UNDERLYING TOPOGRAPHY ESTIMATION AND SEPARATION OF SCATTERING CONTRIBUTIONS OVER FORESTS BASED ON POLINSAR DATA

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ABSTRACT

The work detailed in this paper analyzes the topographic phase retrieval process on forested areas by means of Polarimetric Interferometric SAR data. On the basis of the Random Volume over Ground scattering model, an alternative implementation for the retrieval of the topographic phase, avoiding the bias introduced by the volumetric scattering components is presented.

***Index Terms*—** Polarimetric SAR Interferometry, Ground topography estimation.

1. INTRODUCTION

Forest areas cover approximately 30% of the Earth's solid surface, with a mean tree height of about 20 m. Any attempt to provide global surface mapping based on SAR Interferometry (InSAR) is affected by the presence of the vegetation cover, in such a way, that the interferometric phase due to the surface scattering presents a bias, respect to the actual value, due to vegetation. The magnitude of this bias error depends on the systems parameters, mainly the frequency, and on the forest characteristics, basically the extinction coefficient. Quantitatively, this error may range up to the mean tree height. The evaluation of the volume decorrelation effects in InSAR data has demonstrated that there is no conventional frequency (from P- up to X-band) able to be sensitive only the ground under a vegetation layer without being affected by any volume, i.e., vegetation scattering contribution. In consequence, all Digital Elevation Models (DEM's) generated by means of conventional InSAR are affected by a more or less significant vegetation bias. The correction of this inherent vegetation bias and the estimation of the underlying ground topography is an essential improvement of the topographic information provided by SAR interferometry, with great ecological as well as commercial impact.

This work aims to present a technique for the estimation of the ground topography on forested areas, based on Polarimetric SAR Interferometric (PolInSAR) data. The retrieval of the ground component considers an alternative use and inversion of the so-called Random Volume over Ground (RVoG) scattering model, which models scattering from forested areas [1]. The main contributions of this novel approach, respect to more classical approaches are the ground topography estimation is not based on the fitting of a line to the data giving as a result a non ambiguous estimation of the ground topography.

This paper is structured as follows. Section 2 presents a brief introduction to Polarimetric SAR Interferometry. Section 3 presents the basics of the technique to retrieve ground topography on forested areas. Section 4 shows the performances of the proposed technique considering both, simulated, as well as real PolInSAR data. Finally, the conclusions of this work are presented.

2. POLARIMETRIC SAR INTERFEROMETRY AND COHERENT MODELLING

A PolInSAR system works on the basis of acquiring two fully polarimetric data sets from slightly different positions in space. In case of distributed scatterers, such forested areas, PolInSAR data, under the assumptions of ergodicity and stationarity, may be characterized by the coherency matrix

$$\mathbf{T}_6 = E\{\mathbf{k}\mathbf{k}^H\} = \begin{bmatrix} \mathbf{T}_{11} & \boldsymbol{\Omega}_{12} \\ \boldsymbol{\Omega}_{12}^H & \mathbf{T}_{22} \end{bmatrix} \tag{1}$$

where ^{H} indicates complex transposition. The matrices $\mathbf{T}_{11}$ and $\mathbf{T}_{22}$ correspond to the individual polarimetric coherency matrices of the two passes and $\boldsymbol{\Omega}_{12}$ is the polarimetric interferometric coherency matrix. The assumption that data may be characterized by (1) is only valid for homogeneous data, that is, when the stochastic behavior of the data is fully described by a zero mean, complex, multidimensional Gaussian distribution.

In order to make possible the retrieval of quantitative information in case of forests, (1) is modeled according to a two-layer model, also known as RVoG model, see Fig. 1 [2]. The first layer, with a height h_v m respect to a given heigt reference z_0

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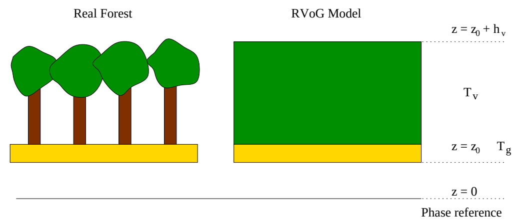


Fig. 1: Modeling of forest scattering by the RVoG model.

