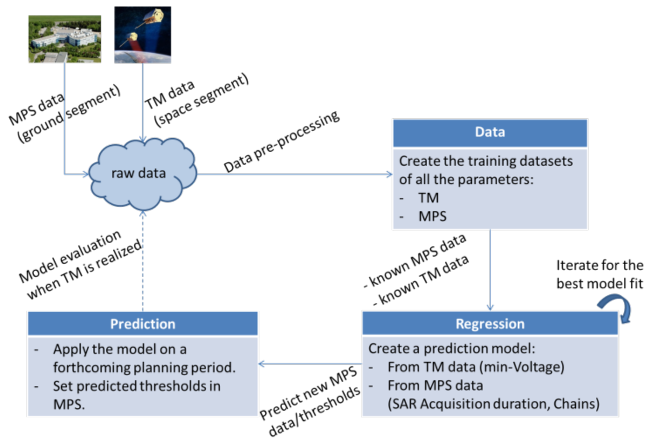

Fig. 3 The block diagram of the machine learning model applied in the Mission Planning System on the batteries of TSX and TDX satellites [16] [17].

4. Results

In this chapter, we describe the operational results obtained from each battery model separately. While both models are operational, only the chain model is currently active, making operational decisions. The machine learning model is currently on passive mode, performing all the estimations and comparisons against the thresholds but not applying the decisions.

4.1 The chain model

The current active operational battery voltage model is the chain model. Since this model was enabled, there have been very few cases where the battery voltage dropped (only marginally) below the defined voltage thresholds. The battery performance is monitored on a daily basis.

The simplicity of the planning rule of this model via an upper threshold on the duration of the SAR acquisition makes it quite user-friendly for the users of the TerraSAR-X and TanDEM-X missions. This duration threshold is not related to any other properties of the SAR acquisition, such as the power consumption or the attitude of the satellite at the execution time. This fact helps them to optimize their ordering process of SAR acquisition requests, minimizing the number of not-planned acquisitions. The acquisitions that are rejected are typically part of a chain.

An additional analysis is performed regularly on the SAR instrument activities that are rejected due to the chain model planning rules. We assess the false positive rate, checking case by case if any of the rejected SAR acquisitions/chains are false- or true-positive. The typical ratio of false-positives is below 0.3%, sufficiently low for our purposes. Consequently, the chain model remains the main operational model of our battery management strategy.

The downside of the present implementation, using a 400s window size, is that due to the ageing battery the limit (especially on TSX) becomes much lower than the window length (presently, in the 400s window, the limit is 110s). Therefore, it is currently under discussion to split the 400s window in two halves. This will be done by adding a new gliding window of 200s, at the same time that the 400s one is active but with a new threshold. In this case, the 200s gliding window will inherit the current threshold of the 400s one, while for the latter we will apply a limit equal (or shorter) than the double of the 200s one.

4.2 The Supervised Machine Learning Model

The regression model is on “passive” mode, meaning that it performs all the calculations and it triggers notification emails automatically. Nevertheless, currently it does not make any operational decisions in the MPS. It can be enabled at any time by a simple setting switch.

The voltage estimations are logged and later compared to the real telemetry values once they are available. The standard deviation of this comparison is lower than 0.35V [17]. As a result, we are confident that every estimation lies within a margin of +/- 2.1V. The objective is to keep the battery voltage above 40V the warning/alarm threshold of the satellite). In order to avoid operating the battery at the edge of its ability, we have set the model-threshold to 42.5V. Any estimation below this value is flagged as ‘not-planned’. As mentioned above, this decision is currently not considered by the MPS for the timeline generation. Such events are rare, since all the activities are already filtered by the chain model.

Another functionality we have developed within the MPS is an automated-email mechanism for candidate activities that might lead to low voltage values. After every planning run, a notification email is triggered, in case an acquisition is estimated to have a voltage lower than 44V. Since the timeline has a length of three days, we get informed well in advance of those candidate cases.

In parallel, all estimations are logged, and processed versus the telemetry values of the battery voltage once the telemetry is downlinked on ground. This process is performed regularly by triggering scripts manually, and now is being fully automated in a telemetry monitoring/processing tool.

The latter process is not only useful for the machine learning model evaluation. Via the comparison of the estimated voltage values versus the real-telemetry we can immediately detect on-board anomalies, even when the telemetry values are within the nominal operational range [17]. Such an event occurred in 2019 on the TDX satellite [18] [19] and is displayed in Fig.4.

Due to an on-board malfunction on the TDX satellite the SAR signal was not amplified for some hours. The instrument operations on TDX were not interrupted autonomously, and the acquisitions were executed even with weak signal. The weak signal was the reason for breaking the inter-satellite link of the sync warning mechanism [15], which made the TSX satellite to interrupt its operations automatically and to raise a flag for this reason. This is how the operations team was informed of the anomaly on the TDX satellite, by the TSX satellite.

