# Tropical forest robust 3D description using advanced multidimensional SAR imaging: techniques and performance in the context of the upcoming BIOMASS mission

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**Keywords:** Tropical Forest, BIOMASS, SAR tomography, radar, polarimetry

## Abstract

This paper proposes to quantitatively estimate the potential of 3D SAR imaging for tropical forest characterization using airborne and spaceborne system configuration. A robust forest characterization technique, relying a low-dimensionality model is proposed and is compared with a well-established polarimetric and tomographic approach. The investigated forest descriptors are the underlying ground topography (DTM) and the forest height (CHM). A quantitative performance evaluation reveals that the presented parametric technique achieves high-precision results at both high-resolution (airborne) and low resolution (BIOMASS) modes, whereas existing approaches meet limitations, due the coarse resolution of spaceborne SAR data.

## 1. Introduction

Monitoring the status and dynamics of forest is a major issue in the frame of current climate change analysis, as carbon stock variations for the biosphere represent the major source of uncertainties within the global carbon cycle. Tropical forests play a crucial role in keeping the Earth’s climate in balance, and quantifying the global carbon cycle in the form of Above Ground Biomass (AGB) mapping is highly important. How- ever, tropical forest characterization via remote sensing tools is challenging, as persistent cloud-covers reduce the availability of multispectral optical data, and many tropical regions include steep topography. Synthetic Aperture Radar (SAR) is an active remote sensing device, able to image the reflectivity of wide environments from space, in a systematic way, independently of weather or light conditions. At lower frequencies (L, P or lower bands), electromagnetic waves are able to penetrate densely vegetated areas and SAR represents a unique tool for 3-D forestry remote sensing applications. In this context, the European Space Agency (ESA) is about to launch the BIOMASS spaceborne mission, that includes a SAR device operating over several polarizations at P band, i.e. with a wavelength of 68 cm. In order to overcome the intrinsic limitation of 2D SAR imaging, which cannot unambiguously characterize volumetric environments such as forests, 3D imaging modes will be operated during the BIOMASS mission. In this paper, a characterization of tropical forests is conducted by applying tomographic processing to both high-resolution airborne SAR data and their BIOMASS-like versions. Important forest descriptors, such as canopy height, underlying ground topography. . . are estimated and compared with airborne lidar- derived estimates. Advanced tomographic imaging techniques which are able to efficiently and robustly extract and analyze some key features of tropical forests are described and evaluated over data sets acquired in the frame of ESA’s campaigns over South America, in both high-resolution (airborne) and low resolution (BIOMASS) modes.

## 2. 3D forest imaging using SAR tomography

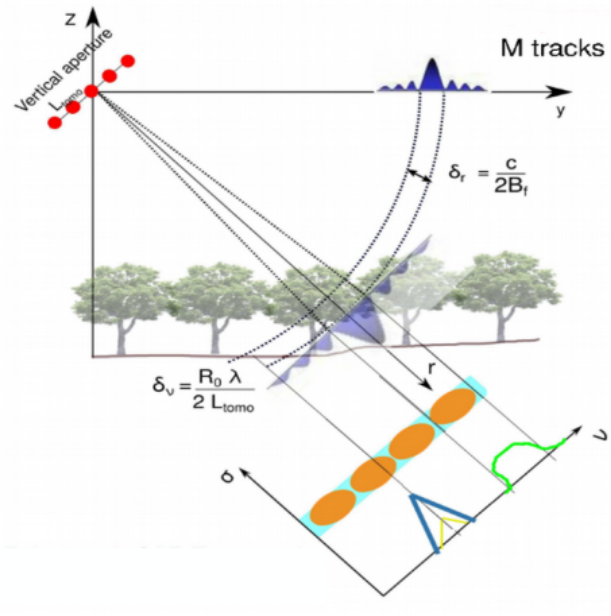
### 2.1 Principles of tomographic SAR focusing

