TanDEM-X Mission: Long Term in Orbit Synchronisation Link Performance Analysis

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Abstract

The German satellites TerraSAR-X and TanDEM-X are flying in a close orbit formation as a bistatic interferometer to generate a high precision Global Digital Elevation Model (DEM). DEM data is acquired in bistatic operation with one active satellite illuminating the swath and both satellites receiving the ground echoes. This mode requires synchronization between the independent oscillators on TerraSAR-X and TanDEM-X, which is achieved by a synchronisation link using horn antennas on both satellites for omnidirectional coverage. This paper describes the synchronisation system and compares and verifies the SNR predictions by evaluating in orbit SNR measurements in different satellite formations.

1 Introduction

TanDEM-X is a spaceborne synthetic aperture radar (SAR) mission that comprises the satellites TerraSAR-X, TSX-1, (launched in June 2007) and TanDEM-X, TDX-1, (launched in June 2010). The primary mission goal is the generation of a high precision global Digital Elevation Model (DEM) [1]. To fulfil the primary mission objective the two satellites fly in a close helix formation with varying horizontal separation of around 120 m - 500 m. These small baselines form a single pass bistatic interferometer for accurate DEM acquisition. In this configuration the satellites are operated in a special mode where only one satellite is actively transmitting and receiving while the other is in receive only mode. To ensure the unprecedented quality of the DEM a precise synchronisation between TSX-1 and TDX-1 is mandatory. Without a synchronisation the smallest differential deviations in terms of phase and frequency would result in considerable phase errors, geometrical image and DEM distortions, [2] and [3]. These problems are induced by independent ultra-stable oscillators (USO) on both satellites with slightly different frequencies and phase variations. To minimize the previous mentioned errors TSX-1 and TDX-1 exchange synchronisation pulses. Based on the synchronisation pulse transmitted by one satellite, received by the other satellite and vice versa, the oscillators' differential phase noise and frequency deviation are compensated on ground during the SAR processing.

Furthermore, the exchange of synchronisation pulses serves as a major safety mechanism on-board. It is important in the close formation flight that one satellite does not illuminate the other satellite with its radar main lobe. For this purpose a special pulse exchange sequence is executed in dedicated small datatakes and the signal levels are directly evaluated on-board. In case of a too low receive signal level the radar transmission is immediately suppressed by the satellites since the partner satellite might not be at the expected orbit position and could be illuminated.

This paper gives an overview about the synchronisation system and the pulse exchange concept and performance prediction in the second chapter. In the third chapter a detailed evaluation of in orbit measurements and a comparison to performance predictions is shown. The last section evaluates the reliability of the safety mechanism.

2 Bistatic Synchronisation Link

The frequencies of the satellites ultra stable oscillators (USO) are the reference for signal generation and timing of the respective satellite. Slight drifts in the USO frequency cause, for example, a variation of the echo window position.

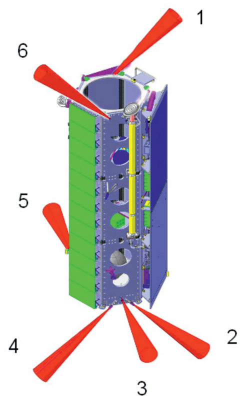

Figure 1: Synchronisation horn configuration and pointing direction on TSX-1 and TDX-1.

The real differences, determine in 2013, are very small (TSX-1 USO frequency: 59.9378838 MHz, TDX-1 USO frequency: 59.9378811 MHz and difference: 2.65 Hz) but still have a considerable effect on USO dependent SAR instrument parameters such as the radar frequency f0 and pulse repetition frequency (PRF). In order to compensate this effect a sophisticated synchronisation strategy is used to determine the time varying frequency and phase difference. During a bistatic acquisition, both satellites exchange interleaved synchronisation pulses in order to determine the time dependent differential phase. For this purpose both satellites TSX-1 and TDX-1 are equipped with a synchronisation antenna system comprising 6 circular polarized X-band horn antennas arranged in such a way, that an omnidirectional coverage is obtained, see **Figure 1**. This ensures synchronisation for all possible relative satellite positions.

