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Operational results of the machine learning-based battery strategy management in the TerraSAR-X / TanDEM-X Mission Planning System

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Abstract

The battery model within the TerraSAR-X / TanDEM-X Mission Planning System has been gradually transformed from a model based on the electro-chemical consistency of the battery to a machine learning based model. The objective of the data driven analysis started in 2017, was to optimize the battery utilization: a) by ensuring the safe operations of the battery, while b) maximizing its workload. Via a regression algorithm we were able to forecast the battery performance in the long term, being able to control the maximum voltage drop that could be allowed in the battery. In the expansion of this model, the battery voltage was estimated for every single activity that was considered to be planned. In this paper we describe the operational implementation of the battery model within the TerraSAR-X / TanDEM-X Mission Planning System, differentiating the model versions for the sun phases or the eclipses phases per satellite. Furthermore, we describe how the initial data driven approach (called the chain-model) was merged with the machine learning-based model expansion. The operational results per model and case are outlined since the models have been operationally applied, in parallel to the offline studies conducted. Besides the efficiency of the models, we present their limitations, together with the measures considered to deal with the latter. In addition, we describe all the functionalities and notification mechanisms that were developed within these battery model versions, allowing the OPS team to have easy access and instant notifications on any event related to the satellites’ batteries. Finally, we address our strategy on the battery management for the future years in orbit.

Keywords: Mission Planning System, lithium-ion battery, voltage control, supervised machine learning

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

Nomenclature

U_{Batt}	Satellite battery voltage
E_{SAR}	SAR acquisition energy demand
P_{SAR}	SAR acquisition power consumption
E_0	Satellite battery energy level in the beginning of a SAR acquisition
$T_{mission}$	Mission elapsed time in the beginning of a SAR acquisition

1. Introduction

The TSX and TDX satellites build a space-born radar interferometer for the TerraSAR-X and TanDEM-X missions, flying in bistatic close formation [1,2]. For more than a decade since 2007 and 2010 respectively, both satellites execute high quality radar data-takes, serving the two missions. Due to the ageing of the satellite batteries, the strategy on the battery management within the TerraSAR-X / TanDEM-X Mission Planning System had to be adapted. In the last years the battery model has been gradually transformed from a model based on the electro-chemical consistency of the battery to a quantitative model. Via a machine learning process, we estimate the battery performance in a future period. Based on this estimation, we define the thresholds in the decision-making mechanism of the Mission Planning System. Under this principle, over the years several model versions have been developed and deployed, based on the operational requirements of each period. In this paper we describe the various model versions for each satellite, in addition to their daily operations within the Mission Planning System. We detail the differences of the various model versions, in comparison to the operational requirements of each deployment period. We conclude with an overview on the operational results of this machine learning battery model applied within the TerraSAR-X / TanDEM-X Mission Planning System. Finally, we conclude with our envisagement on further expansion of this machine learning modeling approach on more telemetry parameters (other than the battery voltage).

2. Energy / Power constraints and mechanisms in the TerraSAR-X / TanDEM-X Mission Planning System

The TSX and TDX satellites fly in formation in a sun-synchronous dusk-dawn orbit with a revisit period of 11 days. The electrical power systems of both satellites are almost identical. The main payload on both satellites requires ten times more energy than the regular energy consumption of the satellite bus. While the latter energy demand is covered sufficiently by the solar panels, during the high consumption of payload operations the contribution by the lithium-ion batteries is required [3].

In case that the solar panels are shadowed, then the full amount of energy is provided only by the battery. This is happening during an eclipse, while the solar panels are under the shadow of the earth. Due to the specific orbit of the satellites, an eclipse season is occurring yearly, in a period around the summer solstice and always over the south pole. A dedicated analysis is performed by the flight dynamics team, and all relevant data are provided to the Mission Planning System for planning the upcoming satellite and payload activities. Similar behaviour is noticed during the execution of the so-called "Left-Looking" SAR acquisitions, which require a satellite attitude roll, in a way that the solar panels are turned away from the sun light. During the execution of such SAR acquisitions minimum or zero energy is provided by the solar panel, and all the required energy is provided by the satellite battery [4].

