Polarization orientation estimation and applications: a review

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***Abstract*— In this paper, we review estimation algorithms and applications of polarization orientation angle shifts induced by terrain slopes. We develop a unified analysis of estimation algorithms based on the circular polarization covariance matrix. The effect of radar frequency, scattering media, and polarimetric calibration will also be discussed. Applications to DEM generation, polarimetric SAR data compensation and ocean surface feature characterization will be mentioned. SIR-C, and JPL AIRSAR L-band and P-band polarimetric SAR images are used for demonstration.**

Keywords: radar polarimetry, polarization orientation, synthetic aperture radar

I. INTRODUCTION

Recently, a new technique has been developed using polarimetric SAR (POLSAR) to measure azimuth slopes that are related to shifts in polarization orientation angles [1-4]. Polarization orientation angle is one of the most underutilized parameters among the wealth of polarimetric information when analyzing POLSAR data. The polarization state of an electromagnetic wave is characterized by its polarization orientation angle θ and ellipticity angle χ. The orientation angle, which is of importance to this study, is the angle between the major axis of the polarization ellipse and the horizontal axis. For distributed media, orientation shifts are induced by azimuthal slopes, which cause the polarization to rotate about the line of sight.

Polarization orientation shifts are frequently considered as a direct measure of azimuthal slopes. This is not correct. Lee [4] and Pottier [6] have found that orientation shifts are also affected by the radar look angle and the range slope. In this paper, we review orientation angle estimation methods, and the radar geometry to relate the orientation angle to the azimuth and range slopes. Difficulties are frequently encountered in the estimation of orientation angles from POLSAR images. These difficulties will be discussed and the effect of radar wavelength and calibration on the estimation will be investigated. Applications to geophysical parameter estimation, and to ocean surface feature sensing will be mentioned.

II. RADAR GEOMETRY OF POLARIZATION ORIENTATION ANGLE

The change in the polarization orientation angle is geometrically related to topographical slopes and the radar look angle [3]. Fig. 1 shows the schematic diagram. Assume that the polarimetric SAR is calibrated so that the horizontal polarization (H) is parallel to the horizontal plane $(\hat{x}, \hat{y})$, and the vertical polarization (V) is in the incidence plane.

This work was supported by the ONR basic research program.

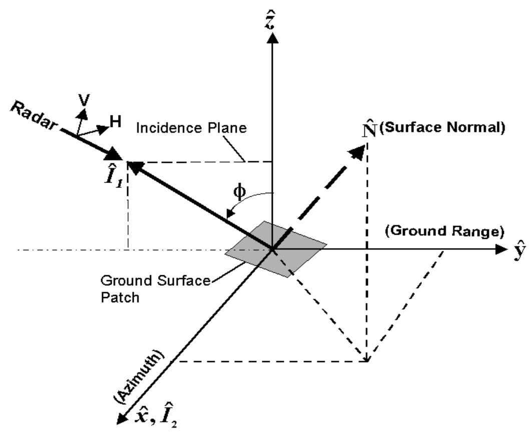


Fig. 1 A schematic diagram of the radar imaging geometry which relates the orientation angle to the ground slopes.

For a horizontal surface patch, its surface normal $\hat{N}$ is in the incidence plane, and no orientation angle shift is induced. However, for a surface patch with an azimuthal tilt, its surface normal $\hat{N}$ is no longer in the incidence plane. The induced polarization orientation angle shift θ is the angle that rotates the incidence plane $(\hat{y}, \hat{z})$ about the line of sight to the surface normal by the following equation [3],

$$\tan\theta = \frac{\tan\omega}{-\tan\gamma\cos\phi + \sin\phi} \tag{1}$$

In (1), ϕ is radar look angle, $\tan\omega$ is the azimuth slope, and $\tan\gamma$ is the slope in the ground range direction. This equation shows that the orientation shift is mainly induced by the azimuth slope, but that it is also a function of the range slope and the radar look angle. For small range slope, the orientation angle tends to overestimate azimuthal slope angle by the factor of $(1/\sin\phi)$. In general, orientation angle measurements overestimate the actual azimuth slope angles, when the range slope is positive (toward the radar), and may underestimate them, if the range slope is negative. The difference between the orientation angle and the corresponding azimuth slope angle becomes smaller for larger radar look angles. For an accurate estimate of azimuth slopes, range slope information, therefore, is required. This can be achieved by imaging the area with POLSAR in orthogonal passes [2].

III. THE CIRCULAR POLARIZATION ALGORITHM

The orientation angle shift causes rotation of both the scattering matrix and the circular covariance matrix about the line of sight. Since the orientation angle information is embedded in the polarimetric SAR data, several methods have been developed to estimate azimuth slope induced orientation angles. The polarization signature method [1] and the circular polarization method [3] have been proven to be effective. Other methods have also been proposed [4]. The polarization signature method is based on the concept that the angle θ corresponds to the change in the polarization orientation angle in co-polarization response, and is estimated by the shift of its maximum (peak). To speed up the optimization process, a steepest ascent algorithm was also developed [1].

