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Research Article

Fine-Resolution Polsar Data Analysis with Compensation Theory for Improved Interpretation

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ABSTRACT

Polarimetric Synthetic Aperture Radar (PolSAR) imaging is a powerful tool for analysing mechanisms of surface scattering, but its accuracy is often compromised by Polarization Orientation Angle (POA) shift. The POA shift occurs due to terrain slopes, vegetation structures, built-up and other structural features, alters scattering mechanisms, and affects decomposition-based analysis. This study used the Yamaguchi four-component decomposition model to investigate the impact of POA shift on EOS-04 (RISAT-1A) Fine Quad-Polarization data, acquired over Nashik District, Maharashtra, India. The investigation was performed before and after POA correction to analyze changes in even-bounce, odd-bounce, and volume scattering components. The statistical and histogram results show that without POA correction, volume scattering was exaggerated while double-bounce scattering was underestimated, resulting in inaccuracies in land cover classification and urban mapping. POA correction enhanced classification accuracy and enabled more reliable identification of scattering parameters. This demonstrates the potential of EOS-04 dataset and also importance of applying POA correction to PolSAR data during the preprocessing stage to obtain more accurate decomposition results, more precise geophysical parameters, and reliable land cover classification.

Keywords: EOS-04, PolSAR, POA shift, Yamaguchi decomposition, POA compensation

INTRODUCTION

The Synthetic Aperture Radar (SAR) system operates by transmitting microwave pulses toward a target area and receiving the backscattered signals, which carry information about the strength and location of the objects. It operates within the electromagnetic spectrum range of approximately 1 mm to 1 m. Since microwaves can penetrate through clouds, SAR can acquire images under any weather conditions, both day and night[1]. It can also penetrate the dielectric medium and is highly sensitive to the dielectric properties of the surface[2], [3], [4]. Polarimetric Synthetic Aperture Radar (PolSAR) imaging is a powerful tool for analyzing earth observation[5]and environmental monitoring due to its ability to characterize surface features through different scattering mechanisms[6], [7], [8], [9]. When a polarized radar wave interacts with the earth surface, the polarization of the wave is modified based on the surface's specific characteristics. These include geometric structure, shape, reflectivity, orientation, and geophysical properties such as moisture content and surface roughness, etc, [10].
In real situations, PolSAR accuracy is often impacted by Polarization Orientation Angle (POA) shift and this shift occurs due to the presence of uneven or tilted surfaces like hills, rooftops, or rugged terrain, built-up environments, and vegetation structures. These features introduce a shift in the Polarization Orientation Angle, which effectively rotates the polarization basis and alters the scattering response of the observed targets. This shift happens because the electric field vectors, particularly the horizontal component, are no longer aligned as expected. Ideally, in flat terrain, the horizontal electric field of radar waves runs parallel to the plane of incidence and keeps a perpendicular relationship with the vertical component. But on sloped or uneven surfaces, this balance is disturbed. The horizontal polarization vector no longer aligns with the ground, and the orthogonality between horizontal and vertical polarizations breaks down [11]. This disturbance causes a shift in the Polarization Orientation Angle (POA).

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The shift can be understood visually using the polarization ellipse, which shows how the wave's orientation rotates relative to the radar's line of sight [9]. Numerous polarimetric decomposition techniques have been proposed built upon simplified scattering models for better understanding, and extracting useful information about surface characteristics from radar data, [12], [13], [14], [15], [16], [17]. The POA rotation leads to significant misinterpretation in polarimetric decomposition results, especially in model-based decompositions such as Freeman–Durden or Yamaguchi [9], [18] and misinterpretation of the scattering behaviour, especially in areas with complex topography. If the POA shift is not corrected, it commonly causes radar data to misrepresent surface features, volume scattering appears stronger than it is, while double-bounce signals are weakened. This misinterpretation reduces the reliability of land cover classification and makes it difficult to identify key geophysical features [8], [19].

