

IQ Bias Channel Deviation on TerraSAR-X and TanDEM-X

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Abstract

The SAR satellites TerraSAR-X and TanDEM-X are experiencing periodically varying solar conditions due to their orbit geometry. As a consequence multiple system parameters are affected by these variations mainly induced by corresponding temperature fluctuation. A long-term analysis has been conducted showing that in particular one parameter, the in-phase and quadrature bias (IQ bias), deviates considerably from expected results. This deviation occurs between the respective channels and also between both spacecraft. In order to identify the driving mechanisms behind this behaviour, the signal path between the antenna front-end and the analogue-to-digital conversion (ADC) block is analysed, putting a special focus on the IQ demodulation block. Within this block, mixer imbalances are the main contributors to the observed behaviour and provide an explanation for the differing channel outputs. The mixer is also the reason for IQ bias deviations between the satellites since the channel imbalance shows a reversed tendency when comparing both systems. Although the effects are corrected in calibration, the results provide valuable information to interpret monitoring results and to gain a deeper understanding of the system.

1 Introduction

TerraSAR-X (TSX) and TanDEM-X (TDX) are two almost identical remote sensing SAR satellites which are operated since 2007 and 2010, respectively. Their major mission goals comprise acquiring multi-mode SAR data in X-band, by each satellite individually [1] and a bistatic configuration to provide a global DEM with 12 m grid sampling and relative height accuracy better than two meters. The global DEM was completed in October 2016 [2] and the TanDEM-X mission continues with the objective to generate an update of the global DEM, the so-called Change DEM [3].

Placed in a sun-synchronous orbit the spacecraft, especially their solar panels, are almost constantly exposed to sunlight. However, due to the retrograde inclination of the orbit, the satellites are entering the Earth's shadow in summer during every pass in the southern hemisphere. As electric circuits are sensitive to temperature changes, the lower temperature during these eclipse periods affect multiple system parameters [4]. A particularly unexpected behaviour in this context can be observed within the IQ bias. Firstly, a long-term analysis shows that the evolution of the bias significantly differs between the respective channels. From the results it becomes apparent that the expected effect from the varying solar condition can only be measured in one of the channels while the other channel shows no response. Secondly, the evolution of the bias furthermore differs between both satellites despite experiencing identical environmental conditions. More precisely, the behaviour of the affected and the non-affected channel is reversed between TSX and TDX.

The observations are made within the scope of systematic SAR raw data screening and long-term systems monitoring (LTSM) which periodically evaluates a variety of satellite parameters. Included are health checks of the SAR antenna's transmitting and receiving (T/R) modules,

exploitation of regular acquisitions over point and distributed targets, Ultra-Stable Oscillator frequency measurements, interferometric baseline monitoring and statistical evaluations of SAR signal properties and calibration parameters that reflect the performance of the overall interferometric SAR system [5]. As the monitoring results, among others, ensure the quality of the SAR product, it is important to maintain a high accuracy.

The following analysis therefore serves to investigate the different reactions of the IQ bias during eclipse periods on the different satellite systems and to identify the driving mechanisms for the observed behaviour. The results will help to gain a deeper knowledge of the systems' functionality, their environmental interactions and to interpret monitoring results for future SAR missions.

2 IQ Bias deviation

A long-term analysis of the IQ channels of TSX and TDX revealed periodic bow shaped trends, as shown later in Figure 4, which result from the annual eclipse period that occurs every year between April and August. Comparing the observations of each channel and between the satellites showed a significant deviation. The following chapter thus explains the determination of the IQ bias, the eclipse impact on the satellites and in particular the nature of the observed behaviour.