All this information, together with the calibrated data for each SAR acquisition, are provided as input to the Mission Planning System in order to schedule the upcoming satellite activities. Concerning the energy and power constraints, an energy consumption model is developed since the very beginning of the Mission Planning System. A linear model is estimating the battery discharge, based on the calibrated power consumption of each activity. It considers all satellite activities (not limited to the payload activities), modelling if the battery is contributing energy in any of them. Obviously if any energy input by the solar panels is anticipated, this is also considered. Once the activity is over, then the battery is recharged by the solar panel input (when not in eclipse, or once out of it). The recharge is modelled linearly [5,6,7,8,9].

Another mechanism developed within the Mission Planning System after a dedicated analysis on the power and thermal performance of the satellite components was the "gliding windows". Within a gliding window, a maximum amount of time (in seconds) of the SAR instrument operations was allowed. This concept was developed since the TanDEM-X satellite was launched (2010) [7], and the combined TerraSAR-X/TanDEM-X Mission Planning System was rolled out. Several gliding windows were defined, with the shortest at that time having the duration of an orbit, at 95min, and an upper threshold of 400sec payload operations. The longest gliding window was defined with a duration of 15 orbits, with an upper threshold of 3150sec of payload operations during the 15 orbits [10].

3. The machine learning-based battery models within the TerraSAR-X / TanDEM-X Mission Planning System

The root cause of the first low battery voltage events since 2015 was found on the diffusion rate effect on the lithium-ion batteries of the two satellites [11]. We have to note that those events were only visible in the telemetry, by warning flags, while the battery voltage remained always within the nominal, operational range. As a result, acting preventively, it was decided to perform an update of the existing battery model of the Mission Planning System. It was noticed that the voltage drop was strongly correlated to the SAR acquisition duration, as shown in Fig. 1 [12]. Therefore we targeted to control the battery voltage drop, by the SAR acquisition duration. In consequence the "chain model" was introduced, initially for the eclipse phases and later for the sun phases of the TSX and TDX satellites. The rationale of the chain model is that for a defined (time-) distance between two consecutive SAR acquisitions, that we consider that the battery is not recharged, the Mission Planning System considers the two consecutive acquisitions as one [10]. In other words, their duration is summed, and it could be planned only if it did not exceed the upper SAR acquisition duration threshold for a chain. Once there is such long separation with the successive SAR acquisition that we consider the battery charged, a new chain is considered, resetting the SAR acquisition duration counter.

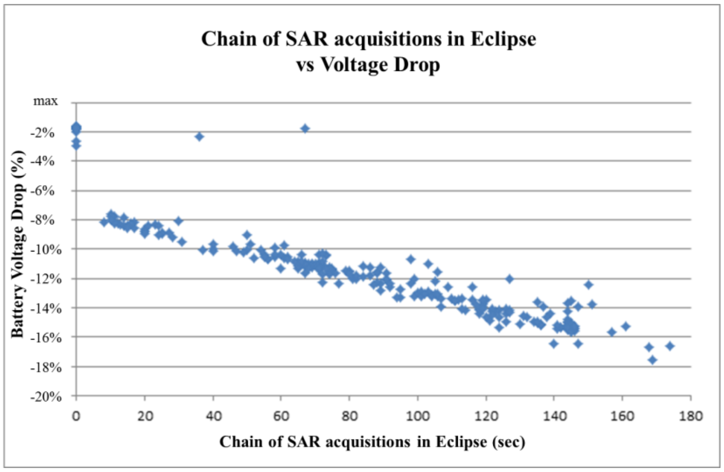

Fig. 1 The voltage drop after a chain of SAR acquisitions
is strongly correlated to the SAR acquisition duration.

Via a regression analysis the upper thresholds of the chain model for both satellites, TSX and TDX, and for both sun and eclipses phases are estimated. Operational data of the battery telemetry are considered, in order to forecast the battery performance in the upcoming year [11]. Then the limits are communicated to the users. Typically, the thresholds are valid for the rest of the year, until the next estimation.

In the next paragraph we describe the rollout of the chain model within the Mission Planning System, at first for the eclipses phases, and then for the sun phases.

