3D SAR TOMOGRAPHY OF THE PARACOU FOREST; METHODS AND RESULTS

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ABSTRACT

Many studies about the vegetation layer by means of SAR tomography are model based or make use of some sort of superresolution algorithms. By one side such approaches are often necessary because of the limited resolution characterizing the datasets. On the other side results can be easily affected by poor accuracy whenever the model does not fit. In this paper a totally model free approach is proposed to perform SAR tomography. It is based on the existing relationship between the complex reflectivity profile along the cross range direction and the multi baseline signal: a Fourier transform. Whenever the baseline distribution is suitable a new stack of uncorrelated complex image can be obtained, each one associated with a particular elevation inside the vegetation layer.

Key words: SAR; Tomography; Polarimetry; Model Free analysis.

1. INTRODUCTION

Recently retrieving information about the vegetation layer has become a major issue. SAR remote sensing is particularly suitable for this task mainly because of the fast coverage of large areas together with the good resolution provided. In particular longer wavelength radar enables the signal to penetrate the vegetation thus gathering contributions coming from various elevations above the ground surfaces. SAR tomography is the operational tool which enables such contributions to be distinguished so that an estimation of the three-dimensional structure of the forest can be obtained. In such a framework polarimetric measurements can supply a further characterization of the scattering mechanisms contributing to the data.

In order to interpret the measurements acquired over forested areas many works on physical modeling have risen in the past years (Ulaby et al. 1988) (Lin et al. 1995). Such works are mainly based on the hypothesis of two scattering contributions: the former coming from the ground level and associated with direct ground return or ground-trunk double bounce, the latter coming from the canopy level and resulting from the interaction of the waves scattered by branches and leaves. By inverting such models information about the physical quantities originating the signal can be obtained.

In the past years many acquisition campaigns have been designed so that the vertical resolution is larger of the extent of the vegetation layer therefore giving rise to the need of super-resolution techniques (Lombardini & Reighber 2003) (Gini et al. 2002). By means of such techniques it is possible to reach a very high detail level although at the same time the radiometric accuracy can be very poor when dealing with distributed targets. In order to overcome this problem together with any issue related with the choice and the fitting of a suitable model, a model free approach is here presented. The processing chain described in this paper can be applied to dataset whose resolution along the vertical direction is smaller than the tree heights. Whenever such condition is fulfilled the possibility of obtaining a multi-height stack starting from a multi-baseline one arises. Each complex image constituting the new stack is associated with the scatterer distribution at a particular elevation above the ground.

Results obtained by processing the P-band TropiSAR (Dubois-Fernandez et al. 2011) dataset are also shown in section 3.

2. MODEL FREE SAR TOMOGRAPHY

A single Single Look Complex (SLC) SAR image gathers the measurements acquired by the radar on a desired zone. In order to enable SAR tomography a set of $N$ different images of the same area is needed, each one observing the scene from a slightly different look angle $\theta$. Let $y_n(r, x)$ denote the measurement associated with the slant range, azimuth coordinates $(r, x)$ in the $n-th$ image. After that each image has been focused, coregistered on a common grid and phase-flattened, the relationship between the multi-
baseline signal and the complex reflectivity profile can be expressed (Bamler & Hartl 1998) as:

\[ y_n(r, x) = \int P(\xi, r, x) \exp \left( \frac{j 4\pi}{\lambda r} b_n \xi \right) d\xi \] (1)

where \( b \) is the normal baseline, \( \lambda \) is the carrier wavelength, \( \xi \) is the cross range coordinate (orthogonal to the Line Of Sight and to the flight direction), \( P(\xi, r, x) \) is the average scene complex reflectivity within the slant range, azimuth resolution cell and the subscript \( n \) refers to the image index.

