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Long-Term Monitoring of TerraSAR-X and TanDEM-X Ultra-Stable Oscillators

Johannes Böer, Ulrich Steinbrecher, Thomas Kraus, Christo Grigorov, Microwaves and Radar Institute, German Aerospace Center (DLR), Johannes.Boeer@dlr.de, Germany

Abstract

The satellites TerraSAR-X and TanDEM-X are operated in close formation to acquire synthetic aperture radar (SAR) images for scientific and commercial applications as well as for global high precision digital elevation models (DEMs). In order to ensure the expected quality of those products and to monitor the performance and stability of the SAR instruments, a long-term system monitoring (LTSM) process has been established for critical system parameters and hardware elements. This paper focuses on the methodology of monitoring of the ultra-stable oscillators (USOs) on both satellites over the extended mission time, the events encountered and the measures that have been taken to restore nominal operations.

1 Introduction

The two German SAR satellites – TerraSAR-X and TanDEM-X – have been in orbit for more than 16 years and 13 years respectively and continue to deliver reliable, high quality SAR products. Each satellite is equipped with a high-resolution X-band active phased array antenna that is capable of acquiring data in several acquisition modes [1]. When operated stand-alone, each of them serves the TerraSAR-X mission by providing high quality monostatic SAR images. When operated together, they serve the TanDEM-X mission by forming the first satellite-based SAR interferometer that delivers cross-track single-pass interferometric products [2].

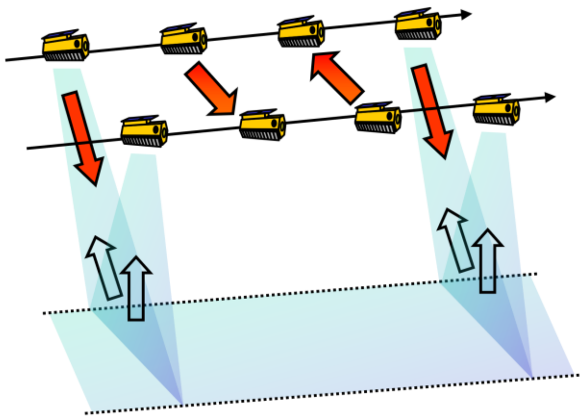

Figure 1 Synchronization via a dedicated intersatellite X-band link interleaved in the bistatic SAR imaging.

For this reason, the satellites fly in a closely controlled formation several hundred meters apart and are commanded in a bistatic way: one of them actively transmits radar pulses while both of them simultaneously acquire the reflected echoes from the ground. Since the two radar systems are independent of each other, phase errors originating from the use of separate USOs will be present in the processed interferograms. In order to eliminate these errors, during bistatic operations the two satellites exchange radar pulses via a dedicated X-band intersatellite synchronization link as illustrated in Figure 1. These pulses are interleaved in the SAR imaging sequence and are subsequently processed on-ground for the generation of a compensation phase that is used to correct the interferometric products.
Although both satellites have by far exceeded their design lifetime of 5.5 years, the quality of the SAR products is well within their specification. In order to keep track of the performance and the stability of the SAR instruments, an LTSM process has been established [3]. This paper presents one of the key aspects of the LTSM, the monitoring of the USOs on both satellites during the many years of operations and focuses on events that have led to active measures by the operations team either performed on-board the satellites or on-ground.

2 Ultra-Stable Oscillators

The USOs are located in the Radar Frequency Electronics (RFE) part of the radar instrument of each of the nearly identical satellites TerraSAR-X (TSX-1) and TanDEM-X (TDX-1). They represent the central timing reference used for the generation of the transmit signal and for the demodulation of the received signal. They are also the reference for the data sampling and radar pulse timing in the digital part of the instrument (Digital Control Electronics, DCE).
Each instrument is equipped with two independent transmit-/receive (Tx/Rx) chains, which offers full hardware redundancy when operated in single-receive-antenna mode (SRA). Furthermore, having two receive chains allows to operate the instrument in dedicated mission phases in a full-polarimetric mode (DRA, dual-receive antenna mode). While, in general, the Tx/Rx chain of the radar instrument (RFE+DCE) can only be switched between main and redundant unit as a whole unit, an exception has been made for the USOs, based on prior space mission experience. Hence, it is possible to only switch the oscillator to the redundant unit (USO2) and back to the main one (USO1), using a dedicated electrical cross-strapping between main and redundant RFE.

