IAC-17-F1.2.8 (36550)

Li-Ion Battery Operations and Life Optimization

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Abstract

The challenges in satellite operations are multi-fold. The battery management in a satellite is a challenge to operations team. The lifetime in orbit is mostly defined by the health of batteries. This paper deals with the efforts undertaken at the German Space Operations Agency (GSOC) to optimize the battery operations on their satellite TerraSAR-X (TSX). The TSX was launched in 2007 and has successfully completed its design life of 5 years. The satellite flies in a sun-synchronous "Dawn-Dusk" orbit where eclipses occur between April and August. In comparison to other missions where the eclipse duration remains constant over its life time, the duration of the eclipse varies during the season. The spacecraft has a power requirement of roughly 5000 W. During eclipse the full power required by the spacecraft bus and the payload is supplied by the batteries.

In the summer of 2014, during the peak eclipse duration combined with instrument operations, a low voltage event was noticed. The same effect was noticed more than once during the summer of 2015. Although, the noticed values were far from any safe-mode trigger limits, it was an indication of some phenomenon other than the degradation within the batteries caused by ageing. It was found upon detailed investigation by the spacecraft manufacturer, that the Li-Ion batteries show a secondary effect which at the initial stages of its life is considered negligible. This effect is called as the "diffusion rate limitation". Several deep-discharge test cycles were performed in order to gather data for further investigation. A detailed investigation revealed that the voltage decrease is nearly linear beyond the first dip. Based on this discovery, the existing battery model was optimized. This optimized model now accounts for the "diffusion rate limitation" by controlling the maximum allowable discharge energy for every payload operation supported by the batteries. This paper discusses in detail the investigation, analysis of diffusion effect and the optimization of the battery model. The updated model was tested during the summer of 2016 and 2017. The results are presented in this paper.

Keywords: Li-Ion, Capacity fade, Degradation, Diffusion effect, Satellite, Low earth orbit

Nomenclature

R_{int} = Internal resistance in mohms
R_{int_BOL} = Internal resistance at Begin of Life
T = Temperature in °C
EMF = Electro Motive Force
E_{max} = Maximum Energy in wattseconds
P = Power in watts (actual)
P_{ref} = Power in watts (reference)
S_{ref} = Time in seconds (reference)
S = Time in seconds (actual)
E_{ref} = Energy in wattseconds (reference)

Acronyms/Abbreviations

BoC – Begin of Charge Level
BoL – Begin of Life
CCR – Charge Control Reference
DLR – Deutsches Zentrum fuer Luft- und Raumfahrt e.V., (German Space Agency)
DoD – Depth of Discharge
DRL – Diffusion Rate Limitation
EoCV – End of Charge Level
EoL – End of Life
GSOC – German Space Operations Centre
Li-Ion – Lithium Ion Battery
MPS – Mission Planning System
OEM – Original Equipment Manufacturer
PCDU – Power Control and Distribution Unit
PTS – Power and Thermal Subsystem
SA – Solar Array
SAR – Synthetic Aperture Radar
SST – Satellite Support Team
TSX – TerraSAR-X Satellite
TDX – TanDEM-X satellite

1. Introduction

The battery is among the most important components of a spacecraft. Battery management is an essential part of mission longevity and success. In the past decade, the Lithium-Ion (Li-Ion) batteries have transitioned into commercial success from merely being a research topic [5].

The following chapters talk about the basics of the satellite, orbit, payload operations and battery model for the mission planning team. The main aim of this paper is to discuss the operational influence of primary and the secondary degradation noticed in Li-Ion batteries. The secondary degradation feature called Diffusion Rate Limitation (DRL). This effect was investigated and analysed. The outcome was then an update of battery model within the Mission Planning System (MPS) tool. The result of such an update is as follows:

1. The MPS battery (energy) modelling is conservative enough to prevent the battery from reaching critical limits but at the same time is flexible enough to accommodate regular payload operations.
2. The batteries are in good shape, better than predicted. The diffusion rate limitation has given the operations team a good overview about the ageing process of a Li-Ion battery, helping them prepare for future and newer missions.