2.1 IQ demodulation and bias

As the incoming radar signal has to be sampled with the Nyquist frequency to avoid aliasing, the ADCs have to be designed accordingly. By dividing the signal into two channels before digitization with an individual down-converter and applying a phase shift of 90° on the complex local oscillator (LO) signal for one of the channels, both the real (I) and imaginary part (Q) of the signal can be

obtained using two ADCs with only half of the original sampling frequency. Since the IQ signal is equivalent to a complex number after conversion, the amplitude A as well as the phase Φ can be restored according to:

$$A = \sqrt{I^2 + Q^2} \quad (1)$$

$$\Phi = \arctan\left(\frac{Q}{I}\right) \quad (2)$$

Figure 1 shows a schematic block diagram of the IQ signal path as it is implemented on TSX and TDX. The received signal is split up by the IQ demodulator, amplified, filtered with respect to the desired bandwidth and then digitized by the respective ADC for the I- and Q-channel.

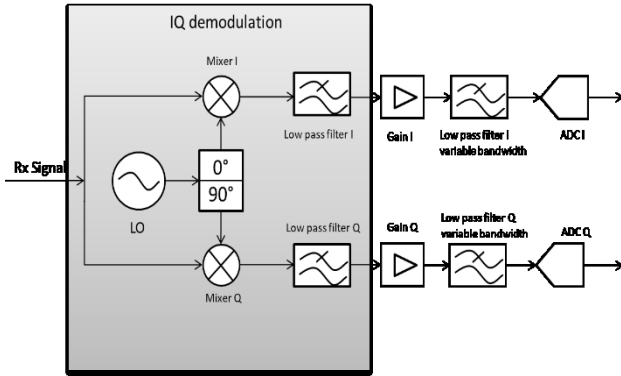


Figure 1: Block diagram of IQ signal path on TSX/TDX.

By reason of the IQ sampling process the recorded raw data has to be corrected for biases, differential channel gains and channel non-orthogonality. This is performed independently on each sub-swath and polarization in the processing on ground. In order to determine the bias, a statistical analysis is performed on the raw data of the extracted calibration pulses. Subtracting the on-ground characterized I and Q offset values from the resulting statistical average yields the bias values that are used for the correction of the echo signal. Since variations in channel non-orthogonality are rather small compared to the bias and gain imbalances, they are neglected in the following analyses.

2.2 Eclipse

TSX and TDX fly in a sun-synchronous orbit using the Earth's gravitational inhomogeneity i.e. the J2 zonal perturbation to rotate the osculating orbital plane in the same speed the Earth revolves around the sun. This allows an almost constant exposure, in particular of the solar panels, to sunlight. However due to a slightly retrograde inclination of 97.4° and an orbit altitude of approximately 511 km in average [2], the satellites are facing an eclipse period between end of April and middle of August culminating at summer solstice, as shown in Figure 2. The satellites then enter Earth's shadow with every revolution for a fraction of the orbit on the southern hemisphere. The duration of the shadow period depends on the inclination angle, the orbit altitude and the transient declination angle between the sun and the rotational axis of the Earth [4].

For TSX and TDX this leads to a maximum eclipse duration of 22.4 minutes or 24 percent of the orbital period.

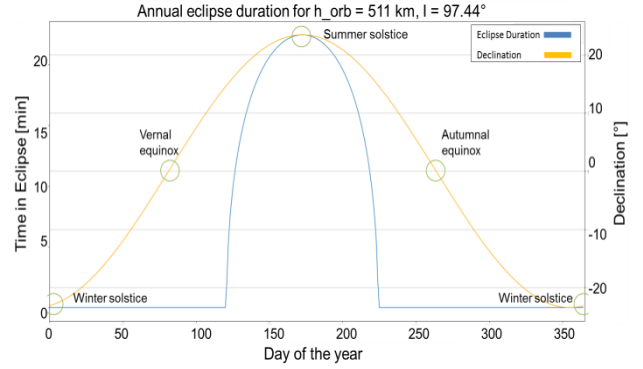


Figure 2: Sun's declination angle and eclipse duration for the TSX/TDX orbit.

One major consequence of passing through Earth's shadow, besides the incapability of the solar panels to produce power, is that the environmental and thus also the system temperature drop rapidly. As the performance of the system electronics, in particular the amplifiers or the ADCs in the IQ branches passing and digitizing the raw data signals, is sensitive to the surrounding temperature, the recorded echo power before calibration is expected to significantly change with a change in system temperature. In fact, this can be seen in Figure 3 where the power of the received raw data signal over a test site in Australia is plotted against the ADC temperature of one of the channels for the TSX satellite.