Prominent features such as large building blocks and dense infrastructure contribute to complex urban scattering mechanisms, including double-bounce, helix, and wire-type reflections, which are particularly sensitive to orientation effects. To reduce these effects, several POA estimation techniques have been proposed [20], and the most effective one method is the circular polarization method. POA compensation techniques have been implemented for the estimation and correction of the orientation angle before decomposition is applied. This pre-processing step involves rotating the coherency or covariance matrices to realign them with the radar LOS, thereby restoring the physical integrity of scattering parameters [8]. Numerous studies, including the work by [21],have shown that such compensation significantly improves interpretation accuracy, particularly in urban and mountainous regions. This study focuses on evaluating the impact of POA shift and its correction on the EOS-04 (RISAT-1A) Fine Quad-Polarization data acquired over Nashik District in Maharashtra, India. We use the Yamaguchi four-component decomposition model to analyze the scattering behavior changes before and after applying POA correction. The focus is on how this correction influences the surface (single-bounce), double-bounce, and volume scattering components in the radar imagery.

STUDY AREA AND DATASET

The study was conducted over Nashik district in Maharashtra, India, a region selected for its diverse land cover types and moderately varying topography. Figure 1 shows the selected study area, which includes a mix of urban settlements, agricultural fields, and open terrain conditions that make it ideal for investigating the impact of Polarimetric Orientation Angle (POA) shift in SAR data.

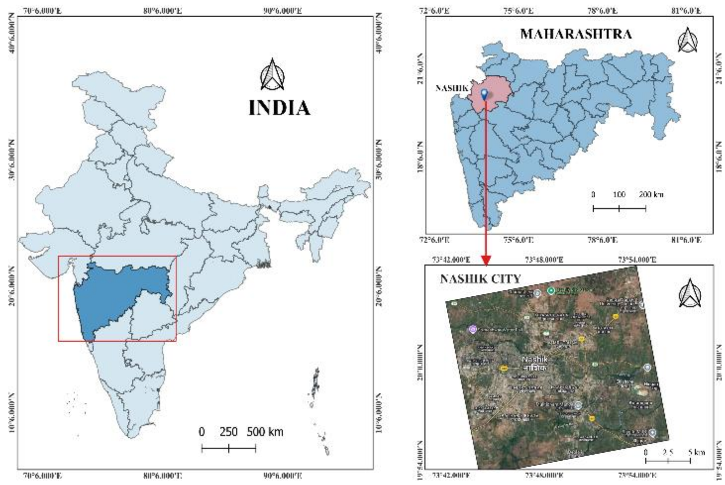

Figure 1 Study Area over Nashik District, Maharashtra, India

The dataset used in this study is a fully Polarimetric Single Look Complex (SLC) image acquired by the EOS-04 (RISAT-1A) satellite on February 29, 2024. The data was captured in Fine Resolution Strip map (FRS-1) mode using the C-band microwave frequency (5.4 GHz), which is well-suited for vegetation, surface, and structural backscatter analysis. The scene covers an area between approximately 19.90° to 19.99°N latitude and 73.80° to 73.87°E longitude, with a long swath width. It provides a spatial resolution of 2.4 meters in range and 3.0 meters in azimuth, and spans an incidence angle range from 26.2° to 28.3°. The slant-range SLC format of the data is ideal for advanced

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PolSAR techniques, especially for focusing on polarimetric orientation angle (POA) shift analysis and compensation, which are central to this research.

METHODOLOGY

The methodology implemented in this study is designed to assess the influence of POA shift and its correction on PolSAR image interpretation. The process involves several key stages, begins with the acquisition of fully polarimetric EOS-04 (RISAT-1A) SAR data in FRS-1 mode. The data undergoes radiometric calibration and speckle filtering, followed by scattering matrix extraction. The coherency matrix (T3) is then generated using Pauli basis representation. Figure 2, shows the flowchart outlining the main steps of the procedure.
The POA shift is estimated using the circular polarization method [22]. To correct this, a unitary rotation matrix is applied to each pixel's T3, resulting in a deoriented matrix. This is then subjected to Yamaguchi four-component decomposition, separating the scattering into surface, even-bounce, volume, and helix components. A comparative scattering power analysis before and after deorientation highlights the impact of POA correction, followed by final result interpretation through visual and statistical evaluation.