2. Satellite, Payload requirements and Mission Planning

2.1 Satellite

The TerraSAR-X (TSX) and TanDEM-X (TDX) are twin radar satellite missions designed to map the Earth in 3D. TSX was launched from Baikonur in 2007 into a 514 km sun-synchronous “Dawn-Dusk” orbit and TDX was launched into in a similar orbit in the year 2010. The two satellites fly in close formation, imaging the earth in 3D. Both these satellites have an 11 day repeat cycle. Due to the nature of the orbit, there is an eclipse period every year between April and August.

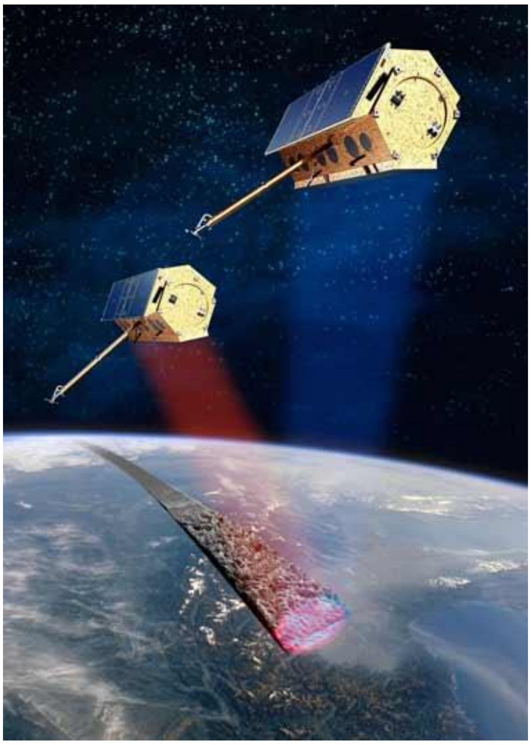

Figure 1: TerraSAR-X and TanDEM-X satellites in orbit

2.2 Power Sources

The two satellites are powered via 2 body-mounted solar panels. During the high power demanding scenarios, the energy from the batteries is used in addition to the energy generated by the solar array. The batteries manufactured by ABSL ltd., have a name plate capacity of 108Ah, distributed in three stacks.

Cell Data			
Cell Type	Sony US 18650 HC		
Cell Capacity	1.5 Ah	Maximum Cell Voltage	4.2 V
Battery Data			
Number of Cells / String	12	Number of Strings / Module	24
Number of Modules	3	Total Capacity	108 Ah
Minimum Voltage (full load)	38 V	Charge Control Reference (=Max.) Voltage	50.4 V
Max. Charge Current	0.5 C	Max. Discharge Current	1.8 C
EOL Resistance	60 mΩ	EOL Efficiency	> 83 %
Battery Mass (3 modules)	42 kg	Self-Discharge Rate	0.15 % / day

Figure 2: Li-Ion Battery manufacturer specifications for TSX and TDX

The Power Control and Distribution Unit (PCDU) controls and regulates [2] the charge and discharge of the batteries. The batteries are charged at full current until the Charge Control Reference voltage (CCR) is reached. Then the charge current is reduced to a taper charge. The end of charge level is a fixed value. The PCDU not only controls the charging and discharging of the batteries but also the distribution of power within the spacecraft bus.

2.3 Eclipses

The eclipse period varies between less than 10 minutes to around 20minutes. During the eclipse periods, the energy requirement (~500 W) of the spacecraft is satisfied by the batteries along with instrument operations (~4500 W) and the X-Band ground station contacts. The total peak power requirement is roughly about 5000 W.

2.4 Special Scenarios

The SAR data takes are performed in two different modes. Nominally, the spacecraft is rotated (see Fig. 3) by +33.8 degrees upon its X-axis. In order to cover certain angles, the satellite is rotated upon its X-axis to -33.8 degrees in order to point the SAR antenna towards the target. This mode is known as the "left-looking" mode.

