The Use Of Polarimetric And Interferometric SAR Data In Floodplain Mapping

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***Abstract*— Recent advances in polarimetric SAR show promise for augmenting the capability of traditional interferometric SAR. In particular, a polarimetric topography technique provides useful slope information, and polarimetric interferometry may be used to decompose the response into vegetation and ground surface contributions. Here we discuss an integrated approach that utilizes the combined capability of regular (single channel) interferometry, polarimetric interferometry and polarimetric topographic mapping for topographic mapping of flood-prone areas.**

Keywords-Polarimetry; interferometry

I. INTRODUCTION

The human and economic impact of flooding in both inland and coastal lowlands is enormous. Inland riverine watersheds are subject to episodic rainfall events, while low relief coastal watersheds are prone to flooding from both uplands and from the sea. Floodplains, both riverine and coastal, present some of the most difficult challenges to remote sensing instruments. First, the topography is usually characterized by exceedingly small relief, so that systematic errors in the remote sensing data can easily be of the same magnitude as the actual topography. Second, floodplains usually contain significant amounts of vegetation, and it is the topography of the underlying surface that is important to the modeling of the hydrologic process. To accurately model the hydrologic response of such a floodplain to changing environmental conditions, it is therefore clear that an accurate description of the topography under the vegetation is of vital importance. As important as the description of the topography is the accurate characterization of the surface in terms of the land cover and soil moisture conditions.

II. ESTIMATION OF TOPOGRAPHY IN THE PRESENCE OF VEGETATION

Recent advances in polarimetric SAR show promise for augmenting the capability of traditional interferometric SAR in measuring surface topography. In particular, a polarimetric topography technique provides useful slope information, and polarimetric interferometry may be used to decompose the topographic response into vegetation and ground surface contributions. We will briefly review these two techniques here. The general methodology is to assume that data have been acquired with a system like the NASA/JPL AIRSAR system. This system is capable of acquiring data in the interferometric mode at C-band, while simultaneously acquiring polarimetric data at both L-band and P-band. The issue is, of course, that the C-band interferometric phase in vegetated areas in general represents scattering somewhere inside the vegetation canopy, and not at the ground surface. The question then is if we could use either polarimetric interferometry data, or the lower frequency polarimetric data, to estimate the topography of the underlying ground surface.

A. Polarimetric Slope Estimation

Schuler *et al.* [1] proposed a method to infer surface slopes in the along-track direction from polarimetric SAR data alone. Their method is based on modeling the effect of the azimuth slope as a rotation of the scattering matrix through an angle equal to the azimuth slope angle. This causes a shift of the maximum peak in the polarization signature away from the VV position (the expected case for a horizontal rough surface) by an amount equal to the azimuth slope angle. The azimuth slope is then estimated from the polarimetric SAR data by calculating the shift in the peak of a polarization signature away from the VV position. They applied this technique, using P-band data from the NASA/JPL AIRSAR system, to an area of the Black Forest in Germany, and report slope estimates that compare favorably with those estimated from maps [1].

More recent work [2], including our own analysis, show that the original assumption about a rotation of the scattering matrix through an angle equal to the azimuth slope only is incorrect. Instead, the position of the maximum of the polarization signature is shifted by an equivalent rotation angle ψ, where

$$\tan\psi = -\frac{\tan\beta}{\sin\theta - \tan\alpha\cos\theta} = -\frac{\tan\beta\cos\alpha}{\sin(\theta-\alpha)} \qquad (1)$$

Here, β is the along-track surface tilt angle, α is the cross-track surface tilt angle, and θ is the angle of incidence for a flat surface. Equation (1) shows that the amount of rotation measured by observing the shift in the polarization signature maximum is influenced by the range tilt, the azimuth tilt, and the incidence angle, and not only by the azimuth tilt as assumed by Schuler *et al.* [1]. Therefore, unless one has some information about the range slopes and incidence angles, this method cannot be used to reliably estimate the topography under vegetation.

