Radar Instrument Calibration of TerraSAR-X

Benjamin Bräutigam, Jaime Hueso González, Marco Schwerdt, Markus Bachmann
German Aerospace Center (DLR), Microwaves and Radar Institute
Oberpfaffenhofen, D-82234 Wessling, Germany
Tel.: 00498153-283121, Fax: 00498153-281449
Benjamin.Braeutigam@dlr.de

Abstract

TerraSAR-X is a high resolution synthetic aperture radar (SAR) satellite launched in 2007. Its active phased array X-Band antenna hosts 384 transmit/receive modules (TRMs) controlling the beam steering in azimuth and elevation. A calibration network provides monitoring of internal instrument behaviour by introducing additional calibration pulses. Evaluation of calibration pulses for every image acquisition guarantees high radiometric stability of all SAR products. This paper shows the latest in-orbit results of the radar instrument stability and TRM performance. The novel PN Gating method is verified in a spaceborne environment for the first time ever.

1 Introduction

In June 2007, the first German SAR satellite for commercial and scientific applications, TerraSAR-X, was launched. TerraSAR-X is a flexible X-Band SAR operating in Stripmap, Spotlight, ScanSAR, and additional experimental modes [1]. For the various antenna beams, an active phased array antenna electronically shapes the patterns. The array consists of 384 radiating sub-arrays for horizontal and vertical polarisation arranged in a matrix of 12 panels with 32 rows. Active transmit/receive modules (TRMs) individually adjust the array elements in gain and phase for tapering and steering of the antenna pattern in azimuth and elevation direction [2],[3]. An antenna model mathematically describes over 10,000 possible antenna patterns by detailed on-ground measurements of the antenna sub-arrays combined with the applied gain and phase excitations of the TRMs.
In order to keep the SAR performance, following functions are implemented into the TerraSAR-X system:

- **Compensation of Radar Instrument Drift** with the help of internal calibration,
- **Individual T/R Module Characterisation** by using the novel PN Gating method.

Temperature drifts and internal hardware characteristics influence the radar signal path causing gain and phase fluctuation during data acquisition. For monitoring the radar instrument stability, TerraSAR-X hosts an internal calibration facility. Instrument drifts can be calibrated to keep the required radiometric stability. The calibration process depends on the inherent stability of the radar, but also on the accuracy of calibrating systematic errors of the instrument. This paper discusses the actual in-orbit instrument performance with respect to internal calibration accuracy.

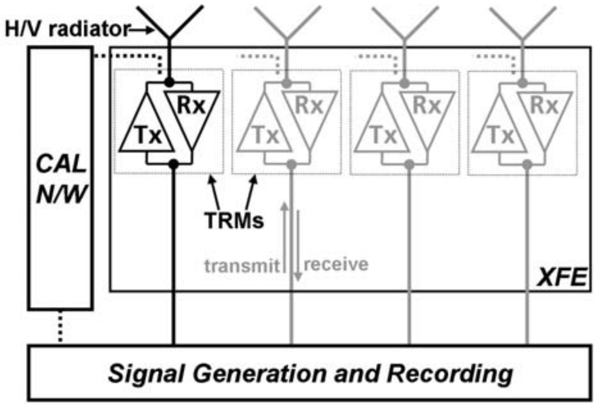

Figure 1 X-Band Front-End (XFE) of TerraSAR-X Radar with 4 of 384 Transmit/Receive Modules (TRMs). The calibration signal is routed via couplers at the TRMs and the calibration network (CAL N/W).

Even though the X-band front-end (XFE) with a large number of TRMs is designed to be insensitive to contingencies like those of individually failed or drifted modules, it is necessary to detect such failures and characterise the TRMs. In the module stepping mode of the ENVISAT ASAR instrument [4], individual measurements on the excitation coefficients of the TRMs are only possible if all modules except the one being characterised are switched off. However, individual measurements of TRMs under most realistic conditions require the same power loads like in the nominal mode with all TRMs operating.
This paper shows the advantages of individual TRM characterisation with the more efficient PN Gating method [5]. For the first time ever, this method is successfully verified and applied to a spaceborne SAR antenna for TRM performance monitoring.