The characterization of forests using two-dimensional SAR images is subject to strong limitations, as this electromagnetic imaging mode cannot separate and characterize contributions from scatterers located at different elevations. Using polarimetric or spectral modes of diversity can lead to a refined analysis of the radar response of the measured environment, nevertheless, such approaches rely on strong assumptions and have limited domains of validity and precision. Tomographic SAR (TomoSAR) processing is a natural solution to this problem (Reigber and Moreira, 2000)(Aghababaei et al., 2020)(Tebaldini and Rocca, 2012) as it implements 3D imaging using an additional spatial diversity, generalizing SAR interferometry to more than two images. The principle of SAR tomography, illustrated in Fig. 1a, is based on a set of 2D SAR images, acquired from slightly shifted trajectories so as to form and additional apertures. The TomoSAR information may be represented, for each 2D resolution cell, by a complex vector, $\mathbf{y} \in \mathbb{C}^{M\times 1}$, whose covariance matrix, $\mathbf{R} = \mathrm{E}(\mathbf{y}\mathbf{y}^H)$, is closely related to the 3D scattering properties of the measured scene. Under the assumption of a locally stationary medium, and neglecting additional sources of decorrelation, an element of the TomoSAR covariance matrix may be written as (Bamler and Hartl, 1998) (Ferro-Famil et al., n.d.)

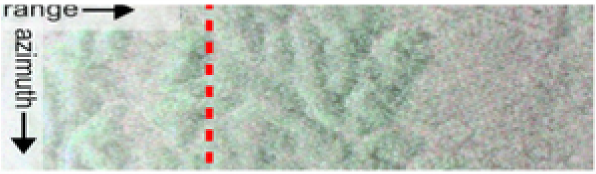
$$[\mathbf{R}]_{pq} = \int f(z)\, \mathrm{e}^{jk_{z_{pq}}z}\, \mathrm{d}z \tag{1}$$

where $k_{z_{pq}}$ represents the phase to height conversion factor for the considered interferometric image pair, and $f(z)$ represents the distribution of reflectivity in elevation. For each 2D resolution cell, the density of reflectivity in elevation of the observed volume may be estimated by coherently combining the set of acquired images. Figure 1c depicts results obtained over the test of Paracou, French Guiana, from P-band SAR data acquired by ONERA in the frame of ESA’s TropiSAR campaign

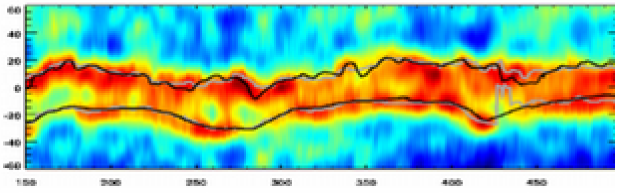
This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-3-2024-163-2024



(a) Geometry of a tomographic SAR acquisition



(b) 2D polarimetric SAR image of a tropical forest



(c) HH intensity tomogram computed along the red path

Figure 1. Tropical forest Digital Surface Models (tree top elevation) estimated over Paracou using high-resolution SAR data

(Dubois-Fernandez et al., 2012). The distribution of the forest reflectivity in the ver- tical direction clearly indicates two main sources of scattering, originating from the ground and from the canopy. The vertical locations of the ground and canopy peaks of reflectivity fit very well the lidar estimates of the lower and upper forest limits.