Each USO generates a signal at about *59.9 MHz*. From this reference, the radar center frequency for pulse transmission (about *9.65 GHz*) is derived by a multiplication with a factor of *161*. The sampling frequency of the Analogue-to-Digital converters (ADCs) in the DCE is derived by applying a frequency multiplication factor of effectively *5.5* to reach a nominal design value of *329,658,384 Hz* that is sufficiently high to sample radar data with the maximum bandwidth of *300 MHz*.
Since the ADC sampling frequency f_{ADC} is directly derived from the USO output signal with a fixed multiplication factor in the instrument hardware, and is the parameter that is accessible for monitoring as part of our LTSM, we use it in our USO frequency estimation and prediction routines as described in the following chapters, instead of the intrinsic USO frequency level of about *60 MHz*.

3 USO Frequency Monitoring

Over time the instantaneous oscillator frequency of each USO is subject to drift mainly due to aging. Nonetheless, the TerraSAR-X mission started in 2007 without the need for a close monitoring of the USO frequency of the TerraSAR-X satellite. Instead, the value used for both datatake commanding and the processing of radar data was initially configured with the nominal design value provided by the satellite manufacturer and it was foreseen to update this rather static value at infrequent intervals only when the deviations due to aging exceeded a certain threshold.
An interest in a closer monitoring and a more precise prediction of USO and radar frequency arose because the TerraSAR-X mission showed, due to substantial improvements and sophisticated algorithms in the processing of radar data [5][6] and considerably improved knowledge of satellite orbit parameters, its potential to provide data products with increased geolocation accuracy [7] compared to the SAR product specification.
A second major factor has been the introduction of the TanDEM-X mission, which acquires bistatic data based on two radar instruments with separate independent USOs. While the relative oscillator frequency can be determined during the interferometric processing using data from interleaved synchronization pulses, there was still the need for an accurate a-priori knowledge of the absolute oscillator frequency, e.g., for resolving phase ambiguities and also for the basic screening of raw data w.r.t. interferometric data quality directly after data reception on ground. Furthermore, the synchronous execution of a bistatic datatake on both satellites is essential for the joint processing of the acquired data, a prediction of the ADC frequency is used on-ground to derive the most precise commanding in terms of radar timing.
We combine two main methods for the estimation of USO frequency with the goal of maintaining an accuracy of 1 Hz in the estimation and prediction of absolute (f_{ADC}) and relative (Δf_{ADC}) ADC sampling frequency. One method is based on special, long monostatic datatakes, out of which we derive an absolute knowledge of the frequency. The second method is based on the evaluation of synchronization pulses of TanDEM-X acquisitions.

3.1 Estimation of absolute USO frequency

USO instantaneous frequency can be estimated based on the evaluation of long monostatic datatakes [8]. This method exploits the fact that the time annotation of the radar data is based on two independent sources. The more accurate one is the onboard Global Positioning System (GPS) receiver which provides a high-precision pulse per second signal (PPS) and thus the integer number of seconds. The other source is the USO itself, which has a significantly higher clock rate but cannot ensure a comparable long-term stability. The correlation allows to calculate an estimate of the instantaneous USO frequency at the time of the analyzed datatake.
USO frequency estimation datatakes are not structured like nominal datatakes, but have to be tailored in several ways in order to provide the required accuracy in the frequency prediction and to still meet the various restrictions for TerraSAR-X datatakes. One characteristic is that the datatakes do not need to be actively transmitting and are therefore commanded and executed with passive radar frontend, since only the time annotation of the datatake raw data is evaluated later on, and the actual radar echo data is not needed, and not even recorded. In this way the power and thermal limits for actively transmitting datatakes do not apply anymore, and the duration of the datatake is made as long as possible to get the desired precision in the frequency estimation. The chosen value of 600s is close to the restriction of 700s of accumulated passive datatake duration over one satellite orbit, thus still leaving some remaining datatake imaging opportunity in the surrounding orbit time for nominal monostatic or bistatic datatakes.
Not recording the radar echoes reduces the data amount of such a datatake down to an acceptable level for onboard storage and data downlink.
Finally, an optimum radar timing in terms of pulse repetition frequency (PRF) has to be chosen for the datatake template as mentioned in [8].