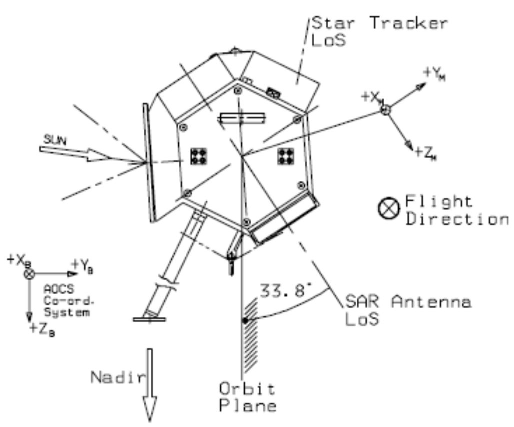

Figure 3: Left Looking and Right Looking modes of the spacecraft [2]

During the left looking modes, the solar arrays are pointed away from the sun. Therefore, the conditions during orbital eclipse phases and during left looking data takes are very similar i.e. the batteries support the bus as well as the instrument during this phase. The left looking data takes are a part of regular operations and are performed often. Apart from the regular data takes on individual satellites, there is also a TanDEM-X mission, where the data take performed by one satellite is repeated by the second.

Due to the nature of the payload and the scientific interest, a special campaign known as "Antartica campaign" to map the movement of the icebergs are conducted from time to time. The timing of this campaign correlates with the eclipse phase of the orbits. As a part of this campaign, there are several short data takes conducted within short intervals from one another. This in total accounts for a very high power demand over a short duration of time. By virtue of the orbit, the TDX flies beneath the TSX which results in an exclusion zone wherein, the TSX is not allowed to operate its radar instrument to avoid subjecting the TDX satellite to radiation.

Apart from the above described regular data takes, a degradation data take is performed every year to ascertain the capacity fade degradation.

2.5 Battery Modelling by Mission Planning System

The model of the battery is based upon the concept of a renewable resource [7] the energy. When adding consumers during the planning-process, energy is depleted and is replenished when no loads are applied. Based on this concept, the energy supply of the solar panels as a source of energy is modelled. It varies only with the season and is interrupted when eclipses occur and when the satellite performs a left-looking data-take.

The main consumer of energy is the radar instrument, whose activities are planned and therefore its consumption is predictable. The same yields for the downlink equipment and some other on-board facilities, which are needed to execute data-takes and downlinks. Some on-board activities however are not planned on-ground but are event-driven. These activities fortunately use much less energy when compared to the radar instrument and therefore is modelled as a constant consumption. Further details about MPS modelling, various sub-models and the modifications done to accommodate the DRL are discussed in chapter 5.

3. Capacity Fade

The analysis of the battery at the regular interval provides the operations team with a good idea of the capacity left and also the amount of capacity lost. Such analysis helps:

1. To gather information on the behaviour during the early mission phases.
2. To provide information to the mission planning team with available energy during the later

stages in the mission when the battery has significantly degraded.

3. To provide continuous health information to the Electrical subsystem team for monitoring and eventually for contingency reactions.

The Li-Ion batteries with age show capacity degradation due to increase in internal resistance [1].

3.1 Degradation Data-takes

The capacity fade calculation is done every year during the month of August or September. This is done to determine the natural degradation process within the battery. The regular degradation measurement during its lifetime will provide a fair indication of how much usable capacity is still left, based on which the future of the mission can be planned. The calculation is based on the conservative model developed by the manufacturer [2, 8] through life tests.