2.1 Performance Prediction

For the predication and later for the evaluation of the data a distinction is drawn between synchronisation link data that on the one hand is acquired during a DEM acquisition and is part of the raw data. These data pass through a on-ground processing where a pulse compression of the synchronisation pulses is performed to improve the signal to noise ratio (SNR). On the other hand the on-board safety mechanism also exchanges pulses via the synchronisation link but this data set, as already mentioned, is evaluated directly on-board and a higher signal quality with respect to SNR is required because no pulse compressing is performed but a simple on-board algorithm evaluates the signal energy. The required SNR after the pulse compression for DEM acquistion is more than 30 dB to ensure the desired DEM quality, whereas the signal to noise ratio for on-board safety mechanism requires more than 15 dB for a reliable exchange of pulses.

A detailed analysis of the synchronisation link performance showed that the main residual error contribution originates from the receiver noise provided that the synchronisation pulses are exchanged at a rate of larger than 5 Hz [4]. Furthermore, the analysis showed that the performance of in-orbit exchange of synchronisation pulses mainly depends on the mutual aspect angle and the separation of the satellites as expected.

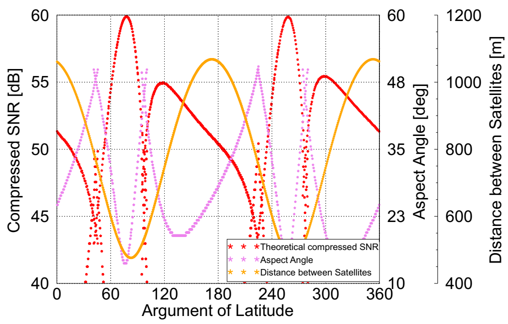

Figure 2: Theoretical compressed SNR for the helix configuration on 2012-04-29.

Figure 2 shows the important parameters SNR, aspect angle and satellite distance for one orbit on April 29th, 2012. The distance between TSX-1 and TDX-1 varies between 500 m to 1100 m. The expected compressed SNR is between 45 dB to 60 dB depending on the aspect angle and the distance. The prediction of the signal to noise ratio is used to command the synchronisation horn antenna on each satellite. In principle this means that the aspect angle is minimized to ensure that always the optimal synchronisation horn combination with the best SNR is selected. During the complete mission the selection of the optimal synchronisation antenna pair for each acquisition is exclusively calculated.

3 In Orbit Synchronistation Pulse Performance Evaluation

As already mentioned the synchronisation pulse performance is an important quality factor for the phase and timing correction and finally for the generation of DEMs [5], [6].

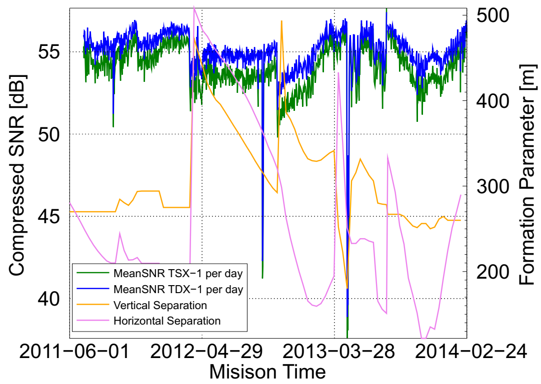

Figure 3: Mean SNR per day over the complete mission correlated with formation parameter.

In **Figure 3** the daily average of the compressed SNR of all acquisitions for the last three years is shown. Additionally, the data set is correlated with the satellite formation change. It is obvious that changes in the distance between the satellites directly influence the measured SNR. The difference in compressed SNR between TSX-1 and TDX-1 of approximately 1 dB is related to the improved Transmit Receive Module (TRM) assembled in the TDX-1 satellite with respect to the noise figure (NF) and the slight higher transmit power of TSX-1. Furthermore two events can be identified where the SNR drops significantly.

The first event in Figure 3 is directly linked to a failure of the primary USO heater on TDX-1 where the synchronisation was no longer reliable and a switch over to the redundant USO had to be performed. The second event was caused by a not optimal selection of synchronisation antenna pairs because the change of relative satellite velocity was not considered as required for polar regions. This leads to the situation that the selected antenna pair at the beginning of acquisition over Antarctica were pointing at wrong directions at the end of the data taking. Hence, no synchronisation pulse exchange was possible at a certain time during the acquisition. The problem was fixed by considering the relative velocity of the satellites during the calculation of the optimal antenna pair.

