An Analysis of Battery Preservation Measures on the DEM Product Performance of TanDEM-X

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Abstract

The satellites TerraSAR-X and TanDEM-X are in orbit since 16 and 13 years respectively. This is much longer than the planned life time of 5.5 years. Hence, components like the lithium-ion batteries age and their performance degrade increasingly. In consequence, operational scenarios need to be adapted, e.g., by reducing the maximal duration of an acquisition. This paper assesses an idea to reduce the stress on the battery by lowering the transmit duty cycle of an acquisition. It provides an analysis on how a decreased duty cycle reduces the power consumption and the voltage drops in the batteries. In addition, the deterioration of the DEM product performance is evaluated and justified.

1 Introduction

The first German radar satellite TerraSAR-X (TSX) was launched June 15, 2007 [1]. It is capable to acquire SAR images in various modes, such as Spotlight, Stripmap or ScanSAR. Due to its flexible commandability, the mode and product portfolio was extended throughout the mission by further high-resolution and wide-coverage modes.

The TanDEM-X mission is the first bistatic SAR mission with two satellites [2]. It was realized by placing a second satellite (TDX) in close formation with TerraSAR-X. The primary mission goal was achieved in 2016 with the provision of a global Digital Elevation Model (DEM) at 12 m posting with a relative vertical accuracy better than 2 m/4 m for terrain slopes less/steeper than 20% [3], [4].

The planned mission duration for the TerraSAR-X satellite was 5.5 years. Joint tandem operations with TanDEM-X was foreseen for 2.5 years. This has already been exceeded by far, as TerraSAR-X has been in orbit for 16 years and TanDEM-X for 13 years. However, this also means a progressed aging of the on-board components. In case of TSX/TDX, the batteries are the most critical components. In the following chapters an analysis is described, how the battery could be preserved to further prolong the mission duration.

The paper is structured as follows: Section 2 generally introduces the batteries and their aging effects. Section 3 describes the power consumption of the nominal SAR data takes. Section 4 provides information about the performed test data takes. Finally, Section 5 explains and discusses the results of the assessment of these test data takes.

2 Battery Performance

The most lifetime limiting on-board components currently are the batteries. Being actively transmitting radar systems, SAR satellites generally have a high demand of instantaneous power. Therefore, they rely on, e.g., lithium-ion batteries for operation of platform and instrument. Such batteries degrade nominally over time. **Figure 1** shows an example for this degradation of the TDX battery. The two plots depict the battery voltage of two acquisitions with similar duration, one from 2011 (about one year after launch) and the other from 2022 [5]. Clearly visible is the much deeper voltage drop down to approximately 44 V in 2022 compared to only 47.5 V in 2011. The overall degradation is though well within the expected range and far better than the predictions.

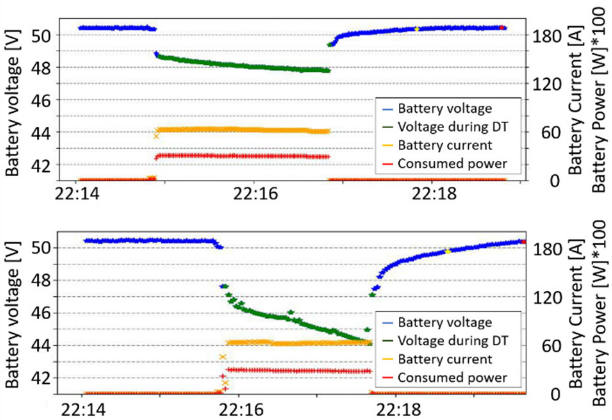

Figure 1: Degradation of the TDX battery in terms of voltage drop comparing data takes (green dots) from 2011 (upper) and 2022 (lower).

However, 16 and 13 years is a very long time for lithium-ion batteries flown in space. After about ten years in orbit, an additional effect unexpectedly appeared in the batteries, the so-called diffusion rate limitation [6]. This effect slowly decreases the ability of the ions to diffuse to the surface of the electrodes. This leads to larger voltage gradients in long data takes after several tens of seconds of high-power operation. Furthermore, it is assumed that the batteries would degrade even faster if operated in this region of larger gradients. As a consequence, the maximum duration of data takes has been restricted stepwise as shown in **Table 1**. If the satellites travel through the eclipse, i.e., through the shadow of the Earth around the South Pole, these numbers are reduced even further.