An important issue to consider when using (1) is to understand under which conditions the polarimetric slope estimates could be considered reliable. For the effects of the slopes to manifest themselves in the polarimetric data, some interaction between the radar waves and the ground surfaces is required. Therefore, if the scattering is dominated by scattering from the vegetation canopy, *i.e.* little to no return from the underlying surface is observed, one would not expect this technique to be able to reliably estimate the slopes. We applied this technique to data acquired over an area in the Black Forest in Germany where the biomass is on the order of 200 tons per hectare; the same area originally used by Schuler *et al.* [1] in their study. Our results show that the slope image derived from the P-band data clearly demonstrates the ability to estimate slopes in vegetated areas. However, the slope estimates from the L-band data are much noisier, and in general quite useless. The scattering from this area was previously analyzed using theoretical scattering models [3]. That study showed the scattering at P-band to be generally dominated by double reflections from the trunk-ground interactions, while scattering at L-band generally was dominated by returns from the randomly oriented branches in the canopy. This confirms that if the scattering shows significant return from the underlying soil, reasonable results can be expected. When, however, the return is dominated by scattering from the canopy itself, the algorithm fails to provide reliable results.

B. *Polarimetric Interferometry*

Cloude and Papathanassiou [4] first published the formulation of polarimetric interferometry and derived an algorithm to select the optimum polarization combination that would maximize the interferometric coherence. Using data acquired in the repeat-track model during the SIR-C mission, they showed that the coherence could indeed be increased substantially by selecting the optimum polarization combination. More importantly, they also showed that using different polarization combinations, the observed *differential* interferometric phase in vegetated areas is quite different from zero, as is observed for bare surfaces. The natural interpretation of the differential polarimetric interferometric phase is that different polarizations scatter from different elevations inside the canopy. In reality, the observed phase is the weighted sum of canopy and ground scattering, but the fundamental interpretation remains the same.

A simple model of a vegetation canopy covering a ground surface was first derived by Papathanassiou and Cloude [5] and later by Treuhaft and Siqueira [6]. In these models, the vegetation canopy is modeled as a layer of randomly oriented scatterers covering a ground layer. They showed that the resulting interferometric coherence lies on a straight line in the complex coherence plane. The algorithm for finding the ground surface elevation is then simply to estimate the slope of this line using the polarization combinations that optimize the coherence, and extrapolate the line to where the unit circle is crossed. The phase of the resulting coherence represents the interferometric phase corresponding to the elevation of the underlying ground surface. In order to estimate the slope of this line reliably, it is necessary to find those points along the line that are separated by the largest distance. We shall now show that the solution to this problem is similar to that of using different polarizations to optimize the contrast between two scatterers.

Consider, as previous researchers did, that the scattering comes from two scattering centers, one representing the ground surface, and one the canopy. These two scattering centers are assumed to be separated by a distance h. We can then show that the interferometric phase measured for the ground surface alone will be

$$\varphi_g = -(4\pi B/\lambda)\sin(\xi - \theta) \qquad (2)$$

where B is the baseline length, ξ is the baseline tilt angle, and θ is the radar look angle. Similarly, we can show that the interferometric phase for the canopy scattering center can be written as

$$\varphi_c \approx \varphi_g - \frac{4\pi Bh}{\lambda R \sin\theta}\cos(\xi - \theta) \qquad (3)$$

The total complex cross-correlation measured by the interferometer when both scatterers are present can be written as

$$\mathbf{V} = V_g e^{i\varphi_g}\left\{1 + \mu \exp\left[-i\frac{4\pi Bh}{\lambda R \sin\theta}\cos(\xi - \theta)\right]\right\} \qquad (4)$$

where V_g represents the strength of the ground scattering and μ is the strength of the canopy scattering relative to that from the ground. The change in the interferometric phase of because of the presence of the canopy is therefore

$$\delta\varphi = -\tan^{-1}\left\{\frac{m\sin\left(\frac{4\pi Bh}{\lambda R\sin\theta}\cos(\xi-\theta)\right)}{1 + m\cos\left(\frac{4\pi Bh}{\lambda R\sin\theta}\cos(\xi-\theta)\right)}\right\} \qquad (5)$$

This function varies monotonically (although not linearly) with m as shown in Figure 1. When m approaches zero, the change in phase approaches zero, *i.e.* the interferometric phase is simply that of the ground surface. When m becomes large, the change in phase approaches the limiting value that is proportional to the canopy height as shown in (3). Since m, in general, changes as the polarization changes, one could use polarization to maximize the change in phase by maximizing the difference in m that is used in the observation. Taking the fact that the extinction through the canopy may also be a function of polarization into account, we can write m as

$$m_{ij} = \gamma_{ij} e^{\tau_{ij}}\, \sigma_{ij}^{c} \big/ \sigma_{ij}^{g} \qquad (6)$$

