TerraSAR-X and TanDEM-X System Status and System Response to Solar Related Events

Allan Bojarski, Markus Bachmann, Ulrich Steinbrecher, Nuria Tous Ramon, Johannes Böer, Manfred Zink
German Aerospace Center (DLR), Microwaves and Radar Institute, Allan.Bojarski@dlr.de, Germany

Abstract

The SAR satellites TerraSAR-X and TanDEM-X are operated to acquire high-resolution SAR images for scientific and commercial applications as well as a high precision digital elevation model (DEM). In order to assure the expected quality of those products and to monitor the performance of the SAR systems, long-term system monitoring (LTSM) is performed for the critical system parameters. Stimulated by this monitoring, studies are made to understand the correlation of on-board system responses with dedicated space events. This paper presents the current status of the two satellites and the results of the correlations studies.

1 Introduction

TerraSAR-X (TSX-1) and TanDEM-X (TDX-1) are the first German remote sensing satellites. They are operated since 2007 and 2010 respectively and were initiated as a public private partnership between the German Aerospace Centre (DLR) and Airbus Defence and Space (ADS). The satellites contribute to two major missions: the TerraSAR-X mission in order to acquire multi-mode SAR data in X-Band, by each satellite individually [1] and the TanDEM-X mission in a bistatic configuration to provide a global DEM with 12 m grid sampling and relative height accuracy better than two meters. The global DEM has been completed in October 2016 [2] and the mission continues with the goal to generate a topographic change layer, the so-called Change DEM.

A key element of the SAR system on both satellites is a high resolution X-Band phased array antenna divided into 12 panels. Each panel is further divided in 32 subarrays fed by individual transmit and receive modules giving a total number of 384 independent radiators. Electronically the antenna is able to steer the beam pattern between 25° and 55° in elevation [3] allowing the operation in different modes such as Stripmap, Spotlight and ScanSAR [1]. The geometric range resolution reaches from 40 m for the 6 beam WideScanSAR mode down to 25 cm for Staring Spotlight application whereby the swath width varies from about 250 km to a few kilometres respectively. In combination with the ability of transmitting and receiving in two polarizations, the two systems produce a multitude of different product variants making it applicable in numerous fields of earth observation and environmental monitoring.

To guarantee the quality of the TSX-1 and TDX-1 SAR products and to monitor the status of their space and ground segments, the SAR performance and the calibration status are constantly monitored and reported for every quarter of the year. The according information is collected for a variety of system parameters like performance of transmit and receive modules or frequency drift of the Ultra Stable Oscillator (USO). By exploiting these results it is possible to give an overview of the satellites' status, to predict the remaining lifetime and to detect long-term trends within the systems. With this information, strategies and actions can be derived to maintain the products quality or to save resources.

Due to the fact that certain events, like the satellites eclipse period or the solar activity, have a considerable effect on various system parameters, they become visible in long-term analysis results. To determine the correlation between these effects and the performance of different parameters, for example the battery voltage, a dedicated study is prepared. It serves to gain a deeper knowledge of the system's functionality and its interactions with the environment.

2 Long-Term Monitoring of Satellite Parameters

To visualize degradation effects, critical systems parameters are constantly monitored. The main source of information is the telemetry data downlinked via S-Band and received by the respective ground stations. The data monitoring consecutively takes place in two steps. The first one, executed immediately after downlink, is an instrument health monitoring integrated in the Mission Operations Segment (MOS) [4]. It is implemented as an automatic procedure to give back the satellites status, to detect limit violations and to initiate procedures and countermeasures in critical situations. Subsequently the instrument related data gets stored in a central long-term database where the data over the entire mission duration is constantly accessible. Here the second monitoring step takes place within the LTSM procedure. An algorithm fetches the required data to compute and visualize the relevant information. Further monitoring results are derived from SAR acquisitions performed by the satellites. Apart from analogue data such as currents and temperature also on-board events in the systems memory, completeness of SAR raw data or degradation of the antenna front-end are evaluated. As an example of long-term monitoring results and to give an overview of the satellites status, battery voltage development and sampling frequency of the ADC are discussed in detail in the following chapters.