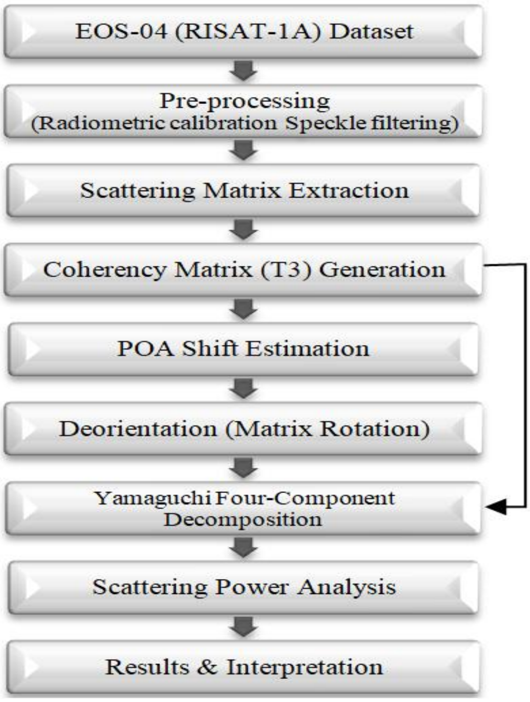

Figure 2 Schematic Representation of the Methodology

RESULT AND DISCUSSION

The EOS-04 (RISAT-1A) Fine Quad-polarization dataset was first pre-processed using standard SAR processing tools. This included radiometric calibration, speckle filtering, and geometric correction to ensure consistency across polarization channels [23]. The scattering matrix elements S_{HH}, S_{HV}, S_{VH}, and S_{VV} were extracted and utilized to construct the Pauli vector representation.

$$S = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \quad (1)$$

Using the Pauli vector, the T3 coherency matrix was computed for each pixel. This matrix encapsulates the polarimetric characteristics of the backscattered signals and provides a foundation for both orientation angle estimation and subsequent decomposition.

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$$T = \frac{1}{2}\begin{bmatrix} |S_{HH}+S_{VV}|^2 & (S_{HH}+S_{VV})(S_{HH}-S_{VV})^* & 2(S_{HH}+S_{VV})S^*_{HV} \\ (S_{HH}+S_{VV})^*(S_{HH}-S_{VV}) & |S_{HH}-S_{VV}|^2 & 2(S_{HH}-S_{VV})S^*_{HV} \\ 2(S_{HH}+S_{VV})^*S_{HV} & 2(S_{HH}-S_{VV})^*S_{HV} & 4|S_{HV}|^2 \end{bmatrix} \tag{2}$$

In Polarimetric SAR (PolSAR) data, variations in polarization orientation angle (POA) often arise due to terrain slope, building orientation, or random alignment of scatterers like forest canopies. These shifts can significantly affect decomposition results, particularly the estimation of volume scattering. To address this, the deorientation process was applied to remove orientation effects and standardize the Polarimetric response across the region of interest. The POA was estimated using the real and imaginary components of the off-diagonal elements of the T3 matrix, as given by the expression:

$$\theta = \frac{1}{4}\left[\tan^{-1}\left(\frac{-4Re((S_{HH}-S_{VV})S^*{}_{HV})}{-|S_{HH}-S_{VV}|^2+4|S_{HV}|^2}\right)+\pi\right] \tag{3}$$

Where, θ is the shift in orientation angle.

To correct for the POA shift, a unitary rotation matrix R(θ) was applied to each pixel's T3 matrix, resulting in the compensated matrix T3′, as defined in Equation (4).

$$T3' = [R(\theta)][T3][R(\theta)^T] \tag{4}$$

$$R(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos 2\theta & \sin 2\theta \\ 0 & -\sin 2\theta & \cos 2\theta \end{bmatrix} \tag{5}$$

This matrix realigns the polarization basis with the radar line-of-sight, eliminating the distortion caused by tilted surfaces. The deoriented matrices were verified for consistency by recalculating the POA, which showed a significant reduction after correction, as shown in Figure 3.