Here the subscripts denote transmit and receive polarizations, the superscripts refer to the canopy and the ground respectively, τ is the optical depth of the canopy, and γ is the decorrelation of the vegetation canopy by itself. In the particular case where the canopy is considered to be formed by randomly oriented cylinders, both γ and τ are independent of polarization, and (6) reduces to a constant multiplied by the ratio of the scattering from the canopy relative to that from the ground. Therefore, optimizing m is identical to optimizing the contrast between the canopy and the ground.

The usefulness of this technique will clearly depend on the relative change in m between its optimum values, as well as the absolute value of m. If the total variation in the example in Figure 1 is such that both optimum values of m lie either below 0.1 or above approximately 3, very little useful information will be obtained. How much m will vary, and what the optimum values are, is of course a function of the canopy and ground parameters.

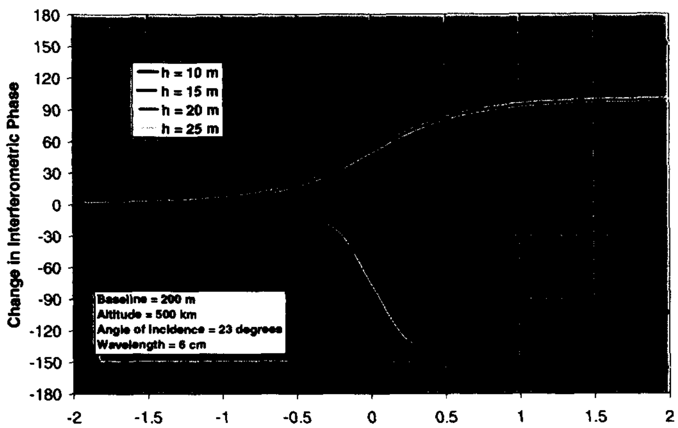

Figure 1. Change of interferometric phase as a function of the ratio of vegetation to ground scattering for different canopy heights. The assumed interferometric parameters are shown in the graph.

To illustrate the results a bit more quantitatively, we show the results of optimizing m for the case of a relatively thin canopy, assumed to be randomly oriented cylinders. The term "thin" here refers to the optical depth being relatively small. We present the results as a three-dimensional plot where the horizontal axes represent the orientation and ellipticity angles of the transmit polarization. The maximum plot (Figure 2) is the one where the receive polarization is varied until the maximum value of m is obtained.

Figure 2. Maximum value of m as a function of the transmit polarization orientation and ellipticity angles.

The results in Figure 2 show that there is quite a variation in the optimum value of m as the polarization is varied. For the particular set of canopy and soil parameters we assumed, the maximum value of 4.5 occurs for a linear transmit polarization with orientation angle of 34 degrees, and an elliptical receiving polarization with zero orientation angle, and ellipticity angle of 25 degrees. The minimum value of 0.25 occurs at either circular polarization transmitted, with a linear receiving polarization with an orientation angle of 146 degrees. It should be pointed out, though that the exact polarizations at which the maximum or minimum occurs are complicated functions of both the canopy and the ground surface geophysical parameters.

III. Summary

We described two potential methods for measuring surface topography under vegetation. The polarimetric slope estimation technique has been shown to measure surface slopes under vegetation under certain conditions. However, in order for this method to provide reliable results, the radar waves must interact with the underlying ground surface. When vegetation scattering dominates, the method does not allow the reliable estimation of surface slopes.

Polarimetric interferometry data may allow the estimation of the ground surface topography if one can reliably estimate the position of the intersection of the linear function of the coherence phase with the unit circle. We have shown that the optimum polarizations that maximizes the difference in interferometric phase are the solution to a polarimetric contrast enhancement problem. If the coherence of the canopy alone has no polarization dependence; hence no line direction can be estimated if the canopy scattering dominates. Unfortunately, progress in using polarimetric interferometry data for this purpose is severely hampered by the lack of calibrated polarimetric interferometry data.

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