## 2.2 Proposed technique

The BIOMASS mission is expected to deliver SAR data having a spatial resolution of about 12.5 m and 50 m in azimuth and ground range direction, respectively. Coarse spatial resolution highly affects the quality of the reconstructed tomographic information, and leads to profiles which significantly differs from the one displayed in Fig. 1c. In this work, the accuracy and ill-conditioning issues related to these input data features are addressed by replacing classical spectral estimation techniques (Gini and Lombardini, 2005), (Huang et al., 2012), usually employed to focus tomographic data, with a parametric method which considers simple models for the response of the forest canopy and of the ground (Ferro-Famil et al., 2022), whose features can be estimated in a robust way, even in the complex BIOMASS case (Ferro-Famil et al., 2021). The vertical reflectivity function is decomposed as a sum of independent ground and volume components

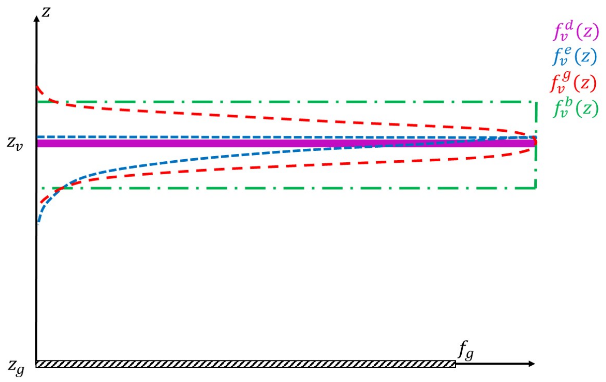


Figure 2. Examples of vertical reflectivity density profiles used to characterize the TomoSAR response of tropical forests with a low-dimensionality model

$$f(z) = f_g(z) + f_v(z) \tag{2}$$

which are described using a low-dimensionality model. As shown in (Ferro-Famil et al., 2022), at P band, the reflectivity profile of a tropical forest can be well approximated by narrow volume profiles. Recent studies showed that the different volume reflectivity profiles proposed in 2 lead to similar characterization results, as long as the spread of their peaky shape remains small enough. The complete vertical reflectivity density function may be parameterized using a small set of variables, and TomoSAR analysis can be performed through the following optimization problem

$$\widehat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} \|\widehat{\mathbf{R}} - \mathbf{R}(\boldsymbol{\theta})\|^2 \tag{3}$$

with the covariance matrix is estimated from the acquired data as

$$\widehat{\mathbf{R}} = \frac{1}{L}\sum_{l=1}^{L} \mathbf{y}(l)\mathbf{y}^H(l) \tag{4}$$

where $\mathbf{y}(l)$ represents a realization of the measured TomoSAR vector. The minimization presented in (3) may be conducted in different ways. One may resort to the use of non-linear optimization techniques, based on a descent algorithm, or to highly non linear functions, whose structure has been designed by a Machine Learning technique, as proposed in (Berenger et al., 2023). The approach developed in (Berenger et al., 2023) proposes to learn a non-linear function, i.e. the weights of a deep neural net, in an unsupervised way, by using the covariance matrix model given in (1), and by comparing the reconstructed tomographic profile with the simulated one.

In this paper the performance of the proposed approach is compared with those obtained using a polarimetric TomoSAR technique, namely the Sum of Kronecker Product Decomposition (SKPD) (Tebaldini, 2010), (Tebaldini, 2009). This method is based on the extension the covariance model in (1) to the case of multi-polarized signals. The PolTomoSAR covariance matrix may be written as

$$\mathbf{R}_{P-S} = \mathbf{C}_g \otimes \mathbf{R}_g + \mathbf{C}_v \otimes \mathbf{R}_v \tag{5}$$

