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. Additionally, polarimetric SAR data are used to provide soil moisture and land cover characterization inputs from the same remotely sensed data.

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. Hydrologic models can be used to predict the occurrence of flooding provided that the required input fields are accurately described. Of these inputs, some of the most important include an accurate description of the topography of the floodplain, as well as the state of soil moisture and vegetation cover.

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.

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, (even polarimetric interferometry) 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.

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 \( \psi \), where

\[
\tan \psi = -\frac{\tan \beta}{\sin \theta - \tan \alpha \cos \theta} = -\frac{\tan \beta \cos \alpha}{\sin(\theta - \alpha)}
\]

(1)

Here, \( \beta \) is the along-track surface tilt angle, \( \alpha \) is the cross-track surface tilt angle, and \( \theta \) 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]. In general, we see from (1) that the rotation angle measured by Schuler et al. [1] will underestimate the azimuth slope. 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.

For floodplains, the topography is very flat; therefore, the range slope correction may not be necessary. In our case, we do have some information about the topography as measured with the SAR interferometer. The additional information provided by the modified Schuler technique is information about the slopes derived independently from the polarimetric data. More importantly, Schuler et al. [1] showed that this slope information can be derived even for vegetated areas; something we cannot easily do from the direct topographic measurements provided by the SAR interferometry or for that matter from laser altimetry. Furthermore, the polarimetric data are acquired during a single pass, and no baseline calibration (as in the case of interferometry) is required.

Several issues potentially arise when using polarimetric estimates of slope to reconstruct topography. The first of course is that any systematic error on the slope estimate will integrate to become a growing error (resulting in a tilt) on the topography. The effect of this type of error could be minimized if one only uses the polarimetrically derived slopes to reconstruct topography when no reliable interferometric data are available. This would minimize the distances over which the slopes are integrated, and therefore minimize the tilt error. A second, and potentially more serious issue, 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.

**Polarimetric Interferometry**

Polarimetric interferometry refers to an implementation of interferometry where the complete scattering matrix is measured at each end of the interferometric baseline. 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. Most of the emphasis of polarimetric interferometry analysis has been to derive the height of the vegetation canopy. Several authors, however, have investigated algorithms to estimate the elevation of the ground surface underneath the vegetation canopy. For example, 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. The resulting interferometric coherence is

$$\gamma = e^{i\phi} \frac{m + I_1}{m + I_2}$$

where $\phi$ represents the interferometric phase of the ground surface in the absence of vegetation, $m$ is the ratio of scattering from the ground relative to that of the vegetation canopy, and

$$I_1 = \frac{\cos \theta}{2\sigma} \left( e^{\frac{2\sigma h}{\cos \theta}} - 1 \right)$$

and

$$I_1 = \frac{1}{2\sigma \cos \theta + j \frac{4\pi B_n}{\lambda R \sin \theta}} \left( e^{\frac{4\sigma h}{\cos \theta} + j \frac{2\sigma h}{2R \sin \theta}} - 1 \right).$$

Here, $\sigma$ is the volume attenuation coefficient of the vegetation layer, $h$ is the thickness of the vegetation layer, $\theta$ is the angle of incidence of the radar waves, $\lambda$ is the radar wavelength, $R$ is the slant range, and $B_n$ is the length of the radar wavelength perpendicular to the radar look direction.

Note that the vegetation canopy scattering itself has no polarization dependence; a consequence of the assumption that the scattering is due to randomly oriented scatterers. The ground surface scattering, however, would show a dependence with varying polarization. For a slightly rough surface, for example, one would expect scattering at VV to be stronger than that at HH, and HV scattering to be significantly weaker than either HH or VV. Since the phase center of the vegetation canopy remains fixed, one would expect the combined phase center at HV to be at the highest elevation (and close to that of the canopy itself), followed by HH and then by VV, which would be the closest to the ground. If on the other hand, the scattering at the ground is dominated by a trunk-ground interaction, one would expect the ground term itself to show a stronger return at HH than at VV (a consequence of the two Fresnel reflections at the ground and at the trunk surface, respectively), and still have low returns at HV. In this case, then, the elevation of the HV phase center would still be the highest, followed by VV, and HH being the lowest. In all cases, however, this model shows that as $m$ varies, such as would be the case if one uses different polarizations, all the measured coherences will lie 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.

Unfortunately, very little calibrated polarimetric interferometry data have been acquired to date. Some initial results derived from this small dataset certainly appear very promising. Progress at present is, however, limited because of the lack of data. This is clearly an area where much more research is required before the full potential of polarimetric interferometry data can be realized.

**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 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. The key in this case is to have enough return from the ground surface that would in turn introduce enough variation of the coherence magnitude and phase with polarization so as to reliably estimate the slope of the line that is to intersect the unit circle. Recall that 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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REFERENCES