The capacity fade is determined as a function of internal resistance over the life time. The internal resistance is affected by the temperature and the estimated degradation. At lower temperatures, the resistance is higher. The percentage increase in resistance is linear with degrading capacity. This rate is given as an increase of 50% of the resistance for every 15% rise in capacity degradation [1]. The overall function for resistance over life at given temperature T and Electro Motive Force (EMF) is given by:

$$R_{int}(T, EMF) = R_{int}(T, EMF)_{BOL} + R_{int}\,(T, 4.2\,V)_{BOL} * \; Percentage\ Increase\,. \quad (1)$$

The capacity degradation calculated is the change in internal battery resistance from the calculated year to that of the launch year. This gives the percentage increase of the internal resistance with the battery. The capacity fade is then calculated based on the empherical fomula (Eq. 2) [1] that contains the ratio of increase in the End of charge (EoC) resistance to the capacity degradation. This ratio is a result of several years of charge, discharge cycle tests at the manufacturer.

$$\text{Capacity } loss = \left(\frac{15}{50}\right) * Change\ in\ Internal\ Resistance \quad (2)$$

The length of a degradation analysis data take is roughly 300 seconds long. The battery was designed [2] for an average Depth of Discharge (DOD) of about 5.2%, whereas, the average actual DOD is between 1.5 to 3% [8]. Therefore, the performance is better than expected. The degradation of TDX battery follows a very similar profile to that of the TSX (Fig. 4).

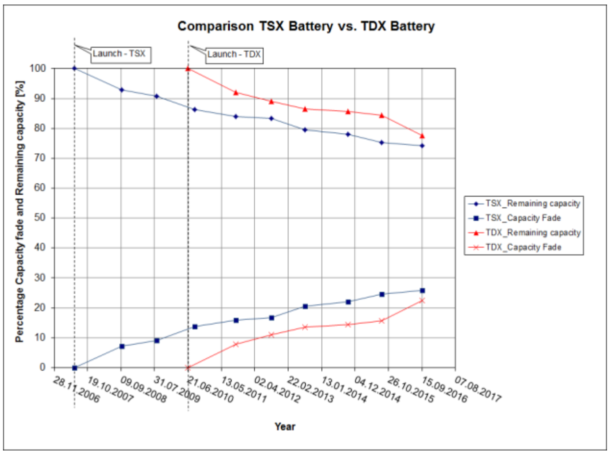

Figure 4: Capacity degradation of TSX and TDX batteries over their lifetime

Both the satellites are operated under almost equivalent loads and therefore the charge and discharge cycles of the both the batteries are comparable. After 7 years in operation, the degradation in the TDX batteries is quite close to that what was seen in TSX after 7 years of operation (see Table 1).

Table 1: Comparitive study of Degradation between TSX and TDX

Year	TSX_Capacity Fade [%]	TDX_Capacity Fade [%]
15.06.2007	0	N/A
18.09.2008	7.127162011	N/A
20.08.2009	9.265356871	N/A
26.08.2010	13.64931198	0
30.09.2011	13.94341543	7.88278649
11.09.2012	16.68447154	11.02069959
06.08.2013	20.56627817	13.42952569
26.09.2014	22.05904629	14.370795
20.08.2015	24.64959464	15.55066949
21.09.2016	25.76523822	22.44418556

3.2 Diffusion Rate Limitations

Apart from the natural degradation, there is another degradation mode where the Li-Ion batteries show reduced performance. This is identified as Diffusion Rate Limitation (DRL) [1, 9]. The DRL is also a consequence of age but depends mostly on the rate of flow of current to and from the battery.

The consequence of DRL is a temporary reduction in the available voltage during discharge and temporary over-voltage at end of charge. This can be noticed, where the total charge drops after a while post reaching the end of charge level [1]. The effect of DRL corresponds to the temperature and current taken from or supplied to the battery. During discharge, the ions diffuse slower to the surface where the reaction takes place and thus leads to a deeper discharged cell than reality. As seen in Fig. 5, the behaviour of the voltage rate when DRL is in effect is linear.