m and a mean extinction coefficient σ dB/m, represents the volume scattering contribution of the forest canopy thought a set of randomly oriented particles. The polarimetric contribution of volume scattering is given by

$$\mathbf{T}_v = m_v \begin{bmatrix} 1 & 0 & 0 \\ 0 & \eta & 0 \\ 0 & 0 & \eta \end{bmatrix} 0 \leq \eta \leq 0.5 \tag{2}$$

where m_v represents the volume scattering amplitude and η accounts for the mean particle shape, ranging from $\eta = 0$ in case of spheres to $\eta = 0.5$ in case of needle like or dipole particles. The second layer of the RVoG model accounts for the ground scattering contribution, as well as for the double-bounce scattering contribution due to the ground-trunk interactions. These contribution are modelled from a polarimetric point, under the hypothesis of reflection symmetry, according to

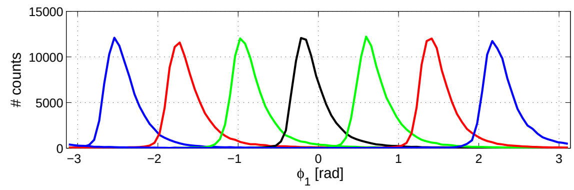
$$\mathbf{T}_g = m_g \begin{bmatrix} 1 & t_{12} & 0 \\ t_{12}^* & t_{22} & 0 \\ 0 & 0 & t_{33} \end{bmatrix} \tag{3}$$

where m_g represents the ground scattering amplitude. It is worth to notice that the location of ground contribution is well located in the vertical dimension at a height z_0 m, that in phase is represented by the term ϕ_1 rad. The contribution of the volume scattering is more diffuse as it ranges from the bottom to the top of the canopy. The bottom limit of this canopy is represented, in terms of phase, by ϕ_2 rad, that is is normally assumed to be equal to ϕ_1 rad, whereas the top of the canopy is at a height $z_0 + h_v$ m, that will present the corresponding phase value. The height information, as measured by the PolInSAR sensor, is encoded in phase through the vertical wavenumber

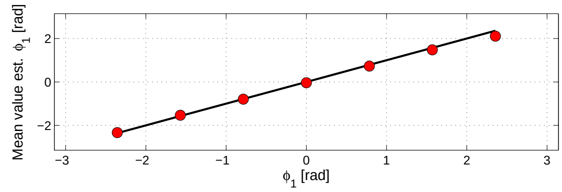
$$\kappa_z = \frac{\kappa \Delta\theta}{\sin\theta_0} = 2\frac{2\pi}{\lambda}\frac{\Delta\theta}{\sin\theta_0} \tag{4}$$

where the interferometric SAR system shall be supposed to operate at a wavelength λ, with a baseline of B m, an incidence angle difference of $\Delta\theta$ rad and a mean incidence angle θ_0.

Considering that forest scattering may be modelled through the RVoG coherent scattering model, the polarimetric matrices $\mathbf{T}_{11}$ and $\mathbf{T}_{22}$ are considered equal and modeled as follows

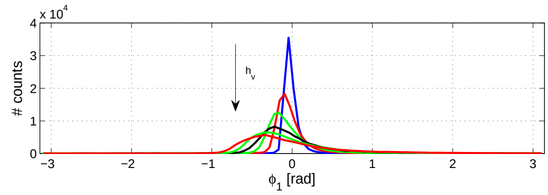


(a) Estimated ϕ_1 histograms

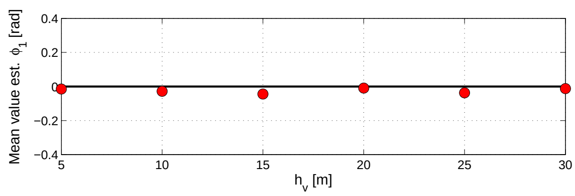


(b) Estimated ϕ_1 mean value

Fig. 2: Estimated ϕ_1 phase with simulated PolInSAR data.