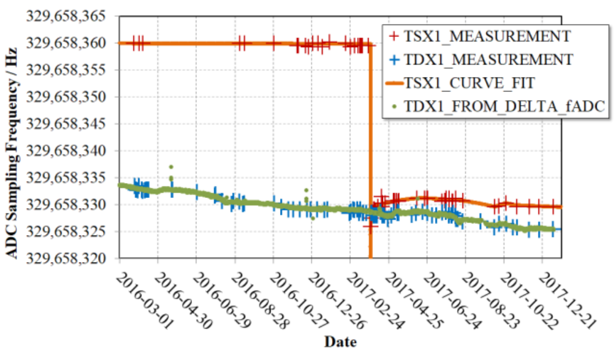

Figure 2 Combined evaluation of absolute and relative USO frequency measurements, where $f_{ADC,TDX1}$ measurement is compared with the estimation based on measurements of $f_{ADC,TSX1}$ and relative frequency Δf_{ADC}.

Datatakes for USO measurements are ordered on a regular basis with the goal of having a measurement for each satellite every 7 – 10 days and more often in case of detected anomalies. We aim to place these measurements as close as possible on the two satellites, in order to get a good estimate on the instantaneous relative USO frequency, minimizing the inaccuracy due to drift. Furthermore, the impact on nominal acquisitions for scientific and commercial users have to be minimized. The unavoidable disadvantage of this frequency estimation method is that each measurement blocks a large fraction of the allowed acquisition time over a satellite orbit and therefore it is not possible to get data samples on a daily basis or even at a higher rate.

One option that has been investigated in order to circumvent this restriction, is the exploitation of nominal TerraSAR-X datatakes, with considerably shorter datatake duration, for the purpose of USO frequency monitoring. They can provide only coarse estimates of the absolute frequency due to their relative short durations of up to a few tens of seconds, and also due to their statistical variability in terms of the used PRF. Nonetheless the derived information was useful in mission phases without bistatic acquisitions and during maintenance phases, when the satellites were not in close formation but separated in along-track, or when nominal acquisitions were only supported with one satellite.

3.2 Estimation of relative USO frequency

The difference in f_{ADC} between TSX-1 and TDX-1 can be estimated by another, independent measurement method. It is based on the evaluation of the synchronization pulses, that are exchanged between the satellites and recorded in every nominal bistatic TDM acquisition. The respective calculations yield very accurate results and are performed by the raw data screening component of the Interferometric TanDEM-X Processor (ITP). Furthermore, the results are available promptly, with little delay after the downlink of the respective datatake.

3.3 Frequency estimation and propagation from the data

The data from the absolute and relative frequency measurements are combined and a piecewise functional fit is applied in order to provide interpolated values for the f_{ADC} of both radar instruments. The combination of results from two independent measurement methods allows for a filtering of strong outliers, detection of discontinuities and a minimization of measurement uncertainty by equal distribution of residual errors.

Figure 2 visualizes the combination of measurement data by showing the sparse, absolute frequency measurements for both radar instruments (+ symbols), a piecewise functional fit of this data for TSX-1 (orange curve), and the combination of $f_{ADC,TSX1}$ with Δf_{ADC} as an estimate of $f_{ADC,TDX1}$ (green dots).