3.1 Operational deployment of the quantitative battery models in the Mission Planning System

In 2017 it was decided to roll out the chain model for the SAR acquisitions executed on TDX satellite. As abovementioned in chapter 2, an eclipse would occur over the south pole. Due to the geometry of the satellite formation only the TDX satellite could operate actively its SAR instrument (the TSX satellite could operate it in passive mode, receiving the radar signal for the generation of DEM acquisitions). The full chain model was developed within the Mission Planning System, defining all the relevant parameters, and programming all the functionalities. Obviously, this required much effort from the software development team, as well as a dedicated test campaign for the integration of this new model within the operational Mission Planning tools, since most of the parameters were new to the system. The model and its functionality were designed for both satellites, TSX and TDX in parallel. This was useful, since in the next year the formation geometry would swap, and in the following years the TSX satellite would be the one operating actively its SAR instrument. In Table 1 below they are stated the upper threshold of total SAR operations allowed in a chain, in eclipse, since 2017.

Table 1. Upper limits of SAR acquisition duration in a chain during the eclipse phases

	TSX	TDX
2017	-	165sec
2018	65sec	165sec
2019	65sec	100sec
2020	50sec	90sec
2021	40sec	80sec
2022	40sec	55sec

This model version was designed and developed dedicated to the eclipse phases. As a result, it could not be applied or adapted for the sun phases. The need of a model version for the latter was met in the next calendar year, 2018, for TSX satellite. Its operational deployment is described in the following chapter.

3.2 Operational deployment of the chain model for the sun phases

In early 2018 it was noticed that low voltage cases were taking place on TSX satellite during the sun phases (similar as for the eclipses, the low voltage events were only visual warnings in the telemetry; the battery voltage remained always within the nominal operational range). The analysis showed that the chain model could be also applied during the sun phases, considering additionally the energy input by the solar panels. Due to the orbit of the satellites, the vast majority of time the solar panels are illuminated, and the satellites are in the sun phases. Therefore, a different workaround could take place, in order to avoid the development and testing effort of the full model in the Mission Planning System. It was decided to expand the gliding window concept, as described in chapter 2. A new gliding window was defined, with same length as the threshold of the shortest existing gliding window (of 1 orbit), which was 400s. Within the new gliding window of 400s, an upper threshold can be defined for the maximum SAR instrument operations. The operational upper limits for the 400s gliding windows are stated in Table 2, below.

Since the functionality was already existing, only an update of the gliding windows table was necessary. Additionally, the corresponding testing was not performed on its functionality, but only on the system performance with the new gliding window. This approach minimized the effort of the operational implementation of the chain model for the sun phases within the Mission Planning System.

The drawback of this version was that in the course of time, while the upper limit of the SAR operations was decreasing, the recharge time is mostly stable, about 60sec. The latter depends only on the energy input by the solar panels, therefore stable amount of energy is provided. Nevertheless, applying all the above in the gliding window mechanism, leads to the fact that within the same window timeframe (i.e. 400sec), with decreasing time-limit, and stable recharge time, there is more spare time that activities could be performed but are prevented by the mechanism. In order to overcome this issue, the 400s gliding window has been reduced in duration to 200s and a larger window of 800s (TDX) and 600s (TSX) has been defined. The limit of the larger gliding window had initially been set to 200s (TSX) and 240s (TDX), respectively, and was reduced for TSX to 170s in 2022. The larger window mitigates the restriction to ever shorter single data-takes by allowing additional data-takes within the larger window.

Table 2. Upper limits of SAR acquisition duration in a chain during the sun phases, applied in the 400s (later 200sec / 600sec or 800sec for TSX or TDX respectively) gliding windows.

	TSX	TDX
2018	200sec	-
2019	170sec	360s
2020	140sec	330s
2021	110sec / 200sec*	200s / 240sec**
2022	91s / 170sec*	140s / 240sec**

* for TSX after 2021 the 400sec gliding window was divided into two separates, one of 200sec and one of 600sec duration
** for TDX after 2021 the 400sec gliding window was divided into two separates, one of 200sec and one of 800sec duration

3.3 Operational deployment of the battery telemetry prediction model

For the chain model we forecast the battery performance for the following year. As an expansion of this approach, we developed a mechanism within the Mission Planning System for a short-term forecast. Based on the data available in the Mission Planning System, it is estimating the battery voltage at the end of each SAR acquisition while planning the mission timeline. The current operational version considers a multiple linear regression model [9]:

$$U_{Batt,\ est} = a_0 + a_1 \cdot E_{SAR} + a_2 \cdot P_{SAR} + a_3 \cdot E_0 + a_4 \cdot T_{mission} \qquad (1).$$

The voltage estimation is performed on every SAR acquisition that is considered to be planned. The decision mechanism work as the following: when the estimated voltage value is higher than the voltage threshold, that we have defined within the Mission Planning System, then this SAR acquisition can be planned. An automated email is sent out once a SAR acquisition is estimated below the low voltage threshold, and therefore not planned. The same automated email mechanism is informing on "soft limits" violation, for SAR acquisitions which are good candidates for a low voltage performance (on a second voltage threshold defined within the Mission Planning System).