2.1 Battery Degradation

Besides the solar panels, the battery as part of the power subsystem is a crucial element for the functionality of the system. It considerably contributes to the life-time of the satellites and constitutes a limiting factor to the acquisition planning strategy. The voltage is measured on the Main Bus with a nominal voltage of 50 V, which is directly connected to the battery and transmits power to all further subsystems. Figure 1 shows the minimum, maximum and average battery voltage over mission duration for the two satellites. The minimum voltage is the most interesting parameter in this case as it displays the level of discharge for example after a datatake execution. It can be observed that over time the voltage reaches systematically lower values indicating ageing effects on the battery. Due to the age the batteries electrical resistance rises causing the mimimum voltage to decrease over time. As the lowest voltages are above the critical system limit of 39 V the battery is still

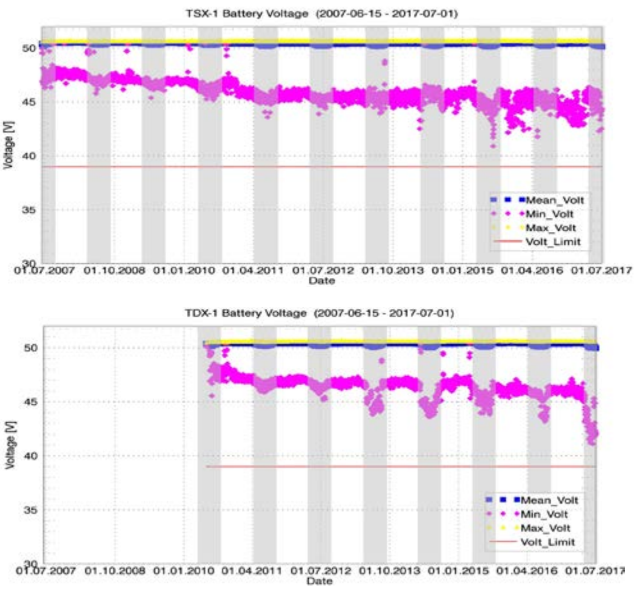

Figure 1: Battery voltage per day over mission duration and eclipse periods. Upper plot: TSX-1, lower plot: TDX-1

capable of providing the necessary amount of power. However the maximal length of datatakes had to be limited to avoid dips like in mid 2017 on TDX-1. A second effect visible in Figure 1, especially for TDX-1, is the influence of the annual period in which the satellites are exposed to Earth's shadow. During this eclipse the solar panels are not able to produce enough power to support the amount of datatakes resulting in a higher load on the battery.

2.2 USO Frequency Drift

For DEM generation from bistatic acquisitions the range difference to a target on the ground is accurately measured via the phase difference derived from interferograms. As the frequency of the USO and the phase noise are slightly different, synchronization between the satellites has to be permanently performed. The compensation of the relative frequency drift relies on pre-knowledge of the absolute radar frequency. Thus the absolute radar frequency, representing the USO frequency and obtained from the ADC sampling frequency, needs to be measured and compared based on 600 s long datatakes, as shown in Figure 2. In general it is to say the drift shows a stable linear trend and thus can be predicted reliably. End of March 2017 the TSX-1 USO had to be switched to its redundant unit as untraceable peak currents, leading to corrupted acquisitions, occurred. The switching event is visible as a large change of measured absolute ADC frequency in Figure 2 (blue line). Since then the redundant unit is working stable and no further peaks emerged. The larger visible drift in Figure 2 due to the switch is expected and has decreased slightly. Also visible is the sudden frequency change due to the activation of the dual receiver antenna (DRA). As this acquisition mode uses, under single receiver antenna mode (SRA), inactive system parts, system temperature rises which causes a drop in the USO frequency.