(a) Estimated ϕ_1 histograms



(b) Estimated ϕ_1 mean value

Fig. 3: Estimated ϕ_1 phase with simulated PolInSAR data.

$$\mathbf{T}_{11} = \mathbf{I}_1^v + e^{\frac{-2\sigma h_v}{\cos\theta_0}} \mathbf{I}_1^g \tag{5}$$

$$\mathbf{I}_1^v = e^{\frac{-2\sigma h_v}{\cos\theta_0}} \int_0^{h_v} e^{\frac{2\sigma z'}{\cos\theta_0}} \mathbf{T}_v dz' \tag{6}$$

$$\mathbf{I}_1^g = \int_0^{h_v} \delta(z') e^{\frac{2\sigma z'}{\cos\theta_0}} \mathbf{T}_g dz' = \mathbf{T}_g. \tag{7}$$

The polarimetric interferometric matrix $\mathbf{\Omega}_{12}$ is

$$\mathbf{\Omega}_{12} = e^{j\phi_2} \mathbf{I}_2^v + e^{j\phi_1} e^{\frac{-2\sigma h_v}{\cos\theta_0}} \mathbf{I}_2^g \tag{8}$$

$$\mathbf{I}_2^v = e^{\frac{-2\sigma h_v}{\cos\theta_0}} \int_0^{h_v} e^{j\kappa_z z'} e^{\frac{2\sigma z'}{\cos\theta_0}} \mathbf{T}_v dz' \tag{9}$$

$$\mathbf{I}_2^g = \mathbf{T}_g. \tag{10}$$

The exploration of the vertical dimension of the scatterer under study is performed through the complex interferometric correlation coefficient. In case of PolInSAR data, it is also possible to determine the dependency of this coefficient with

Fig. 4: Pauli RGB decomposition of the Master data set ($R = |S_{hh} - S_{vv}|$, $G = \sqrt{2}|S_{hv}|$, $B = |S_{hh} + S_{vv}|$)

respect to polarimetry [2, 3]

$$\rho(\mathbf{w}_1, \mathbf{w}_2) = \frac{\mathbf{w}_1^H \mathbf{\Omega}_{12} \mathbf{w}_2}{\sqrt{\mathbf{w}_1^H \mathbf{T}_{11} \mathbf{w}_1 \cdot \mathbf{w}_2^H \mathbf{T}_{22} \mathbf{w}_2}}. \tag{11}$$

where the unitary vectors $\mathbf{w}_1$ and $\mathbf{w}_2$, represent generalized scattering mechanisms. In oder to exploit RVoG model $\mathbf{w} = \mathbf{w}_1 = \mathbf{w}_2$ is assumed giving as a result the following interferometric complex correlation coefficient

$$\rho(\mathbf{w}) = \frac{\mathbf{w}^H \mathbf{\Omega}_{12} \mathbf{w}}{\mathbf{w}^H \mathbf{T}_{11} \mathbf{w}}. \tag{12}$$

In [1], it was observed that the linear behavior of $\rho(\mathbf{w})$ with respect to the polarimetric state $\mathbf{w}$ may be employed to retrieve the different parameters that characterize a forest, under the hypothesis of the RVoG coherent scattering model. From this study, one may observe that there is not a single scattering mechanism where the volume or the ground scattering contributions are canceled, that is, it is not possible to create an interferogram which phase depends only on the ground topography. In general, the phase of any interferogram presents a vegetation bias, that as indicated in (12), may be modulated through the polarimetric scattering mechanism, that depends basically on the SAR system parameters and on the forest morphology. Even at low frequencies, such as P-band, data are affected by the vegetation bias, despite the penetration properties of microwaves at this frequency [4].

3. UNDERLYING TOPOGRAPHY ESTIMATION ON FOREST AREAS

The polarimetric interferometric covariance matrix (8) results from the combination of the ground and the volume scattering contributions. Hence, this matrix may be explicitly written as indicated in (13) where one may see that all the matrix components present a dependency on the ground, as well as on the volume scattering contributions. If one considers the elements elements $\mathbf{\Omega}_{12}(1,2)$ and $\mathbf{\Omega}_{12}(2,1)$, it may be seen that the phase of these elements depend only on the ground scattering contribution due to the full azimuthal symmetry of the volume scattering. These phases present the same interferometric contribution from the location of phase center associated to the ground scattering center, that is, $e^{j\phi_1}$. Nevertheless, the polarimetric contribution through the term t_{12}, see (3), present opposite signs. Consequently, if one considers the product of both off-diagonal terms, it may be written as

$$\mathbf{\Omega}_{12}(1,2)\mathbf{\Omega}_{12}(2,1) = e^{j2\phi_1} e^{-2\frac{2\sigma h_v}{\cos\phi_0}} m_g^2 |t_{12}|^2 \tag{14}$$

where it can be observed that [5]

$$\phi_1 = \frac{1}{2} \arg\left\{\mathbf{\Omega}_{12}(1,2)\mathbf{\Omega}_{12}(2,1)\right\}. \tag{15}$$

