

Impact of the Ionosphere on the External Calibration of ESA's ROSE-L System

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Abstract

The Radar Observing System for Europe L-band SAR (ROSE-L) is an upcoming ESA mission within its Copernicus program. It will expand the program with a fully polarimetric L-band SAR system. The external end-to-end calibration of the SAR system encounters notable challenges due to the propagation effects at L-band including Faraday rotation and ionospheric delay. Due to early availability of a prototype calibration transponder for ROSE-L, the impact of the ionosphere can already be analyzed using other existing L-band sensors like ALSO-2, SAOCOM-1, and NISAR. This allows to test the calibration under realistic conditions already well before the launch of ROSE-L and draw valuable conclusions for the in-orbit calibration activities.

1 Introduction

Compared to previous European systems, such as Sentinel-1 [1], [2], [3] and TerraSAR-X [4], the calibration of the ROSE-L SAR system will present new challenges. The L-band's relatively low frequency is associated with a long wavelength, requiring most RF components to be scaled accordingly. This scaling also applies to reference targets used for external calibration, such as trihedral corner reflectors. However, the physical dimensions of these passive reference targets are limited by practical considerations, including available manufacturing equipment, accuracy, cost, and transportation restrictions on roads. Therefore, active targets, such as transponders and PARCs (polarimetric active radar calibrators) [5], [6], play an important role in the ROSE-L calibration strategy.

1.1 Challenges in the Calibration of ROSE-L

At the L-band, ionospheric propagation effects are prominent and impact geometric and radiometric calibration. These effects include additional range delays related to the total electron count (TEC) along the propagation path and azimuth shifts caused by TEC gradients along the satellite's flight path [7]. Faraday rotation, which is caused by the interaction of the radar pulse with free electrons in the ionosphere and the Earth's magnetic field, induces changes in the polarization of linearly polarized waves. This affects the polarimetric SAR performance.

In this paper, we address the in-orbit calibration tasks most affected by the ionosphere and present approaches to mitigate its impact. We will examine the

- geometric calibration, which is affected by range shifts due to TEC and azimuth shifts due to TEC gradients along the azimuth,
- radiometric calibration, which is affected by Faraday rotation, which shifts energy between polarimetric channels, and

- polarimetric calibration, that needs to separate Faraday rotation from polarimetric channel imbalance and crosstalk.

To analyze the impact of the ionosphere in L-band, we will use data acquired by SAOCOM-1 and ALOS-2 over the DLR calibration field. SAOCOM acquisitions are performed in dual-polarization stripmap mode on a dawn-dusk orbit, while ALOS acquisitions are performed in quad-polarization stripmap mode at approximately midnight and noon. NASA/JPL also commanded some quad-polarization data takes for NISAR in staggered and non-staggered PRI mode over the PARC.

2 Geometric Calibration

Geometric calibration involves assigning pixels in the SAR image to geographic coordinates. This is achieved by extracting the precise sub-pixel position of the impulse response from strong point targets whose locations are well known. Thus, the accuracy of the calibration mainly depends on the accuracy with which the impulse response function (IRF) position is extracted from the SAR image, the geo-location accuracy of the reference target, and the knowledge accuracy of the satellite's orbit.

The pixel accuracy is defined by the signal-to-clutter ratio (SCR) as described in [8]:

$$\sigma = \frac{\sqrt{3}}{\pi \cdot \sqrt{2}} \cdot \frac{1}{\sqrt{SCR}}$$

The knowledge of the reference target's geodetic position is determined by the surveying accuracy. Experience shows that an accuracy below 5 cm can be achieved for a measurement using differential GNSS (Global Navigation Satellite Systems).

For the ROSE-L case, the SCR is the limiting factor, driven by the achievable radar cross section (RCS), and, thus the size of the passive target. Tests with ALOS-2 and SAOCOM-1 demonstrate that 2.8 meters trihedral triangular corner reflectors (those used for Sentinel-1) can achieve an SCR of approximately 25 dB. This results in

0.02 pixels accuracy, or 11 centimeters, for the best ROSE-L resolution of 5 meters.

Due to the PARC's higher RCS (see Figure 1), an SCR greater than 50 dB can be achieved. Under the same conditions, this results in an error of only 0.001 pixels, or 6 millimeters. However, predicting the IRF position of a PARC in the SAR image requires considering its electronic delay. The ROSE-L PARC can measure this delay with an accuracy of about 10 ps or 3 mm using its internal calibration facility. Offsets of cables and antennas not covered by the calibration loop can be calibrated with an accuracy of a few centimeters. DLR has demonstrated that geometric calibration of less than 10 cm can be performed with TerraSAR-X in the X-band. Similar PARC accuracies are expected for the L-band.

In addition to the measurement accuracy, geometric calibration is affected by an additional delay in the ionosphere that is proportional to the total electron count (TEC) along the propagation path. If the TEC value changes along the flight direction, an additional time and phase delay is introduced. The linear component of this phase change is indistinguishable from a Doppler shift during SAR processing. This results in an azimuth shift of the target in the final SAR image.