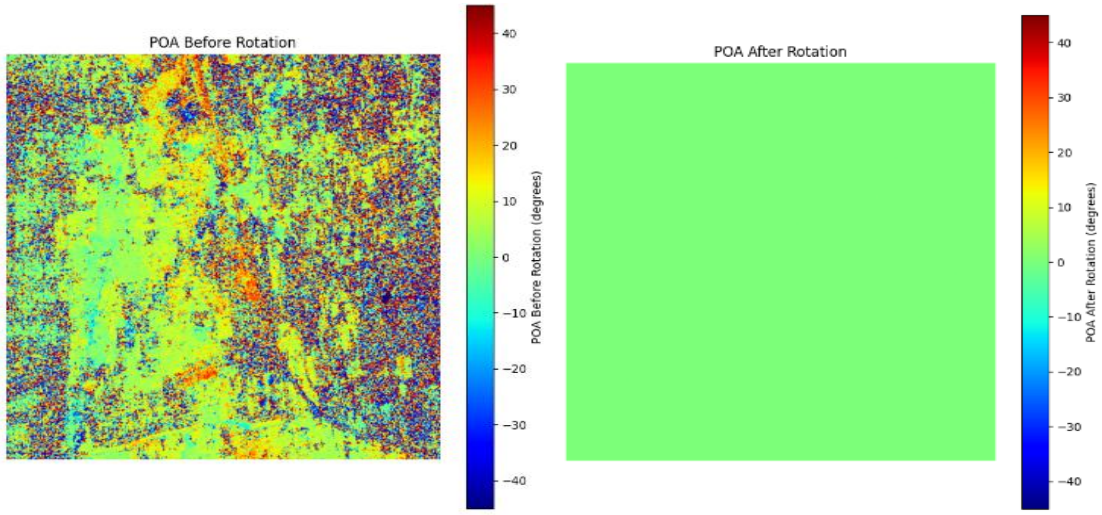

Figure 3 Comparison of POA shift before (left) and after (right) deorientation

The deoriented T3 matrix was then used as input for Yamaguchi decomposition, and the resulting scattering components were compared with those obtained from the original, non-compensated data. Figure 4 shows the Yamaguchi four component model decomposition results of before and after deorientation.

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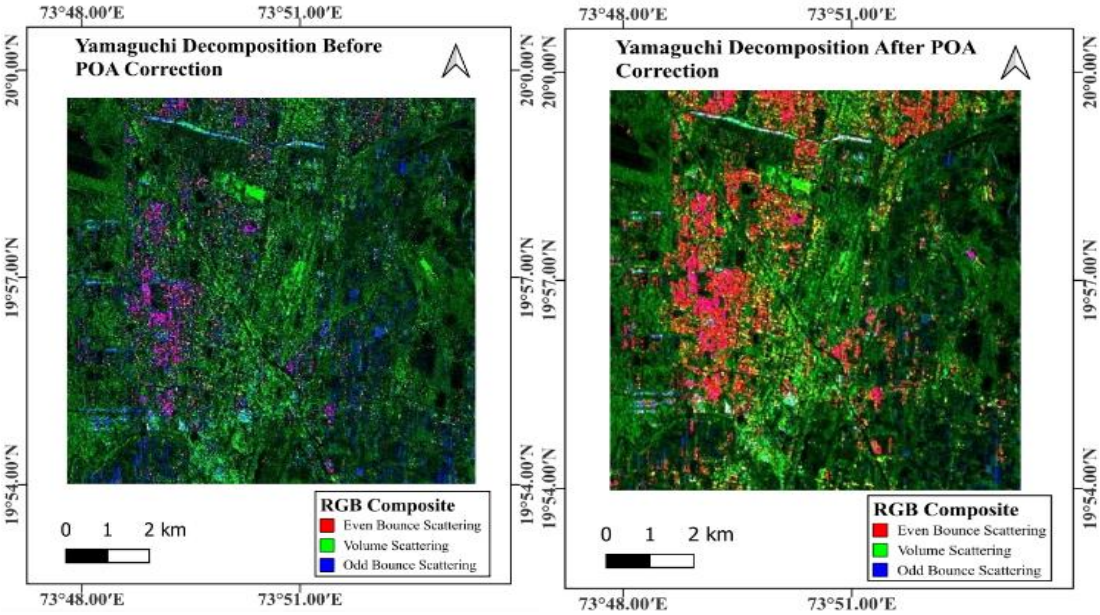

Figure 4 RGB composite of Yamaguchi decomposition before (left) and after (right) deorientation

The Figures 3 and 4 shows the significant changes in scattering behaviour before and after POA compensation. In the RGB composite, red represents double-bounce, green indicates volume, and blue corresponds to surface (single-bounce) scattering[24]. After POA compensation, the double-bounce scattering (T22) component increased, particularly in areas with vertical structures or sharp geometrical features, while the volume scattering (T33) showed a significant reduction across the forested regions. The surface scattering (T11) remained largely unaffected, as expected, due to its roll-invariant nature.