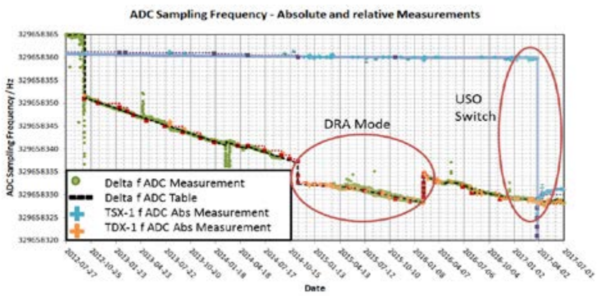

Figure 2: Relative and absolute ADC sampling frequency measurements of TSX-1 and TDX-1

3 Effects of Solar related Events

As shown in the previous chapters the LTSM gives an overview of the systems status of TSX-1 and TDX-1 by analyzing respective parameters over time. Therefore it also captures the effect of events in the satellites' environment such as the satellites' eclipse or the periodic solar activity. An evaluation of the system response to these events provides a deeper understanding of the system functionality and can help explaining certain system characteristics.

3.1 Satellite Eclipse

Due to the satellites' orbit of 514 km and inclination of 97.4° [2] TSX-1 and TDX-1 are facing an eclipse period between beginning of May and middle of August. That means with every revolution the satellites pass through the Earth's shadow on a part of the southern hemisphere. This shadow period depends on inclination, orbit altitude and the transient declination angle of the sun [5]. For TSX-1 and TDX-1 this means a maximum eclipse duration of 22.4 minutes or 24 percent of the orbital period. As a consequence system temperature drops rapidly and the solar panels are incapable to produce power during the pass. The impacts of the changing environment are depicted in the following chapters.

3.1.1 I/Q-Bias

As the received signal is complex, it is usually separated in two channels: An in-phase (I) channel to obtain the real part and a quadrature (Q) channel, where the signal is phase shifted by 90°, to obtain the imaginary part of the signal. Due to this I and Q sampling process the raw data has to be corrected for biases and differential gains on the I/Q channels. The bias in this case denotes the amplitude offset between I and Q signals due to the sampling process. To determine the bias, calibration

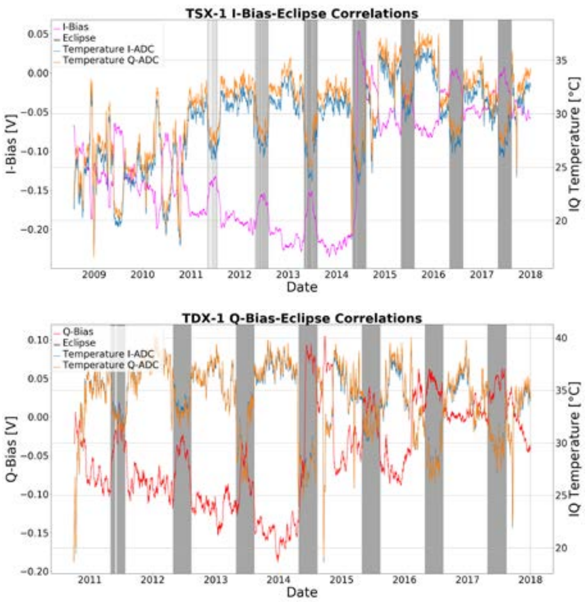

Figure 3: I/Q-Bias over mission duration. Upper plot: I-Bias TSX-1, lower plot: Q-Bias TDX-1

pulses as well as raw data echoes and noise data are used. It is then computed by measuring the mean magnitude of the I/Q signals and combining it with the offset values from instrument characterization data. As the performance of the amplifiers passing the raw data signal are sensitive to the surrounding temperature, the bias changes during the eclipse. This can be observed in Figure 3. As temperature decreases, the amplifier performance and thus the I/Q-Bias increase. Another effect visible in Figure 3 is that the bias behaves differently on both satellites. During eclipse the I-Bias on TSX-1 is affected while on TDX-1 the impact is visible in the Q-Bias. As no explanation has been found yet, the effect is still under investigation and subject to further analysis.

3.1.2 Replica

The instrument replica is obtained by the proper combination of internal calibration pulses acquired within a nominal imaging datatake. It represents the instrument transfer function and is therefore used for SAR range processing on-ground. Also, it serves as a method to monitor the instrument stability in amplitude and phase over time. This makes it possible to determine transmit power and receiver gain and to compensate variations to maintain the radiometric quality of the image. Since the replica represents the instrument transfer function it is directly related to the instrument gain and to the signal-to-noise ratio of the SAR system [6]. Thus, the temperature change due to the eclipse has a considerable impact which becomes visible in Figure 4. Due to the lower system temperatures the amplifier performance is improved resulting in a higher replica amplitude.