	TSX	TDX
2007/2010 (Begin of Life)	360 s	360 s
2019	170 s	360 s
2021	140 s	200 s
2023 (spring)	60 s	90 s
2023 (autumn)	45 s	65 s

Table 1: Maximal lengths of data takes in the sun

From a planning perspective this means, that acquisitions for large coverages have to be chopped into smaller pieces and acquired in consecutive repeat cycles. This slightly increases the overhead due to prologue and epilogue at the beginning and the end of each data take and due to the required overlaps of at least one second between sequential data takes. In addition, pauses after each long data take as long as the acquisition itself are introduced where possible in order to allow the battery to recover completely. This makes the planning process for larger regions more complex. Furthermore, additional repeat cycles are required to cover an area which increases the overall coverage duration.

A further degradation of the batteries is expected for the upcoming years. However, the primary goal of the TanDEM-X mission is the derivation of digital elevation models covering large areas of the world like countries or continents. If the maximal duration for the data takes becomes too short, this becomes impracticable. Hence, countermeasures to keep the maximal length of data takes at a feasible level in the coming years and thus to prolong the mission need to be developed and assessed.

3 Data Take Power Consumption

SAR instruments can be operated in different modes implying various instrument settings. The executed acquisitions have a large variety of power demands and hence different effects on the batteries. One major factor driving the power consumption is the transmit duty cycle DC. This ratio is given by

$$\mathrm{DC} = \frac{\tau_\mathrm{p}}{\mathrm{PRI}} \tag{1}$$

which is influenced by two factors: one the one hand by the transmit event, where the pulse length τ_p describes the duration of an actively transmitted SAR pulse. On the other side, there is the Pulse Repetition Interval PRI. This is the time interval between the start of the pulses.

In TerraSAR-X, the transmit duty cycle can be configured in a range between 10% and 20%. Most modes have a fixed default value. For nominal Stripmap acquisitions this is 18%, for Spotlight acquisitions it can be up to 20%. For certain WideScanSAR acquisitions, it can even be as low as 12% for dedicated beams. The appropriate timing parameters were derived during mode design and performance analysis [7]. In consequence, the power consumption and the load on the battery is largely influenced by the selected mode configuration.

4 Test Data Takes with different Duty Cycles

Based on these constraints, a first analysis was conducted to assess the influence of the reduction of the duty cycle on the product performance. This first study concentrates on bistatic TanDEM-X acquisitions. These are preferably long acquisitions and they make up a significant share of all data takes performed by the TerraSAR-X and TanDEM-X satellites.

The TanDEM-X mission aims to acquire coverages all over the global landmasses. There are many areas on Earth where the performance is much better than demanded by the specification [4]. Examples are dry regions in Australia or Africa or large agricultural areas in America or Asia. One goal of this study is to assess, if the duty cycle can be reduced at least over such areas. A lower duty cycle may deteriorate the height performance. As a benefit, the power consumption of the data takes is reduced as well as the discharge level of the battery.

The influence on the performance of the duty cycle reduction could be analyzed theoretically. However, it is difficult to assess its influence over different types of terrain. Additionally, the selection of the radar parameters during commanding of the instrument is complex and based on information like backscatter or the terrain of the acquired scene itself. It is also difficult to model the battery behavior and to evaluate the influence of the duty cycle reduction on the battery voltage drop due to the diffusion rate effect described in Section 2.

Hence, several experimental acquisitions have been performed to see the effect on real data. Over the same site, data with different duty cycles have been acquired in successive acquisition cycles. The corresponding duty cycle values were stepped in the following sequence: 18%, 10%, 16%, 12%, 14%, 18%. With this sequence, low frequent temporal errors induced by varying ground properties or due to the drifting baseline can be compensated from the data by comparing the first and last acquisition.

These sequences were acquired over four different locations each. The test sites cover different land types like stone and sandy deserts (Gobi region, China), tropical forests (French-Guyana), boreal forests (Russia), dry soil and rock (Australia). Based on the experience from TanDEM-X, good performance is expected over the dry and stone-desert areas, while the performance might be reduced over forested areas. The acquisitions were performed in June and July 2023 and with TDX as the transmitting satellite.