In a final step, after updating the frequency trend lines with recent measurement data, the Long-Term Monitoring procedure calculates a prediction that is later used in the commanding chain of TanDEM-X and by the SAR processors TMSP (TerraSAR-X Multi-Mode SAR Processor) and ITP.

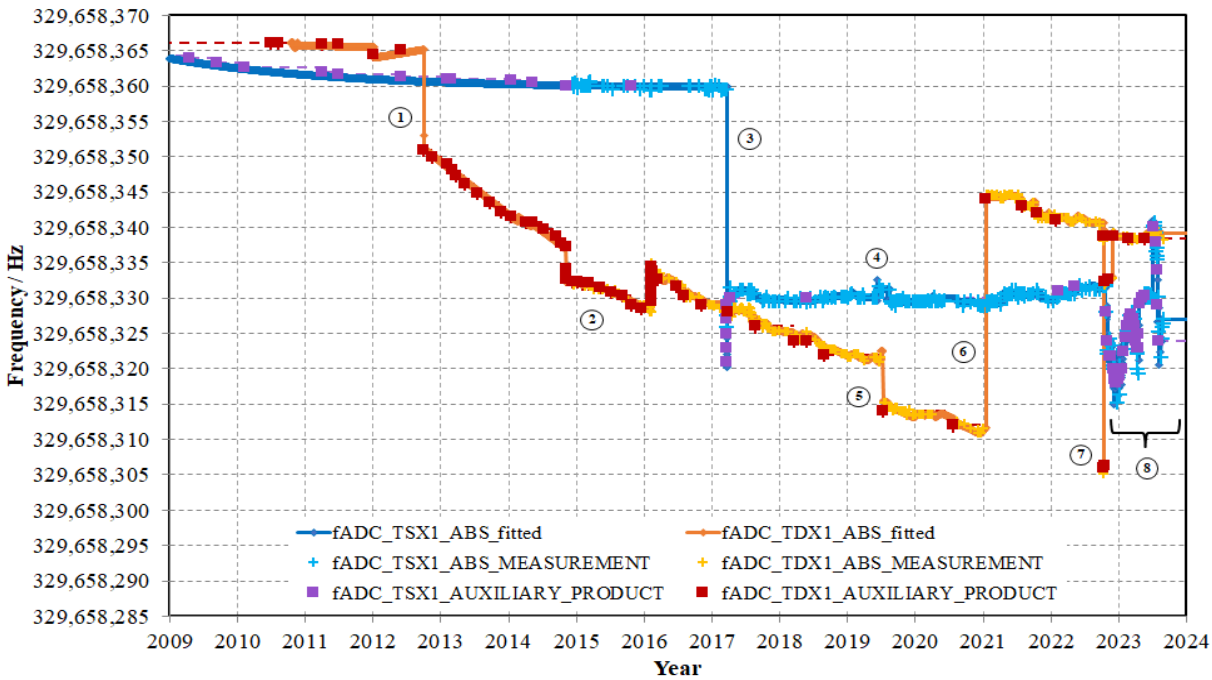

Figure 3 Overview of the progression of ADC sampling frequency for the active USO of TSX-1 and TDX-1. Notable events are marked in the plot: Switching from nominal to redundant USO (1) and (3), frequency shift due to thermal influence on active USO of TDX-1 during an extended DRA campaign for both satellites (2), instability with degradation of TSX-1 USO behaviour (4), switching over from main to redundant radar instrument Tx/Rx chain in 2019 (5), abrupt change of TDX-1 USO2 frequency in 2021 (6), malfunction of internal temperature stabilisation of TDX-1 USO2 for a period of about 1 week (7), permanent failure of internal temperature stabilisation of TSX-1 USO2 (8). Systematic acquisition and evaluation of USO measurement datatakes started at the end of 2014 (+ symbols in the plot).