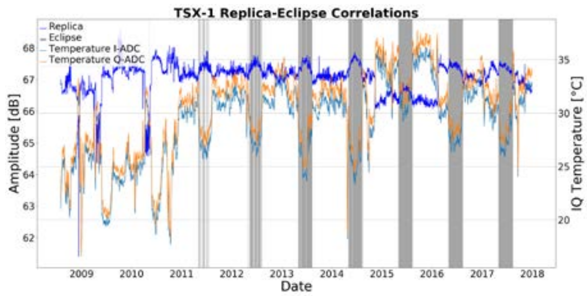

Figure 4: TSX-1 Replica, I and Q Temperature over mission duration on TSX-1

3.1.3 Battery Voltage

The battery is one of the main power sources on board, as mentioned in section 2.1, storing surplus power from the solar panels. During the eclipse the solar panels are shaded and incapable of producing power. Hence the load on the battery becomes higher resulting in lower minimum and mean voltage in that period as displayed for TDX-1 in Figure 5. As the values depend on the amount of executed datatakes and operations, the eclipse period has to be carefully considered in the acquisition planning process in order to ensure the battery qualification limit is not reached and to save the battery itself from degradation. Therefore the voltage varies and can even partly increase during eclipse as visible in 2014 in Figure 5.

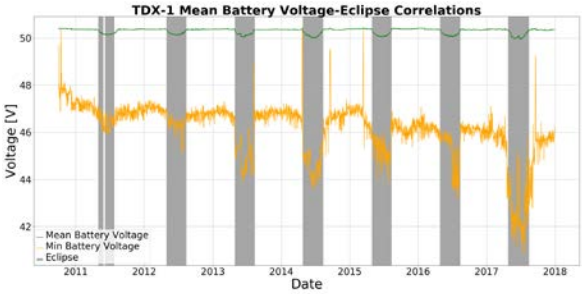

Figure 5: Mean and minimum TDX-1 battery voltage over mission duration with eclipse

3.2 Solar related Activity

The sun follows a periodic 11 year activity change due to its dynamic magnetic field, known as the solar cycle [7]. During active periods the number of sun spots, flares and Coronal Mass Ejections (CMEs) increase significantly thus creating a higher radiation load on any space object. To analyze how these phenomena and the solar cycle affect the TSX-1 and TDX-1 satellites in the near vicinity of the Earth, one can take a closer look at the geomagnetic Ap-Index. It is used to characterize the magnitude of geomagnetic storms and is an indicator for disturbances in the Earth's magnetic field [8]. As the memory modules are vulnerable system parts to radiation, the impact of the geomagnetic index is especially visible within the Solid State Mass Memory (SSMM). It stores the SAR raw data before it is downlinked to a ground station and dumped from the memory. Due to proton and heavy ion radiation, bit errors can occur on the system. In case of single bit errors the effect is corrected directly while multiple bit errors can only be detected. So far multiple bit errors have not been observed on none of the two satellites. Figure 6 shows the amount of daily single bit errors as well as the Ap-Index [9], obtained from a worldwide network of geomagnetic observatories and a measure for the level of geomagnetic activity, over mission duration on TDX-1. The Ap-

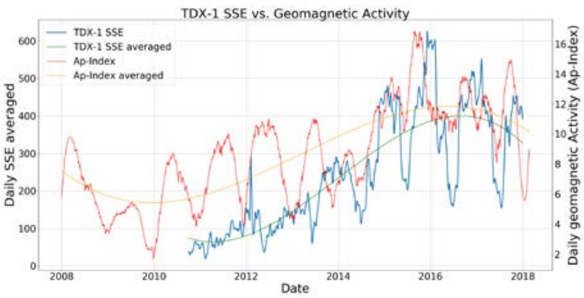

Figure 6: Regular and averaged Ap-Index, daily and averaged TDX-1 SSMM Single Symbol Errors (SSE) over mission duration