To more precisely evaluate the effect of deorientation on scattering behavior, histograms of the estimated Polarization Orientation Angle (POA) were generated for both the original and the deoriented datasets. This helped assess how much the orientation angle varied across the region, and how effectively it was corrected after applying the deorientation theory.

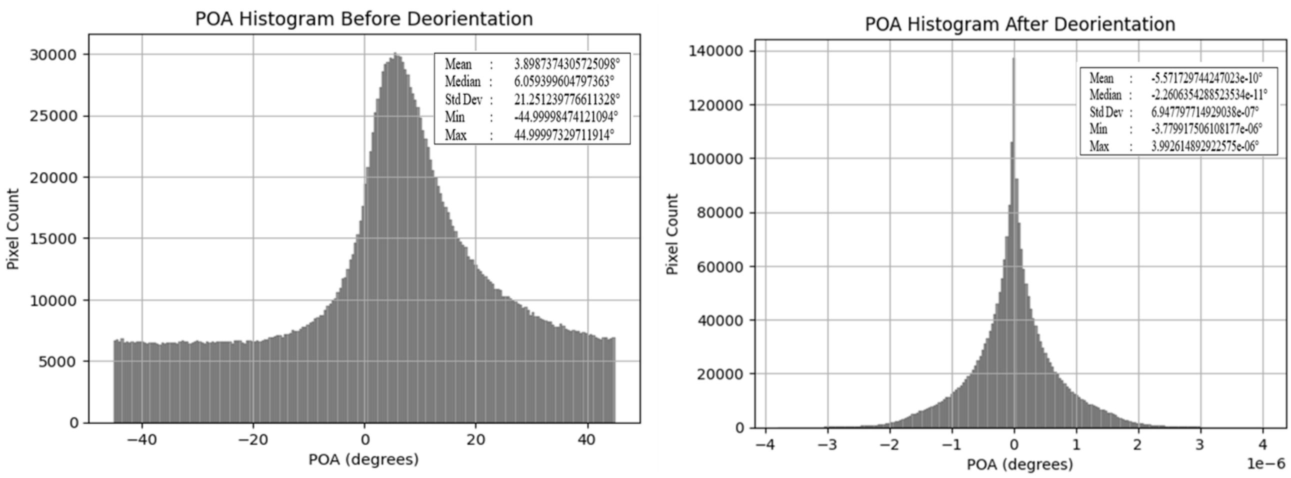

Figure 5 Histograms of Polarimetric Orientation Angle (POA) shift before and after deorientation using the circular polarization algorithm.

In the histogram generated before deorientation, the orientation angles were widely spread, ranging approximately from −45° to +45°. This wide distribution reflects strong variations in the orientation of local features such as sloped terrain, vegetation, and man-made structures. The POA shift is 3.8987° and standard deviation in this shift is 21.25°.

These variations can introduce distortion in decomposition results, often causing the volume scattering to be overestimated.

After applying deorientation, a noticeable reduction in POA variability was observed. The POA shift is -5.57e-10° and standard deviation in this shift is 6.947e-07°.While the theoretical value of orientation shift should ideally become zero, the practical outcome was a very narrow range near zero indicating effective compensation. The effect of POA shift is evident in the increase in volume scattering and decrease the rate of double-bounce scattering in urban regions. The compensation corrects these distortions. As a result, the polarimetric data becomes more balanced, leading to more accurate and physically meaningful decomposition outcomes.

CONCLUSION

This study comprehensively analyses the POA shift and its impact on PolSAR image interpretation. Using EOS-04 (RISAT-1A) imagery, we demonstrate the effectiveness of POA compensation through a well-defined structure, from POA estimation to deorientation and decomposition. The orientation compensation significantly increases the double-bounce power in built-up areas while reducing the volume scattering component. Our findings show that the POA correction improves classification accuracy and physical interpretability. This study highlights the importance of POA compensation in PolSAR image processing. It improves both the visual interpretation and the accuracy of analysis, especially in urban environments. The approach used here can be applied to other sensors and imaging conditions, supporting a wide range of remote sensing applications.

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