4 USO performance during the mission

Over the years many effects regarding the oscillators have been observed and required to analyze and decide about which measures can improve the situation at hand. The major events will be described in the following sections, separately for the two satellites TSX-1 and TDX-1.

4.1 Satellite TerraSAR-X

4.1.1 Nominal USO

The nominal USO in the primary instrument chain of TSX-1 was inconspicuous for many years, by far exceeding the designed life time of the satellite. It was performing without any visible degradations in the satellite telemetry data and showed a low long-term drift rate of the frequency that was settling over time and almost constant afterwards (blue curve in Figure 3).

Since May 2016 the recorded USO1 input currents started to show irregularities, a characteristic 'dips and spike' pattern that typically appeared in bursts for a period of one or two days. An example is shown in Figure 4. The patterns appeared to be very similar to the ones already observed in 2012 on TDX-1. Thus, they were also explained as temporal malfunctions of the USO-internal temperature regulation circuit.

The effect obviously degraded the USO output signal w.r.t. frequency stability, as TanDEM-X acquisitions, that coincided with one of these instabilities, proved to be disturbed in most cases in such a way that the phase difference between the oscillators could not be reconstructed from the synchronization pulses interleaved into the bistatic acquisition. In addition, the timing of synchronization pulse exchange was affected in some parts of the acquisitions, leading to incompletely recorded synchronization pulses that could not be evaluated. Almost all affected bistatic acquisitions were therefore not processable.

To improve the situation, it was decided to switch to the redundant USO2 on TSX-1, which was done on March 27 of 2017 (*3* in Figure 3). After this change, nominal SAR operations could successfully be resumed. Concerning the perspective of a future use, USO1 is still regarded as a redundancy option in case of a major malfunction of USO2.

4.1.2 Redundant USO

The redundant USO is in active use since 2017, which means that by now it has also surpassed the planned operational life time of the satellite. For all of its active time is has been used in combination with the primary Tx-/Rx-chain of the radar instrument, using the redundancy cross-strapping between the two RFE units.

The next notable event (*4* in Figure 3) occurred on June 18 2019, when a slight, abrupt change of relative ADC sampling frequency of about 2 Hz was observed, that could be attributed to the radar instrument of TSX-1. It was not accompanied by any visible disturbances in the telemetry data of the satellite, but it had the permanent effect of a stronger thermal sensitivity of the USO frequency.

This regularly affected some of the TanDEM-X acquisitions, from that time on several bistatic acquisitions per day were reported as degraded. As a remedy it was decided to increase the rate of the interleaved synchronization pulses within bistatic acquisitions from 5 Hz to 15 Hz at the cost

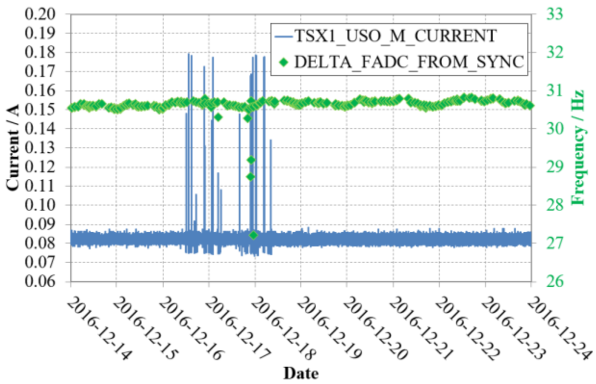

Figure 4 Example of TSX-1 USO1 instabilities observed in December 2016. The telemetry data of USO input current (blue) shows a characteristic 'dips and spikes' pattern. TanDEM-X acquisitions coinciding with one of these disturbances are degraded, the estimated instantaneous relative frequency (green) calculated by the interferometric SAR processor from interleaved synchronization pulses is disturbed.

of losing the respective amount of imaging pulses. This proved to be sufficient for the TanDEM-X interferometric processor to again reliably reconstruct the differential USO phase over the datatake from the recorded synchronization pulses.