2 Compensation of Radar Instrument Drifts

2.1 Radiometric Stability

TerraSAR-X features an internal calibration network coupling into an additional port of each TRM as shown in **Figure 1**. Calibration pulses are routed through the XFE to characterise critical elements of the transmit (TX) and receive (RX) path. The acquired signals can only be measured at the composite ports of the distribution networks [6]. Three different types of calibration pulses are applied, whereby sets of these pulses are needed at the start and end of each data acquisition. All calibration pulses have the same length and bandwidth as the transmit pulse commanded for the radar mode.

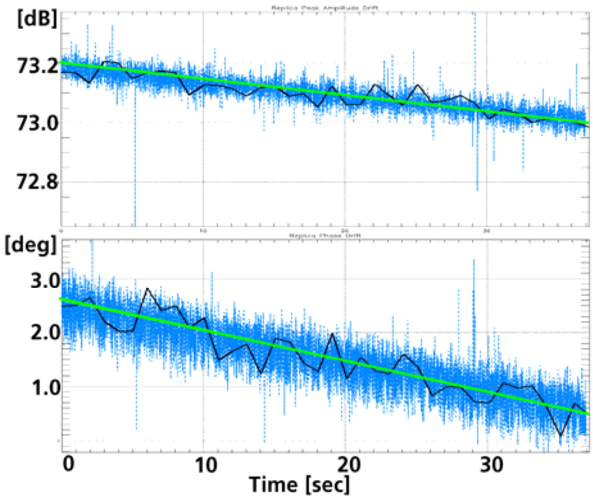

Figure 2 Drift of instrument gain (upper figure) and phase (lower figure) over time in blue. The black curve simulates calibration sequences during acquisition. The green line is a linear fit from start to end calibration sequence.

The calibration pulses are applied to the XFE to characterise the instrument influence on the radar signal. The three types of calibration pulses account for the transmit path, the receive path, and for differences between the routing of the first two pulse types. The acquired signals can be measured at the receiving ports of the distribution networks. Evaluating the amplitude and phase of the calibration signals provides information how to model the instrument drift during data acquisition. Thermal fluctuations as well as internal switching cause variation in gain and phase of the front-end components. This drift is corrected during SAR image processing to obtain high-quality SAR products.
During the first in-orbit check of the internal calibration facility the SAR instrument was operated in nominal mode replacing all imaging pulses with calibration pulses. By this means, the internal instrument drift can be extracted from calibration pulses.

Figure 2 shows the influence of the instrument on the real radar data over time. For a time frame of one minute, the gain drift is about 0.4 dB and the phase drift is less than 6 degrees during nominal SAR operation showing a very stable radar instrument. Applying calibration sequences before, in-between, and after acquisition, the instrument drift can be accurately determined and calibrated. The residual calibration error is very small resulting in less than 0.1 dB in gain and less than 1 degree in phase.

2.2 Compensation of Static Instrument Offsets

All elements not covered by the internal calibration network have to be characterised separately. The antenna radiators are described by a precise antenna model [8]. Instrument components of the radar path are reconstructed from calibration pulses. However the calibration network itself must be well known to compensate its thermal behaviour. Another component to be characterised is the receive signal attenuator that is not varied for calibration pulses but for nominal radar signals.

2.2.1 Temperature Dependent Calibration Network

The insertion loss of the passive calibration network depends on temperature drift. Its behaviour has been characterised on ground. Variation of insertion loss due to different temperatures in the instrument would lead to long-term calibration errors. Thus, a correction in gain has to be applied from data take to data take. The variation inside an acquisition is negligible. The phase of the calibration network during radar operation is constant, too. Hence, phase is no topic of this effect, as only relative variations inside a data take would be of interest.
The relative variation of insertion loss can be more than 0.25 dB from data take to data take (DT), even for a small temperature difference (see **Table 1**). The maximum difference has been found in warm-up tests right after launch. Comparing the first and last DT there is an offset of almost 1 dB that could also be seen in the SAR image's RCS if not corrected. However, it is unlikely for nominal SAR operations to expect much higher or lower temperatures. Thus, the insertion loss variation will be in the order of the values above.
The insertion loss of individual calibration network components is described by polynomials over temperature. The temperature of each component can be read from housekeeping sensors attached at dedicated reference measurement points. The correction is applied to each data take.

Table 1 Calculated insertion loss for data takes (DT) with different temperature loads of the Panel Calibration Network (PCN).