5 Evaluation and Results

5.1 Evaluation of the Battery Voltage

The first evaluation concentrates on the effect of the duty cycle reduction on the power consumption and the discharge of the battery. Various power, voltage and current data are measured on board with one or two second sampling (satellite dependent setting). The information is dumped as part of the satellite telemetry during ground station contacts and made available on ground.

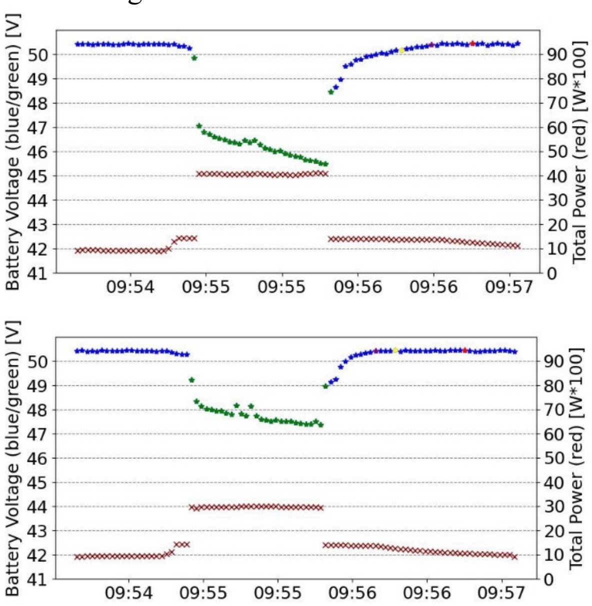

Figure 2: Exemplary voltage and power consumption of two data takes over Australia with 18% (top, DT1 from Table 2) and 10% (bottom, DT2) duty cycle.

Figure 2 shows the battery voltage and power consumption comparing a data take (DT) with 18% duty cycle and one with 10%. The plot indicates a power consumption of around 4.1 kW for the 18% and 2.9 kW for the 10% DT. However, even before and after the data take, the satellite bus and the instrument consume power, around 1.3 kW. The reduction in power consumption only for the data take while transmitting is reduced from roughly 2.8 kW for 18% duty cycle down to 1.6 kW for the data take with 10% duty cycle. This coincides very well with the reduction in duty cycle. In consequence, the voltage drop (green curve) is much lower in the low-duty-cycle case. This also shows up in the minimal voltage at the end of the data take, which drops by only 3 V compared to the 5 V for the high-duty-cycle case. In addition, the recovery time of the battery is much faster, about 20 seconds compared to 40 seconds in case of the high power case.

Table 2 shows the maximum voltage drops for the different data takes over Australia (soil and rock). Already a decrease from 18% to 14% in the duty cycle leads to reduction of about 25% in voltage drop.

Data take	Acquisition date	Duty cycle	Minim. voltage	Absolute decrease	Relative decrease
DT1	2023-06-05	18	45.5	4.9 V	94%
DT2	2023-06-16	10	47.4	3.0 V	57%
DT3	2023-06-27	16	46	4.4 V	85%
DT4	2023-07-08	12	46.9	3.5 V	67%
DT5	2023-07-19	14	46.5	3.9 V	75%
DT6	2023-07-30	18	45.2	5.2 V	100%

Table 2: Battery voltages of the data takes over Australia. The relative decrease is given with respect to the nominal voltage of 50.4 V and referenced to the minimal voltage of 45.2 V (100%).

5.2 Evaluation of the Coherence

TanDEM-X acquires bistatic images in order to generate digital elevation models. One performance indicator of bistatic systems is the coherence. It is a measure for the decorrelation of a scene and hence for the accuracy of the derived height measurements. The coherence depends on factors like decorrelation due to the limited signal-to-noise ratio γ_{SNR}, volume decorrelation γ_{Vol}, temporal decorrelation γ_{Temp}, and decorrelation γ_{Perf} covering performance aspects like ambiguities, quantization, baseline and Doppler spectra effects [2]:

$$\gamma_{\mathrm{tot}} = \gamma_{\mathrm{SNR}} \cdot \gamma_{\mathrm{Vol}} \cdot \gamma_{\mathrm{Temp}} \cdot \gamma_{\mathrm{Perf}}. \tag{2}$$