By analyzing Equation 1 it can be observed that the complex reflectivity along the cross range direction can be retrieved by taking the Fourier transform of the signal along the image index. In particular it is possible to focus on the reflectivity density averaged on an elevation interval centered on the desired height and whose extent depends on the Fourier resolution along the cross range axis. In particular the relationship between the achievable resolution and the baseline distribution is given (Reigber & Moreira 2000) by:

\[ \delta_z = \frac{\lambda r}{2b_{\text{max}}} \sin (\theta) \] (2)

Before actually performing tomography according to this simple approach, in this work two preliminary issues have been considered. The former is the effect of the local topography on the height specification whereas the latter concerns with the platform deviation from its ideal trajectory.

### 2.1. Compensating for the Local Topography

Standard processing of interferometric SAR images includes phase flattening which is usually performed by referring to a single elevation along the whole image, so that each height specification is referred to that particular elevation. In order to study the vegetation layer alone the height contributions given by the local topography should be considered as undesired quantity and thus removed. The goal here is to perform a space-varying shift of the vertical reflectivity profile so that in correspondence of each range, azimuth couple the ground level is always placed at the origin of the cross range axis. As a consequence of such a shift every height specification is referred to the ground level irrespective of the local topography. Because of the Fourier relationship between reflectivity and signal, a translation of the former corresponds to a demodulation of the latter, it follows that the phases associated with the ground are needed.

The procedure to get an estimation of such phases is described in (Tebaldini & Rocca 2009) so it will be just outlined here.

![Figure 1. Representation of the impact of the local topography on the height specifications. Bringing the ground level in correspondence of the origin of the cross range axis ease the analysis of the vegetation layer.](image1)

![Figure 2. Degradation of the Point Spread Function along the cross range direction caused by an irregular sampling of the total baseline aperture.](image2)
they are sensitive to the ground height $z_g$ and to the phase disturbances $\alpha_n$, that is:

$$\varphi_n = \frac{4\pi}{\lambda\sin\theta} b_n z_g + \alpha_n$$  (3)

When removing such phases the ground level is brought at 0m and the propagation disturbances are removed at the same time thus enabling a correct focusing along the cross range direction. An estimation of the terrain slope along the ground range direction can be obtained by further processing the ground phases. Being $\alpha$ the ground slope we have:

$$\tan(\alpha) = \frac{\partial z_g}{\partial r} = \frac{\partial z_g}{\partial r} \frac{\partial r}{\partial gr}$$  (4)

where $z_g$ is the ground elevation, $r$ is the slant range coordinate and $gr$ is the ground range coordinate.

An estimation of the derivative of the ground height with respect to the slant range can be obtained from the ground phases:

$$\frac{\partial \varphi_g}{\partial r} = \frac{\partial^2 z_g}{\partial r^2} + \frac{\partial \varphi_g}{\partial r} \approx \frac{\partial z_g}{\partial r} + \frac{\partial \alpha}{\partial r}$$  (5)

$$\frac{\partial z_g}{\partial r} \approx \frac{k^2}{|k|^2} \frac{\partial \varphi_g}{\partial r}$$  (6)

where $k$ is the phase to height conversion factor, $\varphi_g$ is the vector containing the phases of the ground and $\alpha$ is the vector gathering the phase disturbances. The last approximation in Equation 6 relies on the hypothesis that the average of the derivative of the phase disturbances is negligible with respect to the other term. The derivative of the slant range coordinate with respect to the ground range coordinate can be expressed as:

$$\frac{\partial r}{\partial gr} = \sin(\theta) - \cos(\theta) \tan(\alpha)$$  (7)

By combining Equation 4 with Equation 6 and Equation 7 we get:

$$\alpha \approx \tan^{-1} \left( \left(1 + \frac{k^2}{|k|^2} \frac{\partial \varphi_g}{\partial r} \cos(\theta) \right)^{-1} \frac{k^2}{|k|^2} \frac{\partial \varphi_g}{\partial r} \sin(\theta) \right)$$  (8)

The ground slope is used in section 3 to give a physical interpretation of the results.