Alternatively, this anomaly could have been detected by looking at the residuals between the predicted and the real battery voltage of TDX as depicted in Fig.4. Here we have to note that throughout this event the values of the battery voltage (on both satellites) remained within their nominal ranges. Nevertheless, the deviation of the residuals reveals immediately the on-board issue. Eventually, the instrument on TDX was switched to its redundant unit. Since then, it again produces SAR acquisitions with the same quality as those of before the redundancy switch [18] [19].

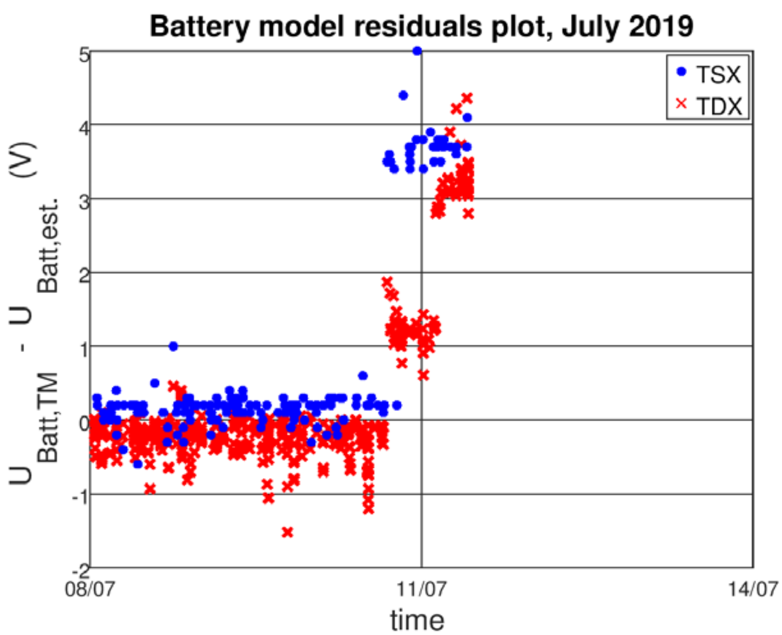

Fig.4 Anomaly detection via the machine learning model of the MPS. During nominal operations the residuals of the model estimations are grouped around zero. When the SAR instrument operations are interrupted the cluster is in the area of (3V - 4V), it is clearly visible the cluster defining the malfunctioning on TDX satellite in the range of (1V - 2V).

5. Discussion

The outcome of the quantitative analysis on the TerraSAR-X and TanDEM-X batteries is a model within the Mission Planning System that estimates the telemetry values while planning the mission. Once the planning is finished and the estimations of future telemetry are logged, they are ready to be compared against the real telemetry once it becomes available. This concept can be further applied on any other telemetry parameter that can be considered by the MPS, such as (but not limited to) any other voltage/current parameter or the on-board memory levels.

Currently this comparison is performed within the ground segment after the telemetry is downlinked and processed on the ground. This process can be implemented within a telemetry processing tool for out-of-limits violation prevention and anomaly detection [20] [21] [22] [23].

The predicted telemetry can also be rooted and then displayed within the telemetry monitoring system of the mission, in parallel to the real telemetry. The comparison between the two sources will be simplified and new (visual or systematic) warning/alarm thresholds can be set on the deviation the real telemetry values to the estimations.

The last comparison, between the estimated values to the actual telemetry, can be also useful for the system check prior to establishing an automated commanding chain [24].

In the future, estimated telemetry produced by the ground-segment could be uplinked to the satellite and a comparison could be performed on-board and in real-time [17]. We believe this will be a step forward towards the enhancement of the satellite's artificial intelligence.

6. Conclusion

The inevitable ageing of the equipment of the satellites in orbit is one of the most crucial factors to be considered by any satellite operations team. Statistical approaches are considered in parallel to the existing physical and chemical models of the TSX and TDX satellite batteries, in order to achieve a better understanding of their performance and eventually optimize their utilization. The target of our battery management strategy is to keep the batteries of both satellites above the telemetry warning/alarm thresholds, and to maximize the mission operations support. The promising results we have obtained in the last years are encouraging us to invest in such quantitative analyses. In parallel, the machine learning model we developed for the TSX and TDX batteries can be considered as a prototype for an automated telemetry monitoring and processing system, not only based on the absolute telemetry values but also on the relative deviation of estimations to real telemetry. We consider this analysis as one further step towards the evolution of the artificial intelligence of the satellite mission operations tools.

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