This paper proposes an analytical formulation of the instrumental errors in multilevel hierarchic SAR architecture equipped with active phased array antennas. The basis of the study is the derivation of the so-called post-calibration errors, which remain as residual error contributions after the application of a dedicated internal calibration procedure. The limitations of the current internal calibration approaches for the state-of-the-art space-borne SAR missions are analyzed and alternative internal global calibration strategies are proposed to reduce the impact of the post-calibration error. Numerical simulations of instrumental errors are presented to evaluate the different proposed calibration procedures.

**ABSTRACT**

This paper proposes an analytical formulation of the instrumental errors in multilevel hierarchic SAR architecture equipped with active phased array antennas. The basis of the study is the derivation of the so-called post-calibration errors, which remain as residual error contributions after the application of a dedicated internal calibration procedure. The limitations of the current internal calibration approaches for the state-of-the-art space-borne SAR missions are analyzed and alternative internal global calibration strategies are proposed to reduce the impact of the post-calibration error. Numerical simulations of instrumental errors are presented to evaluate the different proposed calibration procedures.

**Index Terms**— Synthetic Aperture Radars (SAR), Active Phased Array Antennas (APAA), Internal Calibration (IC)

1. INTRODUCTION

The state-of-the-art space-borne (SBR) synthetic aperture radar (SAR) missions as TerraSAR-X [1], TanDEM-X [2], RADARSAT-2 [3] and the future Spanish SEOSAR/PAZ mission [4], are equipped with active phased array antennas (APAA), which allow a high degree of flexibility from the operational point based on Transmit Receive Modules (TRMs) control. TerraSAR-X, TanDEM-X and SEOSAR/PAZ carry similar strategies in order to achieve an efficient and affordable calibration [1, 2]. The calibration procedure is mainly based on the use of on-ground characterization data, an accurate antenna model, an in-flight internal characterization and calibration data with additional in-flight verifications obtained during the commissioning phase.

This paper focuses on the impact of the internal calibrations assumed in the actual space-borne SAR missions, based on series of pulses routed through the instrument signal path.

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2. ERROR FORMULATION: POST-CALIBRATION ERRORS

The error formulation is considered for the internal calibration procedure used in TerraSAR-X [1] and SEOSAR/PAZ [4], which is based on series of pulses: P1 to characterize the transmit (TX) path, P2 the receive (RX) path and P3 monitors the central electronics and the auxiliary TX/RX ports, applying unitary weights on the TRMs during calibration.

When considering a point target observed with the spherical coordinates $\theta_t$ and $\phi_t$ (referred to the antenna plane in Fig. 1) at the $t$-th acquisition time, the received signal after internal calibration $s_{\text{cal}}(t)$ can be expressed as in (1). The total number of TRMs in the planar array configuration is $N = N_{\text{row}} \cdot N_{\text{col}}$. The impact of the $i$-th subarray or basic element of the array is represented by $S_A^{\theta_t,\phi_t}$ and it is assumed identical for the set of $N$ subarrays (also in terms of frequency response). The complex effective excitations of the $i$-th TRM are described...
\[ s_{\text{cal}} = \frac{\sum_{i=1}^{N} S A_i^{\theta_t, \phi_t, \theta_i, \phi_i} g_{\text{TX}}^i e_{\text{TX}_i}}{\sum_{i=1}^{N} g_{\text{calTX}_i} c_{\text{TX}_i}} \sum_{i=1}^{N} S A_i^{\theta_t, \phi_t, \theta_i, \phi_i} g_{\text{RX}_i} c_{\text{RX}_i} = \frac{\sum_{i=1}^{N} S A_i^{\theta_t, \phi_t} g_{\text{TX}}^i e_{\text{TX}_i} \sum_{i=1}^{N} S A_i^{\theta_t, \phi_t} g_{\text{RX}_i}}{\sum_{i=1}^{N} g_{\text{calTX}_i} \sum_{i=1}^{N} g_{\text{calRX}_i}} (1 + e_{2-\omega}) \] (1)

\[ e_{2-\omega} \approx \frac{\sum_{i=1}^{N} g_{\text{TX}}^i (\theta_t, \phi_t) e_{\text{TX}_i}}{\sum_{i=1}^{N} g_{\text{TX}_i} (\theta_t, \phi_t)} + \frac{\sum_{i=1}^{N} g_{\text{RX}}^i (\theta_t, \phi_t) e_{\text{RX}_i}}{\sum_{i=1}^{N} g_{\text{RX}_i} (\theta_t, \phi_t)} + \frac{\sum_{i=1}^{N} g_{\text{TX}}^i (\theta_t, \phi_t) e_{\text{RX}_i}}{\sum_{i=1}^{N} g_{\text{RX}_i} (\theta_t, \phi_t)} \] (2)

3. CALIBRATION STRATEGIES

From the formulation presented in (1), the post-calibration error becomes zero when the effective operational excitations are coincident with the calibration weights, assuming equal subarray patterns for the \( N \) elements of the array. In case of calibrating with unitary excitations (broadside calibration beam), the calibration procedure is error-free just for those beams with no tapering and for targets located at the beam-center. This can be also justified from the formulation derived in (2), such that the beams with lower orthogonal component (w.r.t unitary calibration weights) of their effective excitations will present a lower residual post-calibration error. These considerations suggest the opportunity to propose alternative calibration strategies in order to reduce the impact of such a residual error.