The following analyses survey an almost constant satellite formation in the period between 2012-04-29 and

2012-06-14. In this range the mean signal to noise ratio for every acquisition was evaluated and compared with the expected SNR.

In **Figure 4** the evaluation over argument of latitude for TSX-1 and in **Figure 5** for TDX-1 is depicted. In both plots the theoretically predicted signal to noise ratio and the actual measured SNR is shown, which show a good agreement.

When comparing the measured SNR of TSX-1 and TDX-1 the before mentioned slight lower signal to noise ratio of approximately 1 dB for TSX-1 can be seen.

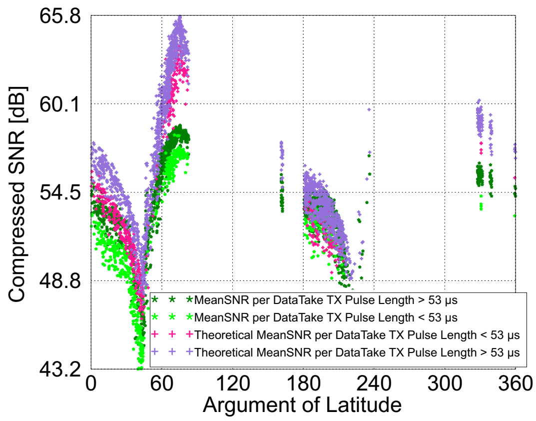

Figure 4: Compressed SNR evaluation of all acquisitions performed between 2012-04-29 and 2012-06-14 and their SNR prediction over argument of latitude for TSX-1.

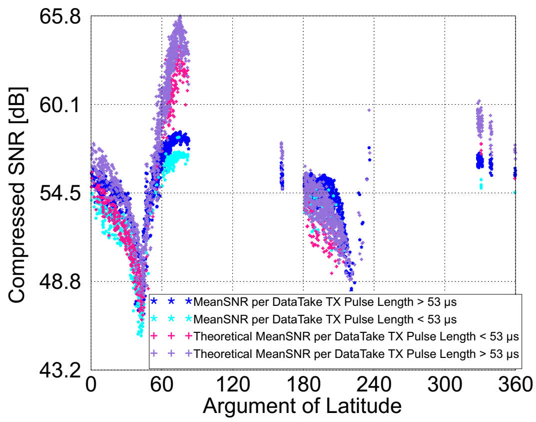

Figure 5: Compressed SNR evaluation of all acquisitions performed between 2012-04-29 and 2012-06-14 and their SNR prediction over argument of latitude for TDX-1.

In addition, two bands are visible for the mean SNR for example at 80° argument of latitude in Figure 4 and Figure 5. This relates to the fact that depending on the geometry of the acquisition and to reduce ambiguities in the images all acquisitions are acquired with adaptive pulse repetition frequencies (PRF). This results in a variation of the compressed SNR because the compression gain G_{comp} is directly linked to the bandwidth B and the pulse duration T_{PL}, see **(1)**,

$$G_{comp} = B \cdot T_{PL} \tag{1}$$

which is derived from the PRF at a constant transmit duty cycle. For improved clarity of the plots two ranges of pulse duration are defined: pulse length greater than 53 μs and duration less than 53 μs. Hence, the two bands are visible with pulse lengths greater than 53 μs having the higher SNR and T_{PL} less than 53 μs the smaller SNR. The remaining spreading of the data set in Figure 4 and in Figure 5 at the same argument of latitude is caused, beside of the pulse duration, by slight different aspect angles and the change of distance between TSX-1 and TDX-1 due to the formation change of the analysed time period.