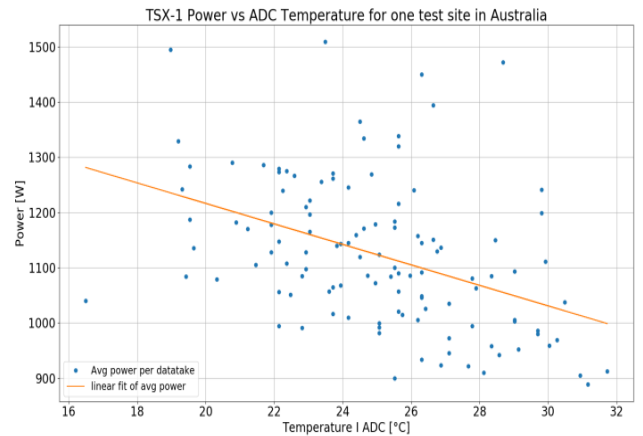


Figure 3: TSX signal power versus ADC temperature of the I channel over an Australian test site acquired between January 2014 and December 2017.

As the determination of the IQ bias is based on the raw data which varies with the signal power, the IQ bias hence is expected to show a similar dependency on the system temperature in particular during the eclipse periods. Therefore the anticipated impacts on the IQ bias of this rapid change in the environmental conditions are described in detail in the following section.

2.3 IQ bias and channel imbalance

The aforementioned computation of the IQ bias and the according raw data correction are performed for every single data take. According to Figure 3 this means both the I and the Q bias should significantly increase for data takes that are acquired during the eclipse. Looking at Figure 4 which shows the mean bias per day for TSX and TDX over the mission duration, one can observe that this is only true for the I bias on TSX and the Q bias on TDX. The respective counterpart biases seem to be only slightly or not at all affected although the same temperature change of the respective system parts was measured. As an annotation, the visible jump in both plots results from an adaption off the IQ offset which was performed to correct the drifting bias. It has no correlation to the described effects.

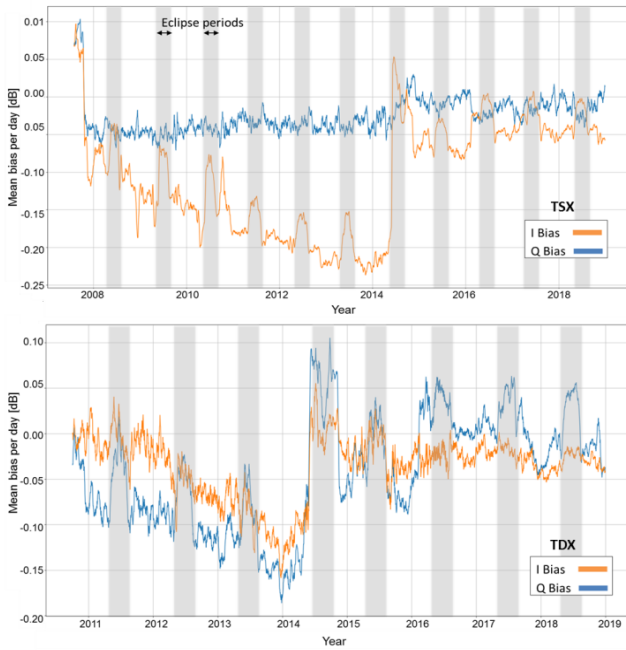


Figure 4: IQ-bias over mission time for TSX (top) and TDX (bottom).

In order to better understand this behaviour single data takes, in particular the evolution of power level and bias over acquisition time, of various scenes acquired inside and outside of the eclipse are analysed. Figure 5 shows a scene from the south-east coast of Australia, acquired by TSX in January 2016, along with the corresponding IQ bias, receive-power and IQ gain imbalance over acquisition time for one of in total five range patches. Although the data take has not been acquired during the eclipse it provides an insight into the underlying mechanism causing the described deviations. One can observe that after approximately seven seconds, at the transition between water and land, the power decreases rapidly due to the change in backscatter. At the same time the Q bias increases whereas the I bias stays nearly constant.