DT Time	Duration	PCN Temperature	Insertion Loss
2007-06-24T 02:45:08	310 sec	+22.5°C	0.0053 dB
2007-06-24 22:47:22	4 sec	+1.91°C	0.7298 dB
2007-07-07 05:26:15	10 sec	-0.73°C	0.8758 dB
2007-07-10 16:51:12	8 sec	-3.54°C	0.9856 dB
2007-07-15 16:59:44	9 sec	-3.69°C	0.9919 dB

For the absolute radiometric accuracy of TerraSAR-X it is necessary to determine the absolute calibration factor including this correction [7]. Finally, temperature variations of the passive calibration network have no more influence.

2.2.2 Attenuator Setting Accuracy

The received radar signal is adjusted by a variable attenuator that is used to control the input amplitude to the dynamic range of the Analog-to-Digital Converter (ADC). Consequently, clipping or quantisation noise can be avoided. Attenuation values from 0 dB to 30 dB in steps of 2 dB within the same data take account for the expected reception power level of the radar echoes.

This variable signal attenuator of the SAR instrument introduces some inaccuracies in the amplitude and phase of the received signal that are not cancelled out by means of internal calibration. Nominally, the calibration pulses are recorded with a constant attenuation value to achieve best SNR at the receiver input.

Characterisation of the real attenuator settings is derived by applying calibration pulses for all attenuation steps while keeping the rest of the chain elements constant. The dynamic range of accurate calibration pulses is 20 dB. Thus, two in-flight measurements with different pre-amplification (10 dB and 20 dB) are necessary to avoid low SNR of high attenuation values and the clipping of all low attenuation values.

Adequate combining of both measurement results offers valid information over the whole attenuation setting range. The overlap region of useful data from attenuation values of 12 dB to 20 dB confirms the validity of the actual settings (see **Figure 3**). The final error curve allows to correct the errors motivated by the receive signal attenuator. Within a data take, a change between attenuation values causes maximum relative errors of 0.4 dB in amplitude and 5 degrees in phase. The deviations are now calibrated by the final error correction curves that have been characterised from in-orbit calibration pulses.

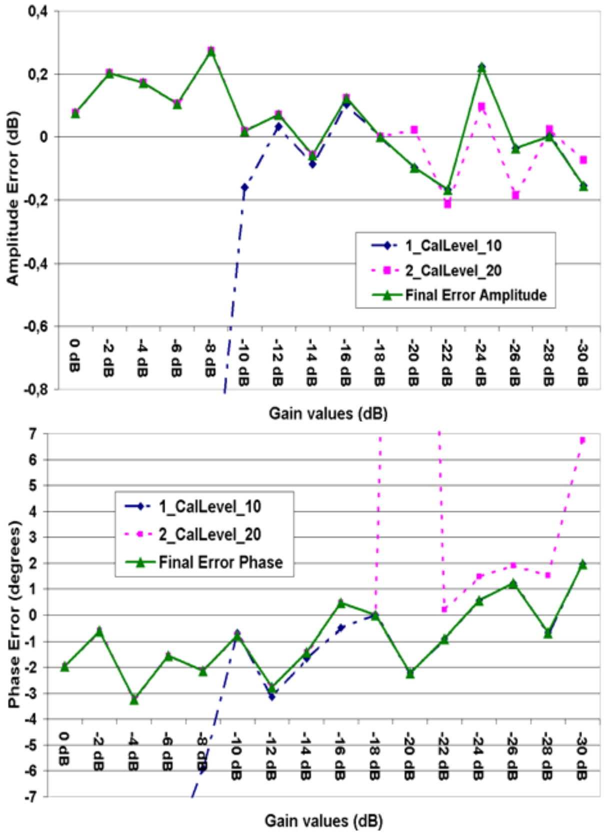

Figure 3 Correction curves from attenuator measurements with calibration pulses. For low pre-amplification (Cal Level_10) only the high attenuation range (negative gain higher than -10 dB) is valid; for high pre-amplification (Cal Level_20) only the low attenuation range (negative gain below -20 dB) is valid. The final error correction curve is derived from an adequate combination of both measurements.