The previous two expressions make it possible to have access to the underlying ground phase, associated to the ground topography, without the effect induced by the volume bias. Eq. (15) retrieves the topographic information in the range $[-\pi/2, \pi/2)$, so it introduces an additional wrapping in the topographic phase. This additional wrapping may be easily eliminated by considering $\mathbf{T}_{11}$ In one observes the off-diagonal elements $\mathbf{T}_{11}(1,2)$ and $\mathbf{T}_{11}(2,1)$ it is possible to determine that these terms do not present an interferometric phase, whereas the polarimetric contribution, in terms of phase, is the same as in the case of $\mathbf{\Omega}_{12}(1,2)$ and $\mathbf{\Omega}_{12}(2,1)$. Hence, considering the combination of the off-diagonal elements of the matrix $\mathbf{\Omega}_{12}$ together with the off-diagonal elements of $\mathbf{T}_{11}$, the addition phase wrapping is eliminated by

$$\mathbf{\Omega}_{12}(1,2)\mathbf{T}_{11}(2,1) = e^{j\phi_1} e^{-2\frac{2\sigma h_v}{\cos\phi_0}} m_g^2 |t_{12}|^2 \tag{17}$$

where it can be observed that [5]

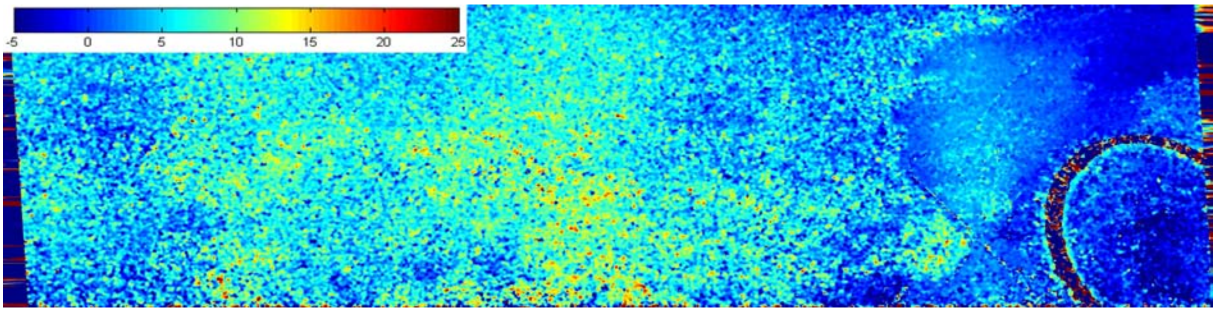
$$\phi_1 = \arg\left\{\mathbf{\Omega}_{12}(1,2)\mathbf{T}_{12}(2,1)\right\}. \tag{18}$$

Eq. (18) provides the topographic phase in the original phase range $[-\pi, \pi)$.

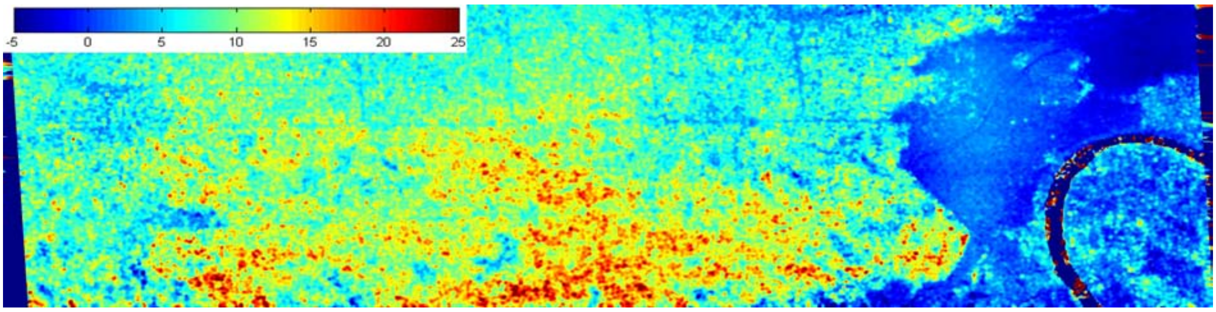
Both expressions, (15) and (18), represent closed analytical expression, under the assumption of the RVoG scattering model, for the unambiguous retrieval of the underlying ground topographic phase in case of forested areas, without the necessity to perform a least squares line fit in the data [1].