This behaviour can be observed in multiple acquisitions and time series for both satellites, particularly if a scene contains larger areas of both high and low backscatter. The sudden change in signal input power level is then dominant

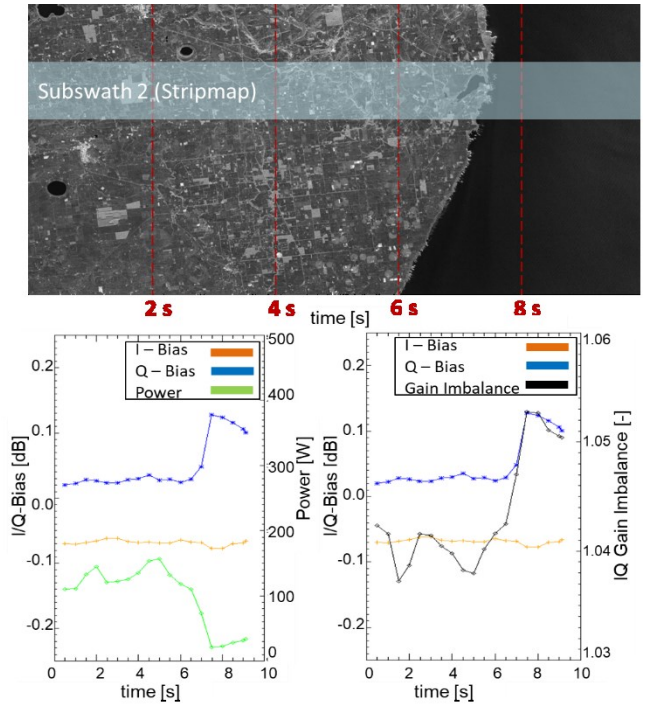


Figure 5: TSX Stripmap image over the south-east Australian coast (top) and corresponding IQ bias with signal echo power (bottom left) and IQ gain imbalance (bottom right) for the second range patch.

towards the overall power level change induced by temperature variations. The explanation that this does not simultaneously affect both channels can be found in the IQ gain imbalance.

IQ gain imbalance is defined as the amplitude mismatch between I and Q channel and occurs due to imperfections in the mixer resulting from amplitude- and phase-impairments between the paths of the local oscillator and from mismatched IQ signal paths after the mixer (see Figure 1) [6]. Looking at Figure 5 one can notice that the imbalance behaves reciprocal to the echo signal power.

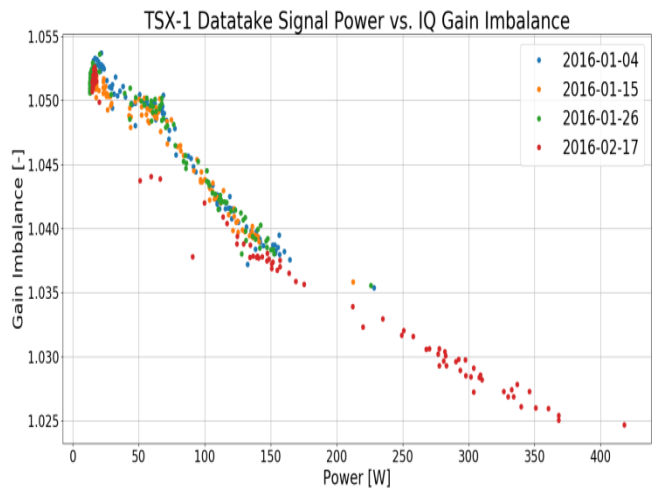


Figure 6: TSX datatake signal power versus IQ gain imbalance for 4 datatakes of a scene at the south-east Australian coast.

Whenever there is a change in backscatter, the IQ gain imbalance changes in the opposite direction resulting in a reversed pattern compared to the signal power. In order to prove this observation the gain imbalance can be plotted against the signal power. Hence Figure 6 displays the correlation between the two by means of four datatakes of the identical scene as shown in Figure 5, underlining the reciprocal behaviour.