2.2. Compensating for the Sensor Motion

During SAR surveys it often happens that the radar platform deviates from its ideal trajectory, especially when dealing with airborne SAR. Such deviations make the sampling of the total baseline aperture no more regular so that the Point Spread Function (PSF) along the cross range direction is corrupted by undesired sidelobes.

In SAR literature many different approaches have been proposed to overcome this issue (e.g. (Lombardini & Pardini 2008)), anyway in this work a quite simple but effective procedure has been followed. Basically the signal has been linearly interpolated on a regular grid sampling the total baseline aperture. Because of the Fourier relationship linking together the reflectivity and the signal it is possible to analyze what is the effect on the former of a linear interpolation of the latter.

A linear interpolation of a signal corresponds, in the dual domain, to a multiplication by the kernel of the interpolator that is a baseband squared sinc. The ground topography removal described in section 2.1 forced the reflectivity profile to be included between 0m and the tree top height, that is not a baseband signal. It follows that the multiplication by the squared sinc heavily distorts the highest part of the reflectivity profile that is the furthest from the flat region of the sinc. In this work in order to reduce
the distortion the profile has been taken in baseband before interpolating and then modulated back. Figure 3 depicts the improvement brought by such an intermediate step.

3. EXPERIMENTAL RESULTS

The proposed tomographic processing chain has been tested on the images coming from the P-band TropiSAR dataset (Dubois-Fernandez et al. 2011). Such a dataset is characterized by a vertical resolution of about 20 m so that it is possible to obtain up to three uncorrelated images inside the vegetation layer. First the stack underwent the ground phases removal described in section 2.1, therefore any height shall be considered as referred to the local ground level. Then the baseline interpolation described in section 2.2 has been implemented and, as a last step, coherent focusing along the cross range direction has been performed thus obtaining a new stack of images corresponding to different elevation with respect to the local terrain level inside the vegetation layer. Standard analyses of such a multi-layered stack are carried out throughout this section. The Guyaux tower is a metallic 50 m tall man made structure dipped in the Paracou tropical forest in French Guyana. Its tomographic imaging may be appreciated in figure 4. As a first analysis of the vegetation layer the backscattered power is shown in figure 5. The uppermost panels show on the left the estimation of the ground slope according to Equation 8, on the right the backscattered power of the original SLC image. The other panels show the backscattered power associated with the multi-height stack in correspondence of 0, 15, 30 and 45 m. A correlation between the ground slope and the backscattered power can be clearly noticed in almost every panel except from the one associated with the middle of the vegetation layer. In order to understand such a behavior it is possible to refer to figure 6 where three slant range, cross range resolution cells are shown. The intermediate cell only is always filled up with leaves and branches not being affected by local topography.

![Figure 6](image_url)

**Figure 6. Physical interpretation of the correlation between the backscattered power and the ground slope shown in figure 5. The intermediate cell is always filled up irrespective of the ground topography.**

The copolar phase is the difference between the phase associated with the signal in the \( hh \) polarimetric channel and the \( vv \). In SAR literature (Freeman 2007) it has been shown that the copolar phase is a very meaningful quantity providing information about the backscattering mechanism which has raised the radar echo. In particular low absolute values are associated with direct ground return or canopy backscattering whereas values far from zero indicate a dihedral one, typically made possible by the perpendicularity of the ground surface with respect to the trunk. Figure 7 enables to compare the copolar phase associated with the original SLC image and the one associated with the 0 m slice. The latter shows a better separation between areas characterized by double bounce and areas characterized by single bounce by discarding the zero copolar phase.
contribution coming from the canopies. The lowermost histograms show that the backscattered power associated with the dihedral mechanism is greater than the one associated with low copolar phase magnitudes.

By comparing the copolar phase in figure 7 with the ground slope shown in figure 5 a high correlation can be noticed. Previous results show that the ground slope has a strong influence on both the backscattered power and the kind of scattering mechanism so that a further analysis is suggested. Figure 8 top panels show the link between the ground slope and the copolar phase for both the SLC image and the one associated with the ground level. By comparing the two panels it may be appreciated that only by neglecting the contributions of the canopies by means of the tomography quantitative analyses can be carried out. Figure 8 bottom panels show the impact of the ground slope on backscattered power: a peak due to the double bounce can be noticed.