Finally, an active/passive/off concept is developed for the decision mechanism of this model. In the active mode, this is the main battery model that is considered by the Mission Planning System, while in the passive mode all estimations are performed and logged but no decision is made based on them by the Mission Planning System. Since its development the passive state is continuously selected.

4. Operational results of the machine learning-based battery strategy management

The quantitative battery models have been running within the TerraSAR-X / TanDEM-X Mission Planning System since 2017. Since then the satellite battery voltage has always remained within the nominal range. Via this machine learning based strategy we managed not only to control the drop of the battery voltage, but we are able to optimize the planning of the SAR acquisitions as long as the battery voltage remains in the nominal range.

Our assessment on the machine learning models is focusing on the false (positive and negative) cases of the decision making. The false negative cases, corresponding to SAR acquisitions that were eventually planned and resulted to a low voltage event. The analysis showed they are below 0.05% of all executed SAR acquisitions yearly. In addition we want to highlight that in all those cases, the low voltage was only a visual warning on the telemetry, and the battery voltage was always within the nominal operational range. This is how we have achieved the first of the twofold target of the model, that is to ensure the safe battery operations. Moreover, even if those cases were planned by the "chain" model, all of them have been captured by the "soft limit" mechanism of the battery voltage prediction model. This is a great advantage of the "passive mode" introduced for the battery voltage prediction model, that allows us of knowing all the information beforehand (while planning the mission) including a reliable voltage estimation, while letting the chain model making all the decisions.

Regarding the false positive cases, i.e SAR acquisitions that are not planned even if they could eventually be planned, they are below 0.3%. This result is proving that we have achieved the second of the twofold objective of the model, that is to optimize the planning of SAR acquisitions (while respecting the first objective that is no other than having safe battery and satellite operations). Under this perspective, the chain model remains the prime battery model for the TSX and TDX satellites. Nevertheless, continuous monitoring of the battery and the model's performance is essential for maintaining the most reliable results. Assessing the battery performance is driving to the model updates, performed when necessary. The latter are not only related to the upper thresholds of SAR operations within a chain, but also on the mechanisms such as the introduction of the additional (shorter in length) gliding window.

5. Discussion

Via this machine learning approach in the battery model of the TerraSAR-X / TanDEM-X mission we achieved to control the battery voltage while planning the satellite operations. On a broader perspective, we forecasted the performance of a satellite telemetry parameter while planning, and via this estimation we make decisions on the satellite activities. Therefore, we believe that we can expand the same approach on more telemetry parameters under the same perspective. This could be either on similar telemetry parameters, that their value should be estimated, or on a simpler example when their value can be calculated (such as the onboard memory).

In parallel it is important to automate the assessment of the model performance, visualizing the estimated value, in order to compare this value against the real telemetry. The deviation of those two values can be the source of useful findings, in parallel to the absolute values of the telemetry parameters. In other words, a large deviation can trigger a warning, even when the absolute values are within the nominal ranges.

As a final step, the estimated telemetry produced within the ground segment can be uplinked on-board the satellite. An on-board comparison could be performed even at real time, and decisions can be made immediately. We believe this will be a step forward towards the enhancement of the satellite's artificial intelligence.

6. Conclusion

The experience of operating the TSX and TDX satellites for more than a decade in orbit, made us investigate novel approaches for the battery management. In this paper we present an overview of the battery models running operationally, followed by their quantitative performance analysis. The well-established results allow us to be confident for the battery operations in the future. In addition we investigate on further expansion of the machine learning based approach, either on the same battery models, or even or different telemetry parameters. We believe that the operational experience of this machine learning approach is creating a significant knowledge input for current or upcoming missions that are dealing with similar challenges. Eventually we consider our machine learning based battery strategy as one step further on the enhancement of artificial intelligence in the space missions operations.

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