This leads to the conclusion that the imbalance between both channels is sensitive to the echo signal power, hence the scene's surface characteristics, which creates a dynamic offset between the channel biases.

The bias of the imbalanced channel (in this case the Q bias) thus appears noisier as the surface backscatter constantly changes. As a consequence the effect of the temperature change due to the eclipse disappears in the respective channels since it is superimposed by the much stronger impact of the scenes surface variations. Figure 7 shows the biases for both spacecraft for every single datatake as well as a ten-day averaged value over a period of two years. One can easily notice the amplitude difference of the different channel outputs resulting from the power sensitive gain imbalance. It becomes apparent how the temperature effect vanishes, in particular after averaging and therefore why the eclipse is visible in only one channel.

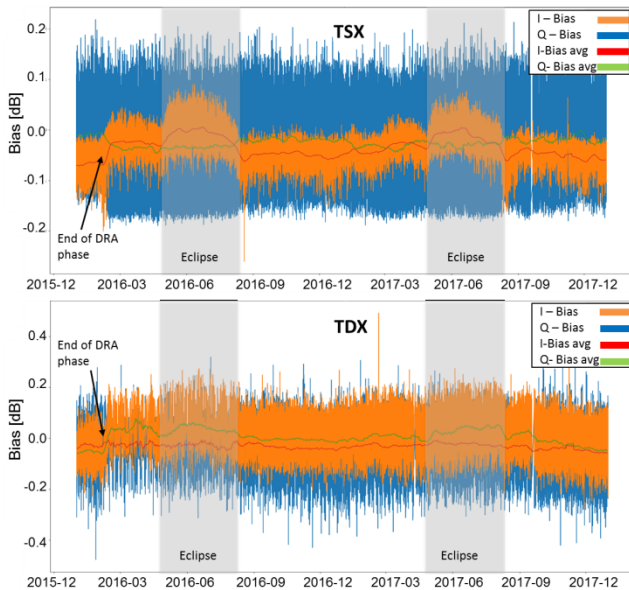


Figure 7: IQ bias for every datatake and as 10-day average for TSX (top) and TDX (bottom)

A further proof to that conclusion is given by the end of the dual receive antenna (DRA) mode in the beginning of 2016. During the operation in DRA mode the antenna was electronically split into two independently operating parts, each using an individual system path [7]. This was realized by activating the redundant chain on both satellites which consequently increased the system temperature. When the redundant chain to support this mode was eventually deactivated, system temperature decreased again thus creating a similar effect to the IQ bias as observed during the eclipse, marked on the left in Figure 7. Also in this case the

temperature effect disappears in one of the channels due to the superimposition caused by the backscatter dependant gain imbalance.

3 Conclusion

Long-term system evaluation of TSX and TDX has shown that thermal changes in the environment of the spacecraft have a visible effect on their electronic systems. A prominent example for such a thermal change is the annual eclipse as the environmental conditions change dramatically between sunlit and shadowed periods. In particular the IQ bias is prevalent in this context as the observed behaviour deviates from the anticipated one within the satellites themselves and also between each satellite. For both problems the analysis results point towards gain imbalances of the mixer within the IQ demodulation block. Furthermore, the deviation in the evolution during eclipse periods has shown to be a consequence of this gain imbalance which will be used for the continuous interpretation of monitoring results of TSX and TDX as well as for future SAR missions.

Since the main cause for the bias deviation is not accessible from long-term data due to averaging, single datatakes and acquisition time series have been analysed. In particular datatakes with a land-water transition were used as they provide a sudden change in receive signal power and thus, as the analysis revealed, also in gain imbalance.

For the current as for future space-borne radar mission the analysis results provide valuable information of the system's environmental interactions. This paper in particular explains the cause for the different IQ channel outputs. However, the reason for the signal power dependency of the gain imbalance is not yet clarified and should be addressed in future research.

4 Literature

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