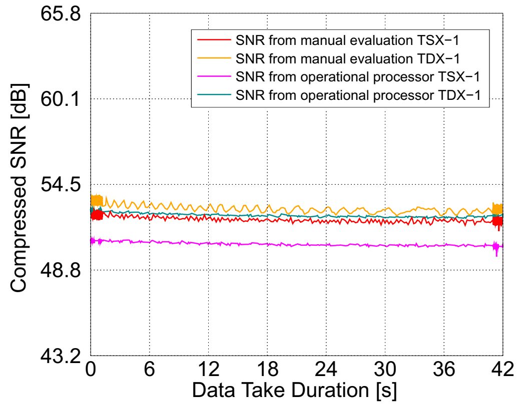

Figure 6: Compressed SNR of acquisition at 10° argument of latitude

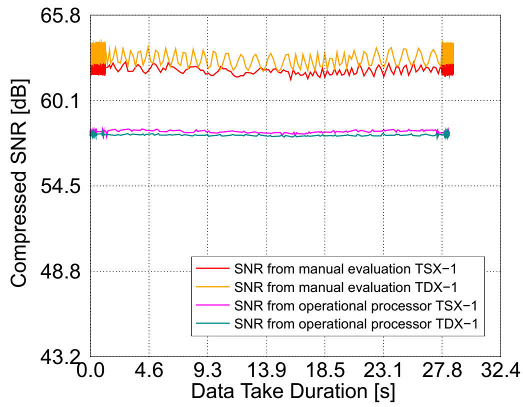

Figure 7: Compressed SNR of acquisition at 80° argument of latitude

In the range of 60° to 90° argument of latitude a larger deviation between the prediction and the measured data can be seen. To locate the source of deviation the raw data of two acquisitions were analysed in detail. Apart from the SNR annotated by the SAR processor a stand alone verification software to calculate the synchronisation SNR has been implemented. It uses the mean signal power of each synchronisation pulse and the measured noise from the corresponding signal free part of the same echo window to calculate the SNR. Finally the theoretical compression gain, see (1), was added.

Figure 6 shows the results for one acquisition at 10° ar-

gument of latitude. The SNR for TDX-1 agrees with the operational results while TSX-1 shows a constant difference of approximately 2 dB.
Figure 7 shows one of the acquisitions with a larger discrepancy at 80°. In this case a constant difference of approximately 5 dB is found. The SNR values calculated with the stand alone verification software fit the theoretical SNR. The reason for the difference to the SNR annotated by the SAR processor is currently under investigation. A probable reason could be the different algorithm for the noise determination.

4 Evaluation of the Reliability of the On-board Safety Mechanism

The on-board safety mechanism, also called sync-warning mechanism, is performed on both satellites simultaneously and evaluated on-board autonomously. Therefore both satellites form a communication link using a pair of Sync Horns, see Figure 1, to exchange pulses. The detection of a poor receive signal level results in immediate suppression of radar transmission since the cause could be an unexpected orbit position of the partner satellite which could result in unwanted radar illumination. **Table 1** gives a statistic of all up to now executed pulse exchanges for safety reasons. Since the beginning of the mission more than 33000 sync-warnings have been commanded and only 6 on TSX-1 and 5 on TDX-1 failed due to on-board problems like a leakage in a thruster or reboot of the GPS receiver, thus confirming the correct functioning of the sync-warning mechanism. All on-ground calculated opportunities for successful pulse exchange were correct.
The difference in the number of exchanges between TSX-1 and TDX-1 is caused by lost satellite telemetry due to downlink problems. Furthermore the deviation in the number of failed pulse exchange is related to the fact that the threshold of sufficient signal level was passed on TDX-1 but on TSX-1 not.

Satellite	Successful	Failed
TSX-1	33477	6
TDX-1	33529	5

Table 1: Synchronisation Pulse Exchange Statistic

5 Conclusions

The evaluation showed that over the complete TanDEM-X mission except for two short events, the USO heater failure and the not optimal selection of synchronisation antenna on the two satellites the SNR is always above the desired level of 30dB. Furthermore it could be shown that the predicted signal to noise ratio and the actual measured SNR show a good agreement over the complete orbit. The deviation in the range of 60° to 90° argument of latitude can be partly explained but further investigation are currently ongoing. Furthermore, the exchange of synchronisation pulses as a safety mechanism works perfectly since the start of TanDEM-X Mission. The small number of failed pulse exchanges is due to spacecraft anomilies. The results and expertise of the synchronisation pulse analysis is required for the more accurate prediction of synchronisation channel for the upcoming science phase.

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