To mitigate the impact of the ionosphere on the external calibration of ROSE-L information about the state of the ionosphere is required. Permanent GNSS stations provide valuable information about the ionosphere, and maps of TEC values are operationally available e.g., from [9]. Therefore, the calibration site for ROSE-L will be established in Central Europe, a region where good ionospheric measurements are available and the effects of the ionosphere are well understood.

Measurements taken during a solar maximum in the years 2024-2025 show a standard deviation of the range shift of less than 0.6 m after TEC correction and 1 m along azimuth without any TEC gradient correction.



Figure 1: DLR's novel dual L- and X-band calibration PARC designed for ROSE-L.

3 Radiometric Calibration

According to ITU-R P.531-14 [10], Chapter 6, absorption in the ionosphere is below 0.01 dB at mid-latitudes for ROSE-L frequencies and can therefore be disregarded.

Although no energy is lost, it shifts between polarimetric channels due to Faraday rotation. For a single polarimetric channel, e.g. HH, the energy transmitted in horizontal polarization shifts to vertical polarizations on the transmit path. Consequently, less energy is received at the ground target in horizontal polarization. Similarly, the energy scattered back in horizontal polarization is affected by Faraday rotation and shifts to vertical polarization. Consequently, the measured energies differ from what would be expected in the absence of Faraday rotation.

To mitigate this effect of Faraday rotation, the combined image energy in horizontal and vertical polarizations is used as a reference for radiometric calibration.

$$I_H = I_{HH} + I_{VH} \quad (1)$$

$$I_V = I_{VV} + I_{HV}, \quad (2)$$

where I is the target IRF energy in the SAR image, and the polarization indices reflect the mathematical convention of receiving polarization first and transmitting polarization second. For instance, the reference energy in the horizontal polarization, eq. (1), is defined as the total energy received in the horizontal and vertical polarizations when the horizontal polarization is transmitted.

This approach decouples radiometric calibration from polarimetric calibration. Indeed, compensation for potential polarimetric channel imbalance, as determined during polarimetric calibration, must be performed in a manner that preserves the total energy of eq. (1) and eq. (2), which is generally easy to accomplish.

4 Polarimetric Calibration

During the commissioning phase, when the SAR system has not yet been calibrated, some commonly used assumptions, such as scattering symmetry $S_{HV}=S_{VH}$ (e.g. used by Bickel and Bates [11]), will not necessarily hold. These assumptions are often used to distinguish Faraday rotation from other system effects, such as channel imbalances (in amplitude and phase) or the impact of limited cross-polar isolation.

For the polarimetric calibration of ROSE-L, the algorithm designed by Chen et al. [12], [13], which is also employed by ESA's BIOMASS mission, is used. Therefore, a calibration transponder that can generate four polarimetric signatures, namely, $\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$ in a single SAR image has been developed. The prototype was deployed in fall 2023 at the DLR premises in Oberpfaffenhofen (see Figure 1). Tests with SAOCOM-1 and ALOS-2 have proven the concept, and test data has been collected since then (see Figure 2). This allows DLR to test the calibration algorithms already well before the launch of ROSE-L.

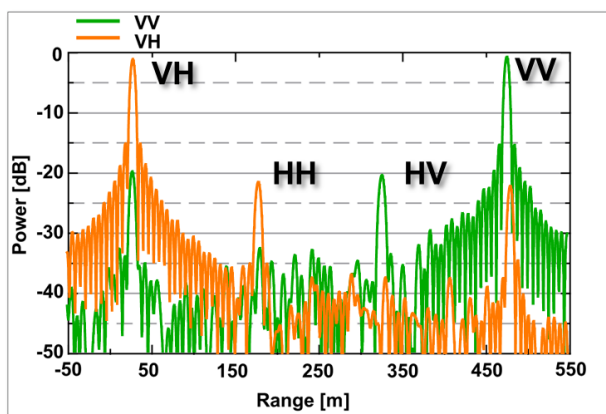


Figure 2: IRFs of four targets (VH, HH, HV, VV) generated by DLR's transponder along range. Data is extracted from a dual-pol SAOCOM L1 Product® (©CONAE – 2024. All Rights Reserved).

5 Summary

Although disturbances due to the ionosphere present challenges for the external calibration of ROSE-L, promising concepts have been developed for all aspects of external end-to-end SAR calibration of the ROSE-L system. The early availability of a prototype calibration transponder enables testing of many calibration algorithms under realistic conditions. This enables DLR to improve the calibration accuracy and limit expected uncertainties, as the test conditions are already nearly identical to those expected during the upcoming commissioning phase. In fact, the current tests are being conducted during a solar maximum, when more challenging ionospheric conditions are expected than during the ROSE-L's commission phase.

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7 Literature

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