The factor concerned in terms of the duty cycle is the decorrelation caused by the signal-to-noise ratio: $\gamma_{\mathrm{SNR}} = \frac{1}{1+1/\mathrm{SNR}}$. The SNR in turn depends the backscatter coefficient σ_0 and on the NESZ:

$$\mathrm{SNR} = \frac{\sigma_0}{\mathrm{NESZ}} \tag{3}$$

$$\text{with } \mathrm{NESZ} = \frac{4(4\pi r)^3 \sin(\theta) k T B_{\mathrm{rg}} F L}{P_{\mathrm{Tx}} G_{\mathrm{Tx}} G_{\mathrm{Rx}} \lambda^3 c \tau_{\mathrm{p}} \mathrm{PRF}}, \tag{4}$$

with the slant range distance r, incidence angle θ, Boltzmann constant k, system temperature T, range bandwidth B_{rg}, noise figure F, system losses L, transmit power P_{Tx}, transmit gain G_{Tx}, receive gain G_{Rx}, wave length λ, speed of light c, pulse length τ_{p}, and pulse repetition frequency PRF.

The affected term connected with the duty cycle is the pulse length of the transmit pulse. It becomes shorter when the duty cycle is reduced while the PRF remains constant. Hence, also the NESZ and the coherence deteriorate.

For TanDEM-X products, the coherence is estimated during the processing of the acquisitions [9]. It is derived from the two co-registered single-look slant-range complex (CoSSC) scenes, where each long data take is split into 50 km long scenes for computational reasons. Coherence maps are provided to the user in form of a quicklook image for each scene. For a first assessment, the quicklooks of one scene per test site and duty cycle setting were evaluated. **Figure 3** shows the measured coherence values per test site. It can be seen that there is a worst-case coherence loss of 0.08 between the duty cycle of 18% and the duty cycle of 10%.

Especially when the coherence is rather high, like in case of deserts or soil and rock, a decrease to 14% duty cycle seems to deteriorate the performance only slightly.

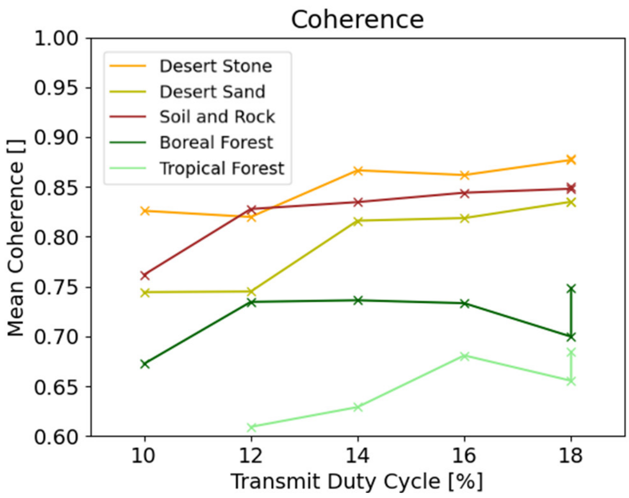

Figure 3: Degradation of the coherence. Note: Two acquisitions were acquired with 18% duty cycle (cf Table 2)

5.3 Evaluation of the Height Accuracy

Finally, also the effect of the duty cycle on the relative height accuracy of the DEMs needs to be assessed. The probability density function (PDF) of the relative height error is derived by [2][8]:

$$p = F(\gamma_{\mathrm{tot}}, n, \varphi) \qquad (5)$$

where F is a function that depends on the total coherence, the number of looks n and the interferometric phase difference φ. From this, the standard deviation of the interferometric phase error σ_φ is calculated by:

$$\sigma_\varphi = \sqrt{\int_{-\pi}^{\pi} \varphi^2 p_\varphi(\varphi) d\varphi}. \qquad (6)$$

Similar to the coherence maps, also the height accuracy provided with the processed products in form of Height Error Maps (HEMs). The evaluation of the relative height error is currently ongoing and the results will be published in an extended journal paper.

6 Conclusion

The on-board battery is a critical component for the SAR satellites TerraSAR-X and TanDEM-X. Due to prolonged age, the battery degradation is already severe. In order to limit the stress on the battery, an evaluation on the effect of a reduced transmit duty cycle was performed. The performance in terms of coherence is still in an acceptable range for certain terrain types in the world that show a high coherence. The reduction in power consumption on the other hand would help to preserve the batteries. For a final recommendation, further analyses need to be performed on the relative height accuracy and will be presented at the conference and in an extended journal paper planned to be published in 2024.

7 Literature

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