4. Analysis and Modelling of Voltage slope

4.1 Analysis

The yearly capacity-fade degradation provides information about the change in internal resistance. Based on this information, the natural degradation within the battery is calculated. The power consumption during such a degradation test data take is not high enough to provoke any noticeable DRL effect. Therefore, in order to calculate the DRL, special data takes with high power requirement were carried out during the eclipse. The eclipse season was specifically chosen as there is no additional energy available from the solar panels for a specific amount of time in every orbit. Specific duty cycles or load conditions were chosen to carry out these tests. This method was chosen, as the instrument power consumption for various duty cycles is well documented. The data takes in 5 different (between 16 % till 20%) duty cycles for a duration of maximum 95 secs were planned and executed. For all the 5 data takes, the surrounding boundary conditions were kept as similar as possible.

The outcome of the data takes were analysed to understand the rate of drop in voltage with respect to the power consumption. According to theory [1], the DRL is mostly influenced by rate of change in current, voltage and the temperature at which the battery is operated. The temperature affects the internal resistance of the battery which then affects the flow of ions within the battery. The effect of temperature on DRL is yet to be investigated.

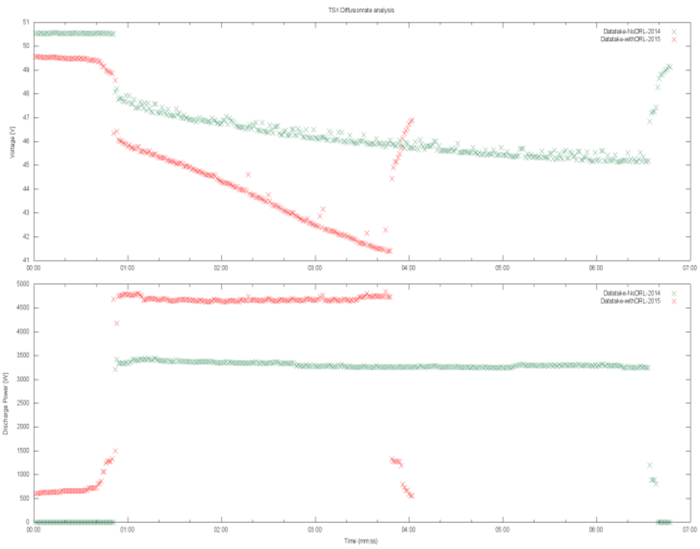

Figure 5: Voltage analysis for TSX

Initial understanding showed that the several short duration data takes with minimum interval between them, caused the batteries to drop to voltages that were close to the manufacturer set safe limit. There has to be sufficient time allocated for the ions to recover between successive data takes.

The slope analysis revealed the relationship between discharge power and the voltage rate. The rate of change in voltage after the initial drop was calculated for every data take carried out during eclipse. This resulted in a set of data points of change of voltage for respective power ranges. The power range was a direct outcome of different types of data takes possible and hence, a useful information to understand the behaviour under different load conditions. A linear fit over several such data points provided a slope equation which then could be used by MPS.

4.2 Modelling

The satellite telemetry provides battery voltage values. The MPS model works based on the energy and not on voltage. In order to be able to translate the TM based calculation to the MPS model, certain assumptions were made:

1. The voltage under discharge when the limitation is in effect is linear.
2. The present MPS modelling of linear energy reduction from BOL till EOL under nominal conditions (without DRL) is fairly accurate.
3. The State of Charge excel tool [2] provided by the manufacturer is still valid for the current degradation state.
4. The energy discharged and added to the battery is modelled accurately by the MPS model.

The voltage rate related to the corresponding power is linearized. The ratio of the voltage gradient of the reference data take to that of the new data take provides a factor which then is used to calculate the maximum useful energy. An additional factor is introduced to compensate for the difference in actual power and the reference power. It is given by the following equation:

$$E_{max} = \frac{P}{P_{ref}} \frac{S_{ref}}{S} E_{ref} \quad (3)$$

Where,
E_{max} = Maximum Energy in wattseconds
P = Power in watts (actual)
P_{ref} = Power in watts (reference)
S_{ref} = Time in seconds (reference)
S = Time in seconds (actual)
E_{ref} = Energy in wattseconds (reference)

The outcome of such a model is to allow MPS to calculate the maximum possible energy that can be discharged from the battery without violating any limits. As a second safety net, within the MPS model, the duration of the data take under consideration was increased artificially by a certain margin, so that any successive data take requests that might lie close the previous one will be excluded. This prevented too many data takes being planned that otherwise would have been too close to each other and not allowing enough time for the battery recuperation.