Figure 9 shows the same analysis performed on copolar phase in figure 8 by varying the look angle. Even though the images are noisier because of the smaller amount of pixel contributing to the statistic, the "hole" is still evident and its dynamic is clear too. The larger is the look angle, the slower is the disappearance of the double bounce mechanism as the slope drives away from zero.

In order to perform quantitative analyses of the behavior of the double bounce a simple model has been considered here. It expresses the received intensity $I$ due to a double bounce as a function of the look angle $\theta$, the height of the trunk $H$ and the ground slope $\alpha$. This model computes the intensity $I$ by coherently summing waves delayed according to the optical paths associated with the double bounce due to a set of isotropic scatterers placed at height $h$ ($0 < h < H$) above the ground. By referring to the top panel of figure 10 it is possible to have a graphical representation of the model. By performing the sum of the contributions from $0m$ to $Hm$ we get:

$$I \propto \frac{\sin \left( \frac{2\pi}{\lambda} (\cos(\theta - 2\alpha) - \cos(\theta)) \frac{H}{\lambda} \right)}{\frac{2\pi}{\lambda} (\cos(\theta - 2\alpha) - \cos(\theta))}$$

(9)

By setting $H = 7m$ and $\theta = 40^\circ$ (an average of the look angles exploited in the computation of the histogram of figure 8) the main lobe of the $\text{sinc}$ is as large as the lobe shown in figure 8. In order to fit this model on the measurements when varying the look angle $\theta$, the assumption of $H$ depending on $\theta$ is necessary. Assuming $H = H(\theta)$ does not necessarily mean that the physical heights of the trunk is changing with the look angle, but it rather can be
related to a limited ground area in front of the trunk which enables the double bounce. In other words the double bounce is limited by either the length of the trunk or by the extent of a suitable ground depending on the look angle $\theta$. The bottom panel of figure 10 shows such a physical interpretation of an effective height $H$ as a function of the look angle $\theta$.

4. CONCLUSIONS

This paper presents a processing chain to perform SAR tomography over forested areas. The two main features of such an approach are the absence of any physical model and the need of a particular baseline distribution so that the vertical resolution is smaller than the extent of the vegetation layer.

Working without a physical model removes all the issues connected to the choice of the most suitable model for the observed scene and so the retrieval of a-priori information. A baseline distribution which leads to a Fourier resolution along the vertical axis smaller than the tree top heights allows to obtain uncorrelated measurements associated with different elevations inside the vegetation layer. This goal is accomplished by means of coherent focusing along the cross range direction. Therefore a new stack of complex images can be retrieved and processed as standard SLC images.

Results on a real dataset have been also shown. They come from the P-band dataset acquired in the framework of the TropiSAR campaign by ONERA in French Guiana. The observed scene is a very thick tropical forest with trees whose top height reaches 40m; the vertical resolution is about 20m thus enabling the generation of three uncorrelated images associated with three different elevations inside the vegetation layer.

The multi-layer stack has been further processed by standard algorithms and interesting results have been found. First of all it has been shown that the backscattered power of the original SLC image is affected by the ground topography: by means of SAR tomography it is possible to focus on the middle of the vegetation layer to remove almost completely such correlation. It has been also shown that the power associated with the ground trunk double bounce is stronger than the one associated with the direct return. Focusing on the ground level allowed a good characterization of the scattering mechanism contributing to the radar signal and also enabled a quantitative analysis of the double bounce as a function of the ground slope.

The relationship between the double bounce and the ground slope has been analyzed by means of a simple model. Such a model enabled the retrieval of an effective trunk height rising the double bounce. This effective height can also be related to the size of the ground in front of the trunk which enables the double bounce mechanism. Still further analyses are required in order to reach a good comprehension of the physical mechanisms underlying the experimental results.

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