The other method is derived using circular polarizations. It is based on the concept of reflection symmetry. This method is also simpler and more accurate than any other methods. The circular polarization method [3] extracts the orientation angle, using right-right (RR) and left-left (LL) circular polarizations from either single-look complex, or from multi-look, data. The rotation by an orientation angle θ causes the phase of circular scattering terms to be shifted by

$$\begin{aligned} \tilde{S}_{RR} &= S_{RR}\, e^{-i2\theta} \\ \tilde{S}_{LL} &= S_{LL}\, e^{i2\theta} \\ \tilde{S}_{RL} &= S_{RL} \end{aligned} \tag{2}$$

In (2), S_{pp} is the RR circular polarization before the rotation, and $\tilde{S}_{pp}$ is the one after the rotation.

From the above equations, we have found that the product of the RR and the LL is a good estimator based on the concept of reflection symmetry,

$$< \tilde{S}_{RR}\tilde{S}^*_{LL} > = < S_{RR}S^*_{LL} > e^{-i4\theta} \tag{3}$$

Other combinations of circular polarizations can introduce bias and errors [4]. From (3), we can derive the circular polarization estimator for the orientation angle,

$$\theta = \begin{cases} \eta, & if \quad \eta \le \pi/4 \\ \eta - \pi/2, & if \quad \eta > \pi/4 \end{cases} \tag{4}$$

where

$$\eta = \frac{1}{4}\left[\tan^{-1}\left(\frac{-4\,\mathrm{Re}(< (\tilde{S}_{HH} - \tilde{S}_{VV})\tilde{S}^*_{HV} >)}{-<|\tilde{S}_{HH} - \tilde{S}_{VV}|^2> + 4<|\tilde{S}_{HV}|^2>} \right) + \pi \right] \tag{5}$$

The arctangent in (5) is computed in the range of $(-\pi, \pi)$. This algorithm has proven successful for orientation angle estimation [3]. An example is given here of applying it to the JPL AIRSAR L-band data of Camp Roberts, California. A photo of Camp Roberts in Fig. 2 shows the rugged terrain in the background with sparsely distributed oak trees. In the valley, the vegetation is much more dense. The polarization image of Camp Roberts is shown in the top of Fig. 3. We use the Pauli matrix based color-coding for the combination of polarization channels: red for |HH-VV|, green for |HV|, and blue for |HH+VV|. The rectangular shaped object in the fork-like valley is the site of Camp Roberts. The middle image shows polarization orientation angles derived by the circular polarization method from the polarimetric data. The streaks at the top are from instrument noise.

Fig. 2 This photo shows the topography and vegetation in Camp Roberts, California