4. RESULTS

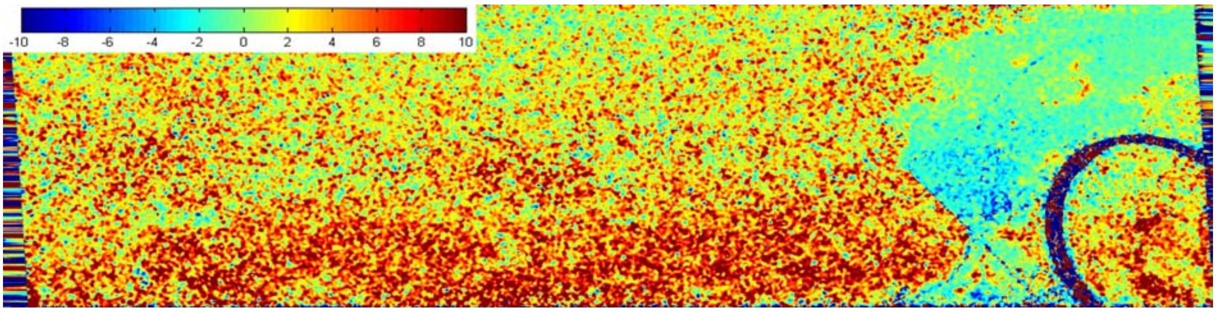
Eqs. (15) and (18) are equivalent with respect to the retrieval of the undelying topographic phase. Hence, results shall be provided in the case of (18).



(a) Estimated underneath topography in meters



(b) Height corresponding to $S_{hv,1}S^*_{hv,2}$ in meters



(c) Height difference in meters

Fig. 5: Indrex-II P-band data set with 15 m interferometric baseline.

In order to validate (18), PolInSAR data have been simulated according the the RVoG coherent scattering model. In this case, the forest parameters are fixed to: $h_v = 15$ m, $\eta = 0.25$ and $\sigma = 0.3$ dB/m. The ground scattering contribution is simulated according to the X-Bragg scattering model considering a flat, rough, loamy terrain with 2.2 water content. Finally, a nominal ground-to-volume ratio $m_g/m_v = -5$ dB has been imposed. The different simulated data sets present a variation of the topographic phase ϕ_1 ($\phi_2 = \phi_1$ has been assumed) with the following values $\phi_1 \in \{-3\pi/4, -\pi/2, -\pi/4, 0\pi/4, \pi/2, 3\pi/4\}$ rad in order to simulate different topographic heights. Fig. 2 details the histograms of the retrieved topographic phases considering (18), together with the corresponding mean values against the simulated topographic phase values. As one may observe, the proposed expression is able to retrieve the correct topographic information, without the bias due to the volume contribution. The performance of the previous expression to retrieve the topographic information remains contant in all the phase range and no wrapping problems are observed as the topographic phase may be retrieved in the range $[-\pi, \pi)$.

In a second set of simulations, the topographic phase is constant with a value of $\phi_1 = 0$ rad, whereas the forest height varies in the range $h_v = \{5, 10, 15, 20, 25, 30\}$ m. Fig. 3 details the retrieved histograms together with the corresponding mean value of the retrieved topographic phase. Again, topography is correctly estimated. Nevertheless, despite the volume contribution does not introduce a phase bias, it introduces a decorrelation factor that induces a degradation of the retrieved topographic phase. This effect may be observed in (18).