The last event that shall be described here is a further degradation of USO2 w.r.t. its internal thermal stabilization (*8* in Figure 3). Starting from November 1 2022 USO2 experienced permanent and strong current spikes, again correlated with frequency shifts, which made the processing of bistatic acquisitions impossible. The situation was analyzed by the satellite manufacturer and as a first measure a power cycle of the USO was performed in order to rule out any single event functional interrupt. As this did not resolve the situation, it had to be concluded that a component failure in the Oven Control Circuit of USO2 was causing the internal operational temperature not to be reached. The next option was to turn on the external heater of the RFE2 in order to try to bring the USO2 closer to its nominal temperature range. This action proved to be successful, and after activation of the heater on November 8 2022 the measured USO currents, and also the USO signal characteristics went back to a stable level, as expected. Nonetheless, the applied solution comes with two drawbacks. First, the permanently increased power consumption, and also the increased thermal level of the redundant RFE (~30 K) need to be operationally handled. Second, without an effective internal temperature stabilization the USO output frequency is subject to a substantial thermal drift estimated to be about 7 Hz/K in ADC frequency, or 200 Hz/K in radar frequency. It is possible to compensate this additional uncertainty during the processing of the radar data, because the variation is directly proportional to the USO temperature, which is recorded in the satellite telemetry data. The approach is described in [9].

4.2 Satellite TanDEM-X

4.2.1 Nominal USO

On TDX-1, first signs of USO1 degradation showed up relatively early in the mission - about 1.5 years after the launch of the satellite. It started in September 2011 with the observation of characteristic dips and peaks in the USO currents, at irregular intervals. This affected the spectral performance of the USO and degradations were reported in the quality evaluation of bistatic acquisitions due to unexpected frequency offsets in the estimation of differential USO phase or low synchronization pulse signal-to-noise ratio (SNR).

One year later, in September 2012, the situation deteriorated further. The instabilities occurred almost permanently and to such an extent that not only the radar frequency of TDX-1 was degraded but also the radar timing of the synchronization pulses that were exchanged over the intersatellite link during each bistatic acquisition. Even the monostatic datatakes recorded with TDX-1 for the TerraSAR-X mission had to be considered as degraded w.r.t. the TerraSAR-X product specification. The signal distortion and offsets in radar frequency resulted in range shifts and therefore errors in geolocation in the order of several meters. Therefore, the decision to switch over to USO2 was urgent, and the respective procedure was executed on October 1 2012 (*1* in Figure 3). At the time of switching USO1 was considered lost and not useable any more. Yet, this assessment has changed by now, based on the experience with the USOs of TSX-1, as described in Chapter 4.1.2. There is now a perspective for a potential future re-activation of USO1. With a similar operational approach as the one described in that chapter, i.e. the combined use of the redundant Tx-/Rx chain of the TDX-1 radar instrument with cross-strapped USO1 in an externally heated RFE1, there is the chance to get USO1 back into stable operation.

4.2.2 Redundant USO

As mentioned in the previous chapter, USO2 is active since October 2012, which means that by now it has also surpassed its originally intended operation life time. USO2 showed a higher frequency drift rate than the previously used unit, which is visible in Figure 3 (orange curve).

The next notable event for TDX-1 was the switching from primary to secondary Tx-/Rx chain in 2019 (marked as *5* in Figure 3). It had only minor impact on the operation of USO2. As RFE2 was now in active use and at a higher thermal level, USO2 output frequency experienced a corresponding shift to a lower frequency, as expected.

5 Conclusion

Long-term monitoring of the USOs was established with the start of the TanDEM-X mission and was not only an operational tool for measurement and prediction of frequency drift in nominal TanDEM-X operations, but also a valuable source of information for analysis and investigations of USO hardware issues. This is even more important now that the satellites including the USOs are of advanced age and start to experience anomalies never observed before. The USO monitoring has therefore become an essential part of the satellite operations and contributes to the effort to prolong as much as possible the duration of the TerraSAR-X and TanDEM-X missions.

6 Literature

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