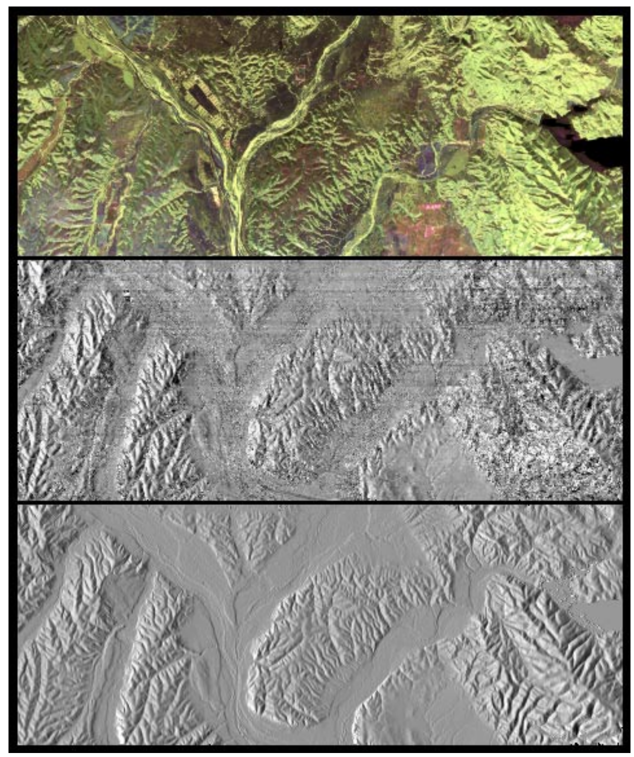


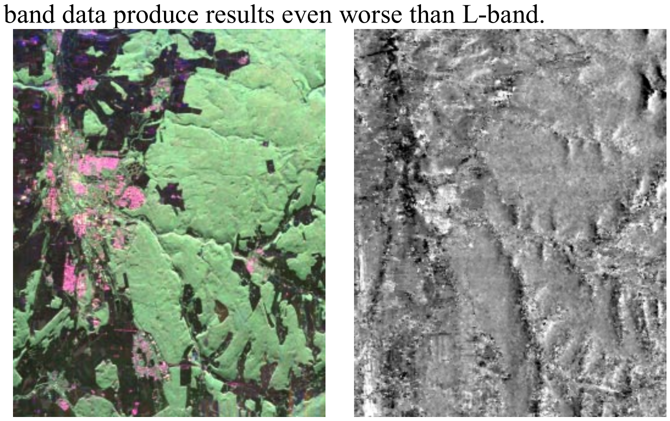
Fig. 3 The top image shows the POLSAR data of Camp Roberts, The middle image shows polarization orientation angles derived by the circular polarization method. For comparison, the lower image shows orientation angles derived from a DEM, generated by C-band interferometric SAR. These two images are strikingly similar, except for the streaking in the middle image due to instrument noise.

JPL AIRSAR simultaneously imaged this area with C-Band TOPSAR to obtain interferometric data. This permits verification of polarimetric SAR derived orientation angles by those obtained from the interferometric generated DEM and equation (1). Orientation angles derived from the DEM are shown in the lower image. The similarity between these two images indicates the validity of this estimation algorithm. The capability of deriving polarization orientation angles enables us to measure azimuthal slopes and to compensate polarimetric SAR data for terrain slope variation [3]. The compensated data improves the accuracy of geophysical parameter estimations, as well as land-use and terrain type classification.

IV. DISCUSSION

A. Radar Frequency

Orientation angles can be derived from L-band and P-band POLSAR data, but less successfully from C-band or higher frequency data. Higher frequency POLSAR responses are less sensitive to azimuth slope variations, because electromagnetic waves with shorter wavelengths are less penetrative and are more sensitive to small scatterers within a resolution cell. JPL AIRSAR data from the Black Forest, near Freiburg, Germany is used for illustration shown in Fig. 4. The area is heavily forested as shown in Fig 4A. The orientation angles derived from the P-band data (Fig. 4B) are well defined and show the strength of penetration from P-band. The orientation angles derived from the L-band data (not shown) are noisy, and are less sensitive to the under-canopy topography. C-band data produce results even worse than L-band.



(A) Original P-band data *(B) P-band orientation angle*

Fig.4 In heavily forested areas, orientation angles can be extracted from P-band data, but not from L-band or higher frequency data. JPL AIRSAR P-band and L-band Data of the Black Forest, Freiburg, Germany, is applied to extract orientation angles. (A) |HH-VV|, |HV| and |HH+VV| color coded P-Band SAR image, (B) Orientation angle image derived from the P-band data.

B. Polarimetric Calibration

POLSAR data calibration is a crucial step in the process of deriving accurate orientation angles. The accuracy in phase difference between co- and cross-polarization especially affects the orientation estimation. Many polarimetric SAR calibration algorithms assume zero correlation between co-polarization and cross-polarization terms (Quegan, 1994). This assumption could introduce errors in orientation angle estimation. Recently, a revised method has been introduced by Ainsworth et al. (IGARSS 2001) to account for this deficiency.

C. Dynamic Range of Radar Response

The dynamic range and polarization channel isolation of the radar receiver are critical to the success of the orientation angle estimation. The success of the circular polarization methods depends on the accuracy of measuring the co-polarization and cross-polarization correlation terms. A lack of dynamic range makes correlation terms very noisy. The extraction of orientation angles becomes an impossible task for SAR systems with small dynamic range and poor channel isolation.

V. ORIENTATION ANGLE APPLICATIONS

A. Polarimetric Data Compensation

The derived orientation angle can be used directly to compensate POLSAR data in rugged terrain areas. It is important to compensate the POLSAR data to ensure accurate extraction of geophysical parameters, such as, soil moisture, surface roughness, snow cover, and biomass. A study on POLSAR data compensation has been carried out by Lee et al. [3].

B. DEM Generation

The derived orientation angles can be used to generate topography (Schuler et al. [1, 2]). Two orthogonal POLSAR flight passes are required to derive orientation angles in perpendicular directions. By applying equation (1), the ground slopes in two directions can be computed. The slope data is then used to solve a Poisson equation to estimate the elevation surface.

C. Ocean Applications

Another interesting application is for the direct estimation of ocean surface slopes. Backscattering from the ocean surface can be assumed in most cases to be homogeneous, and is characterized by two-scale Bragg scattering. This type of scattering provides excellent conditions for orientation angle estimation. In a study of convergent current fronts within the Gulf Stream (Lee et al. [5]), it was found that there existed a sudden change in the orientation angle from positive to negative across a convergent front with the maximum slope change being smaller than 2°. This study has been expanded by Schuler et al. and Kasilingam et al. to estimate ocean wave slope spectra, and to study internal wave radar signatures.

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