3 Individual T/R Module Characterisation

Apart from measuring the stability of the instrument it is necessary to retrieve information on the performance of individual transmit/receive modules (TRMs). Tapering and steering of the antenna beam depends on the beam excitation coefficients defining gain and phase of the TRMs. The actual status of TRM setting has to be known, especially considering performance degradation or malfunction. The actual settings are fed into the antenna model to derive the real antenna patterns [8].

A detailed analysis of individual TRMs within an active phased array antenna is based on the PN Gating method developed at the German Aerospace Center (DLR) [5]. Compared to the module stepping mode of ENVISAT ASAR the advantage of this technique is that individual TRMs are characterised while all modules are operating, i.e. a characterisation under the most realistic conditions.

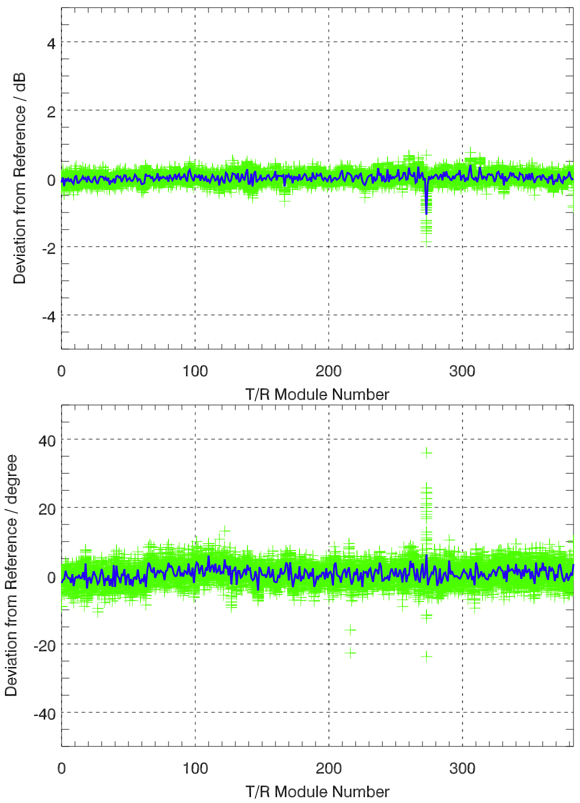

Figure 4 First 42 TerraSAR-X in-orbit measurements of individual TRMs. Upper figure shows TX gain in dB, lower figure shows TX phase in degree. The crosses mark the single data sets. The blue line is a fit over all measurements.

In this special characterisation mode the actual phase of each TRM is individually shifted by ±90 degrees from pulse to pulse according to a defined code sequence. Consequently, the superposition of all TRM gains and phases at the composite port of the distribution network yields the composite signal. To extract the information for one TRM the composite signal is correlated with the corresponding code sequence providing the estimated gain and phase setting of this module.

In **Figure 4** all in-orbit PN Gating measurements during the five months TerraSAR-X commissioning phase are plotted. The measurements have been referenced to on-ground tests with the same configuration. Green crosses mark the evaluated transmit gain and phase values of 42 different measurements. All of them are in the same range as well as there is no absolute offset to the reference data. The blue line is a fit over all data acquisitions showing a stable antenna performance. It has to be mentioned, that one TRM was detected to be switched off already before launch. It was analysed that the performance degradation of one TRM being switched off is negligible.

These measurements prove the successful implementation and verification of the Individual TRM Characterisation Method into TerraSAR-X with an accuracy of better than 0.2 dB in gain and 2 degrees in phase for TRM setting determination.

4 Summary

TerraSAR-X produced its first operational SAR image already four days after launch. The processing inherently accounts for internal calibration sequences within the data take to provide a high-quality product better than the required radiometric stability. Besides nominal calibration with calibration pulses, the internal calibration network provides direct monitoring of the radar instrument performance. The instrument drift can be derived and compensated with a calibration accuracy of better than 0.1 dB for gain and 1 degree in phase. The influence of other static instrument components can be compensated, too.

The presented TRM characterisation method based on the novel PN Gating technique has become a valuable diagnostic tool during satellite operation for fast and realistic TRM performance checks. The results from repeated in-orbit measurements prove the high reliability of the PN Gating method better than 0.2 dB for amplitude and 2 degree for phase estimation. The presented internal calibration facility ensures excellent instrument performance even for degraded transmit/receive modules. The calibration techniques described in this paper are also applicable for characterisation and calibration of other advanced sensor systems coping with active phased array antennas.

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