5. Battery Modelling by MPS

5.1 Diffusion Rate Model

It was foreseen that the ageing of the battery results in a reduced battery capacity, which means that the capacity at begin of life CAP_BoL has been set to a different value than the capacity at end of life CAP_EoL. Although this model was sufficient for the designed lifetime of the satellites, further ageing showed that the available energy within the battery could no longer be retrieved in one piece.

In order to solve this problem, two models have been considered. As critical situations only occur when high power consumptions occur, both models restrict the maximum durations of data takes only.

5.2 Physical Model

A formula is defined which specifies for each data take a local lower bound on the state of charge, which must not be exceeded when planning this data take. This formula depends on the power consumption of the data take only. In case of eclipses and left looking data takes, this local lower bound covers not only the data take, but the whole eclipse.

After implementing the physical model, it was realized that we can't restrict to checking individual data takes but we need to consider chains of data takes, in case the solar panels don't supply energy in between these data takes. This is the case within an eclipse or in case the data takes are left looking data takes with short separation.

5.3 Empirical Model

The empiric model considers the current state of charge and thus might solve this issue to a certain extent, as the state of charge comprises the history of data takes. However, reality showed that the battery recovers even during eclipse phases, even though the satellite consumes more energy than the solar panels supply. Thus we search for an even better model.

As the physical model proved insufficient and search for a suitable model is still ongoing, we introduced a third ad-hoc model, which prevents critical situations, even though it may be a bit restrictive.

Chain restriction is for a data take chain that is defined as a chain of data takes with configurable maximum separation (currently 180 sec), all of which overlap with the same eclipse or left looking manoeuvre. The sum of the durations of data takes within one data take chain must not exceed a configurable duration (currently 180 sec).

6. Results and Findings

6.1 Battery Model update

The result of the voltage analysis is that the MPS model is conservative to prevent low battery voltage and at the same time flexible to accommodate regular pay load operations. The flexibility comes from the fact that the parameters can be adapted based on the actual situation. The current situation is determined via degradation analysis data takes.

The battery modelling within the planning tool was updated with the latest slope equation based on which the long data takes are excluded from the list. As a further step, a load balancer between the two satellites was introduced to make sure that neither of the satellite is over-loaded. There is still the possibility that some of the long data takes have to be performed on TSX because the TDX satellite is within the exclusion zone. The exclusion zones are certain locations in the orbit where there is a high risk of radiation of the satellite flying below by the one in the higher orbit.

The figure (Fig. 6) shows the behaviour of batteries on TSX and TDX under different load conditions. The TDX battery test results are the upper data set, starting with the purple till yellow. The second data set starting with purple (below 45 V) until yellow represents the TSX battery.