Additionally, an evaluation of (18) to retrieve the underlying ground topography based on experimental PolInSAR has been considered. These data correspond to the second Indonesian Airborne Radar Experiment (INDREX-II), that was

$$\boldsymbol{\Omega}_{12} = e^{j\phi_1} e^{-\frac{2\sigma h_v}{\cos(\theta_0)}} \begin{bmatrix} C_v m_v e^{j(\phi_2-\phi_1)} + m_g & m_g t_{12} & 0 \\ m_g t_{12}^* & C_v \eta m_v e^{j(\phi_2-\phi_1)} + m_g t_{22} & 0 \\ 0 & 0 & C_v \eta m_v e^{j(\phi_2-\phi_1)} + m_g t_{33} \end{bmatrix} \quad (13)$$

$$\mathbf{T}_{11} = e^{-\frac{2\sigma h_v}{cos\theta_0}} \begin{bmatrix} m_v \frac{cos\theta_0}{2\sigma}\left(e^{\frac{2\sigma h_v}{cos\theta_0}} - 1\right) + m_g & m_g t_{12} & 0 \\ m_g t_{12}^* & m_v \eta \frac{cos\theta_0}{2\sigma}\left(e^{\frac{2\sigma h_v}{cos\theta_0}} - 1\right) + m_g t_{22} & 0 \\ 0 & 0 & m_v \eta \frac{cos\theta_0}{2\sigma}\left(e^{\frac{2\sigma h_v}{cos\theta_0}} - 1\right) + m_g t_{33} \end{bmatrix} \quad (16)$$

conducted in 2004 on the Kalimantan island of Indonesia. A P-band PolInSAR data set, with an interferometric baseline of 15 m, has been considered where the Pauli RGB decomposition is presented in Fig. 4. As one may observe, most of the data set corresponds to tropical forest, whereas on the right-hand side an sparsely vegetated area and a river may be observed. Fig. 5 presents the estimated underneath topographic height, the height corresponding to the interferogram $S_{hv,1}S_{hv,2}^*$ and the corresponding phase difference. Since the phase center associated to $S_{hv,1}S_{hv,2}^*$ may be assumed to be the highest or close to the highest one, the height difference presented in Fig. 5 is consequent with this argument. Additionally, one may compare the retrieved topography on the sparsely vegetated area (right-hand side) against the topography obtained in the forested one. As it may observed, the height variation in the transition between both areas is more diffuse in the case of the retrieved underneath topographic height, confirming that topography is correctly retrieved. Additionally, the height difference for the sparsely forested area obtained from the difference of the retrieved topographic height ϕ_1 and the height corresponding to the interferogram $S_{hv,1}S_{hv,2}^*$ is close to zero, whereas this difference presents an approximate mean value of 7 m in the case of the forested area.

5. CONCLUSIONS

As demonstrated, the analysis of the RVoG coherent scattering model has made possible to derive two analytical expressions, based on PolInSAR data, that allow a direct and unambiguous estimation of the underlying ground topography without the bias induced by the vegetation cover in case of forested areas. As it has been shown, the estimation of the underlying topography considering the approach presented in this work may be considered as a low coherence problem, making necessary the use of strong speckle filtering, i.e., a large number of averaged samples. In addition, the form of the expressions (15) and (18) would suggest that underlying topography estimation, in case of forest areas, comes from a differential interferogram, as the underlying topographic phase is obtained from the product of two term of the coherency matrix. Results based on both, simulated as well as experimental PolInSAR data confirm the validity of the proposed approach.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] S. Cloude and K. Papathanassiou, “Three-stage inversion process for polarimetric SAR interferometry,” *Radar, Sonar and Navigation, IEE Proceedings* -, vol. 150, no. 3, pp. 125–134, 2003.

[2] S. R. Cloude and K. P. Papathanassiou, “Polarimetric SAR interferometry,” *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 36, no. 5, pp. 1551–1565, Sep. 1998.

[3] S. Papathanassiou, K.P.; Cloude, “Single-baseline polarimetric SAR interferometry,” *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 39, no. 11, pp. 2352–2363, 2001.

[4] I. Hajnsek, F. Kugler, S.-K. Lee, and K. P. Papathanassiou, “Tropical-forest-parameter estimation by means of pol-insar: The indrex-ii campaign,” *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 47, no. 2, pp. 481–493, 2009.

[5] C. López-Martínez and K. Papathanassiou, “Procedimiento para la estimación de la topografía de la superfície de la tierra en áreas con cobertura vegetal,” Spanish Patent Request P201 000 793, June 16, 2010.