Index is derived from the globally averaged K-Index which is related to the maximum fluctuations of horizontal components observed on a magnetometer relative to a quiet day. After averaging and linear scaling of the K-Index to an equivalent amplitude index, the Ap-Index denotes the 24 hour average of this conversion and thus a daily average level for geomagnetic activity. The plot furthermore shows a polynomial fit of both parameters over mission duration to better visualize mutual trends. A correlation can be observed as for geomagnetically active periods, errors occur more frequently and in periods of lower activity the amount decreases. Periods in which the Ap-Index reaches higher and the bit error lower values, hence does not follow the geomagnetic activity, result from the annual eclipse during which the bit error rate decreases due to the shading of the satellites from solar radiation. In summary a mutual trend for both parameters can be observed over the entire mission duration.

4 Conclusions

This paper shows the long-term evolution of critical system parameters and provides an insight of the environmental impact on TSX-1 and TDX-1. Therefore, relevant results of the LTSM and an ongoing research of the correlation between solar related events and dedicated systems responses are presented. The previous chapters point out to what extend battery degradation has advanced and what caused the necessary switch to the redundant USO system on TSX-1. It can be seen how ageing and transient effects have affected the two satellites but also the quantity of resources left to manage these inevitable progressions. As a consequence the satellites are currently still working within their specifications and as expected. The performance is very stable and as resources are still available they are prognosticated to continue their mission for several more years.

Furthermore the influence of solar events on certain system parameters is discussed. It is shown that on the one hand the annual eclipse affects components related to power generation because of shaded solar panels. On the other hand it affects also signal amplification parameters as their performance depends on the environmental temperature which decreases significantly in that period. Moreover the correlation between the geomagnetic index Ap and the amount of bit errors on the mass memory for SAR data storage is depicted. It is shown that the higher the geomagnetic index the higher the impact of geomagnetic storms thus the higher the probability of memory errors to emerge. For the current as for future space borne radar mission the analyzation results provide valuable information to interpret the monitoring results and get a deeper understanding of the system operating principles.

References

[1] S. Buckreuss, R. Werninghaus, W. Pitz: *The German Satellite Mission TerraSAR-X*, IEEE Aerospace and Electronic Systems Magazine Vol. 24, pp.4-9, 2009

[2] J. Bueso-Bello, C. Wecklich, D. Borla-Tridon, C. González, M. Martone, T. Kraus, M. Bachmann, P. Rizzoli, M. Zink: *TanDEM-X mission status and final DEM performance*, 18th International Radar Symposium (IRS), 2017.

[3] B. Grafmuller, A. Herschlein, C. Fischer: *The TerraSAR-X antenna system*, IEEE International Radar Conference (RadarConf), 2005

[4] U. Steinbrecher, D.Schulze, J. Böer, J. Mittermayer: *TerraSAR-X Instrument Operations Rooted in the System Engineering and Calibration Project*, IEEE Transactions on Geoscience and Remote Sensing (TGRS) Vol.48, Issue 2, 2010.

[5] X. Jia, M. Xu, X. Pan, X. Mao: *Eclipse Prediction Algorithms for Low-Earth-Orbiting Satellites*, IEEE Transactions on Aerospace and Electronic Systems, Issue 99, 2017.

[6] H. Breit, M. Lachaise, U. Balss: *Bistatic and interferometric processing of TanDEM-X data*, European Conference on Synthetic Aperture Radar (EUSAR), 2012.

[7] D. H. Hathaway: *The Solar Cycle*, Living Reviews in Solar Physics Journal Vol. 7, pp. 5-11, 2010.

[8] J. Li, J. Wu; Y. Zhi-qiang, L. Chao-zhen, X. Qing: *The study of periodic regularity of solar activity with data analysis method*, Proceedings of the 9th International Symposium on Antennas, Propagation and EM Theory, pp. 600-605, 2010.

[9] *Space Weather Prediction Center- National Oceanic and Atmospheric Administration - Ap-Index data*, https://www.swpc.noaa.gov, (Visited on 01/03/2018).

.