3.1. Calibration with operational excitations

Since the residual post-calibration error arises from the fact that differences between the operational and calibration excitations exist, the first alternative approach is to set the operational weights on the different TRM during the internal calibration procedure, both in transmission and reception. In this case the excitations correspond to the operational ones except for the linear phase term that steers the beam (in elevation) from broadside. This latter term depends on the position of the subarray in the planar array and the DOA corresponding to the beam-center position.

3.2. Beam calibration

As expected, simulations show that the calibration proposed in section 3.1 is accurate at beam-center for the different set of operational beams (covering different incidence angles). Thus, this calibration provides a qualitative improvement just for a specific part of the imaged scene in terms of post-calibration error reduction. In this sense an alternative calibration strategy is proposed, such that the impact of the residual post-calibration error is minimized according to the portion of the observed scene in the range dimension (related to the elevation dimension).

For this strategy, the calibration measurements, which are
obtained by means of specific calibration pulses (P1, P2 and P3) routed through the instrument path, can be extended to carry out a range/elevation dependent measurement. From the operational point of view, during the internal calibration measurement the different set of TRMs are loaded with the operational excitations with the adequate linear phase term related to the range line to be further calibrated. These calibration measurements can be repeated for different linear phase variations to sweep the swath of interest minimizing the number of measures. In the approach here presented five different calibration measures have been performed: near, far edges as well as center of the swath, and middle point positions (at both sides of beam center) between edges and beam center. Then, this (range/elevation dependent) information is interpolated to calibrate the whole imaged swath.

4. NUMERICAL SIMULATIONS

The impact of a TRM setting error has been evaluated for the different calibration strategies in terms of relative accuracy, understood as the standard deviation of the measured radar cross section (RCS) of a point target within the scene (spatial radiometric variation); and radiometric stability, as the standard deviation of the RCS for a fixed point in the scene for different data takes (temporal radiometric variability).

Assuming saturated operation of the TRM power amplifiers in transmission, the source error has been modeled as a zero-mean Gaussian process with a standard deviation of 0.5 dB (RX) and 5.0 degrees (TX, RX). The number of rows and columns of the APAA are \(N_{\text{row}} = 32\) and \(N_{\text{col}} = 12\). The number of trials for numerical simulation is 1000. In the computation of the accuracy impact (spatial deviation) a set of 101 range lines have been considered in the simulations. In the case of stability different results are represented: worst case and mean value over the different set of 101 range lines, and the results for a location at the near and far edges as well as beam center are also considered. The different errors have been integrated during the formation of the synthetic aperture (within the -3 dB azimuth one-way beamwidth).

The residual two-way error impact on the relative accuracy and stability for the different calibration strategies is represented in Fig. 2. The beam labeled as 0 correspond to unitary excitations (broadside calibration) used in the conventional calibration. As observed in Fig. 2(a) and (b), the set of beams labeled from 1 to 6 have higher error impact due to the phase spoiling used in transmission, which induces a higher level of orthogonality\(^1\) as represented by the dashed (TX) and dotted (RX) lines in Fig. 2(a). When calibrating with operational excitations (except for the linear phase to steer the beam), the radiometric accuracy is kept similar, Fig. 2(c), while a clear improvement is obtained in terms of stability for the beam-center location of the swath and small improvement in terms of mean value, see Fig. 2(d). The worst case impact on stability follows a similar trend to the conventional approach, being the edges of the beam the terms that limit the performance. From these considerations, a beam calibration strategy is carried out, i.e. performing a range dependent calibration measurement with five measures and interpolating this information to cover the set of range lines within the swath. In this case the residual error impact on both accuracy and stability terms decreases to negligible values, see Fig. 2(e)-(f), with a reduction of two orders of magnitude compared to the conventional and operation calibrations.

5. CONCLUSIONS

A new formulation of the instrumental errors in SAR sensors with active phased array antennas has been presented, which considers the residual post-calibration error. Two alternative calibration strategies based on pulse routing through the instrument path have been proposed, one considering operational excitations on the TRMs during calibration and a second approach providing an elevation/range dependent calibration. Both have been compared to the conventional approach with unitary calibration excitations, leading to improved results, negligible error impact in the case of the second alternative calibration.

6. REFERENCES


\(^1\)The orthogonality is represented as a mean value of the orthogonal vector’s norm over different range lines and normalized by the norm of the broadside calibration beam.
Fig. 2. Impact of the residual TRM setting error in terms of relative accuracy and radiometric stability when calibrating with broadside beam (unitary excitations) (a), where TX/RX orthogonality is also shown, and (b); with operational excitations (except a linear phase to steer the beam) (c), broadside calibration is superimposed, and (d); and an elevation dependent calibration (beam calibration) (e) and (f). In all cases error integration during the synthetic aperture formation is considered.