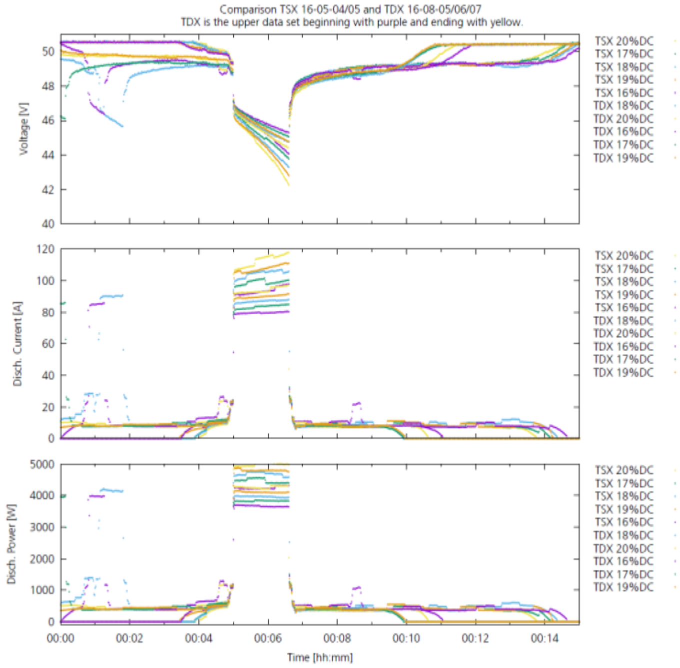

Figure 6: Comparison between TSX and TDX (2016) different Test data takes with varying duty cycles

6.2 Voltage Slope Analysis

The analysis of the two sets of DRL specific data takes has shown that the behaviour of voltage slope is linear and is dependent on the discharge current. It needs to be further investigated to ascertain whether DRL also shows similar linear behaviour. Further, the number of discharges done within a very short duration of time where the battery does not have enough time to recuperate could lead to voltages close to critical limits. The slope analysis adds to the information available about the health of battery which is not available via the regular capacity fade test data takes.

The fixed scheme of 5 different data takes with different duty cycles will be repeated every year at the peak eclipse to determine the actual status of the diffusion rate limitation. The regular capacity degradation data takes will be performed to assist the analysis of the natural capacity fade and to monitor the increase in internal resistance.

Based on the outcome of the voltage slope analysis, the available energy limit modelled by the planning tool will be fine-tuned. Outcome of the regular degradation data takes and information provided by the manufacturer will be used as the primary source to determine the available energy within the battery for its corresponding age.

7. **Conclusions**

The comparatively older battery in the TSX provided the engineers with a good overview on its health and the ability to foresee the likely future behaviour of the TDX battery. The performance of these batteries on both the missions is as expected. Continuous analysis and monitoring of the health of these batteries, supported by regular degradation data takes provides up to date information on their status. The test data takes performed during eclipse provides information on diffusion rates within the batteries.

The scheme of data takes will be updated, alongside the battery model for the planning tool to stay up to date with the reduction in available energy due to ageing.

The information gathered on both the satellites is of great help for upcoming and future missions based on Li-Ion chemistry.

Acknowledgements
Satellite Support Team, Airbus DS
Kay Mueller, PTS Team Lead, GSOC, DLR
Fotis Stathopoulos and Alice Bonfanti, LSE Space, PTS Engineers, GSOC
MPS operators and GSOC management

References

[1] C. Thwaite, Modelling of Battery Effective Resistance, LION-AEA-BD-RP-0012, Project Internal Document, 2001

[2] TX-AED-DD-0001 Space Segment User Manual, Airbus Defence and Space, 2006

[3] K. Mueller, Technical Note on Assessment of Battery Degradation Effects and their Operational Handling, TX-GS-TN-2016, Project internal document

[4] C. Lenzen, Implementation of Power and Thermal Constraints in Mission Planning, TD-MOS-TN-3043, GSOC, DLR, Project internal document, 2010

[5] D. Linden, T.B. Reddy, Handbook of Batteries, third ed., McGraw-Hill Handbooks, 2002, ISBN 0-07-135978-8

[6] DLR Flyer TerraSAR /TanDEM-X

[7] Thomas Uhlig, Florian Sellmaier, Michael Schmidhuber: Spacecraft Operations, Springer-Verlag Wien 2015, ISBN 978-3-7091-1802-3 resp. ISBN 978-3-7091-1803-0 (eBook)

[8] N. Simmons, TerraSAR-X Battery Health Assessment, TX-ABS-RP-0069, ABSL space, Project internal document, 2009

[9] F. Schiemenz, TerraSAR/TanDEM-X Technical Note on Analysis of Battery Low Voltage Events, TSX-AED-TN-122, Project internal document, 2015