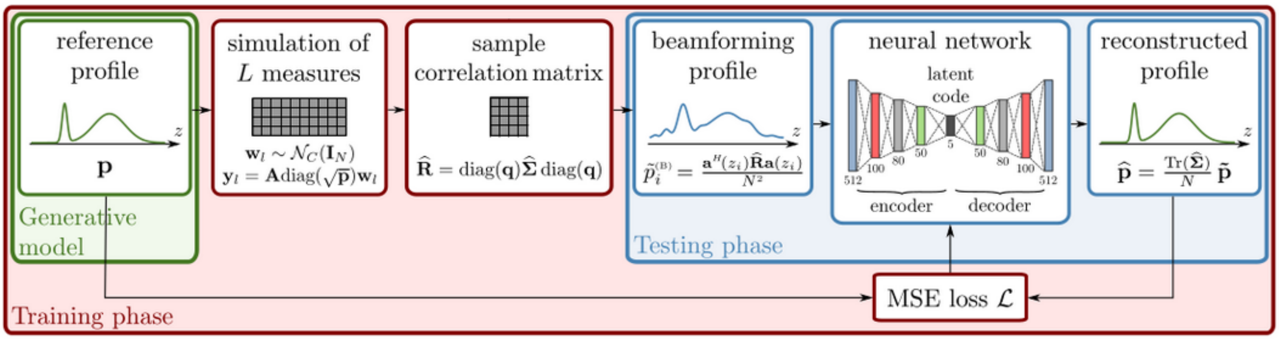


Figure 3. Example of pipeline, sampled from (Berenger et al., 2023) , for the unsupervised training of a deep neural net, able to estimate the structural parameters of a forest tomogram

where ⊗ stands for the Kronecker product operator, $\mathbf{R}$ represents a TomoSAR covariance matrix, whereas $\mathbf{C}$ is a polarimetric covariance matrix. The objective of SKPD is to estimate all four components without using a reflectivity model, by exploiting the complementary information provided by spatial and polarimetric diversity. The elements of the Kronecker products are usually obtained through a singular value decomposition of a linear function of $\mathbf{R}_{P-S}$.

## 3. Tropical forest characterization using airborne high-resolution data

### 3.1 Test site and data set

The different techniques mentioned in this paper are applied to PolTomoSAR data, acquired at P band over the tropical forest test site of Paracou, in French Guiana, during the TropiSAR campaign in the sum- mer 2009, using the ONERA's SETHI system (Dubois-Fernandez et al., 2012). The Paracou site located in a lowland tropical rainforest near Sinnamary, consists of savannah, bare soils, undisturbed forest and logged plots. Forest height ranges from 0 to 50 m. The acquired TomSAR stack consists of six polarimetric and interferometric images having a spatial resolution of 1.5m in azimuth and 1.2m in range (Dubois-Fernandez et al., 2012), and a vertical resolution of around 15 m. The time interval between the acqusitions is small enough so that temporal decorrelation effects may not be considered as significant over the whole acquisition duration. Optical aand SAR images, as well as lidar-derived DSM and DTM are given in Fig.4

### 3.2 DTM and forest height estimation

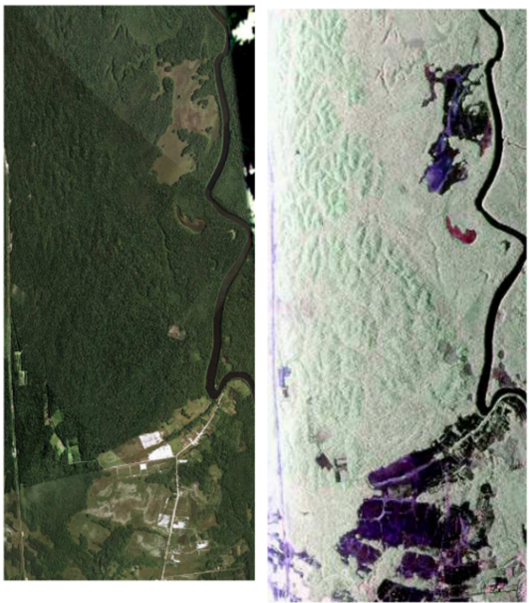
The proposed approach, as well as the SKPD are run over the Paracou test site in order to estimate the different parameters of the model. DSM, i.e. tree top height, estimates are given in Fig. 5, and show that both methods can successfully retrieve this descriptor.

The performance summary given in Table 1 depicts a very good agreement with lidar estimates for both methods.

## 4. Tomographic features of simulated BIOMASS data

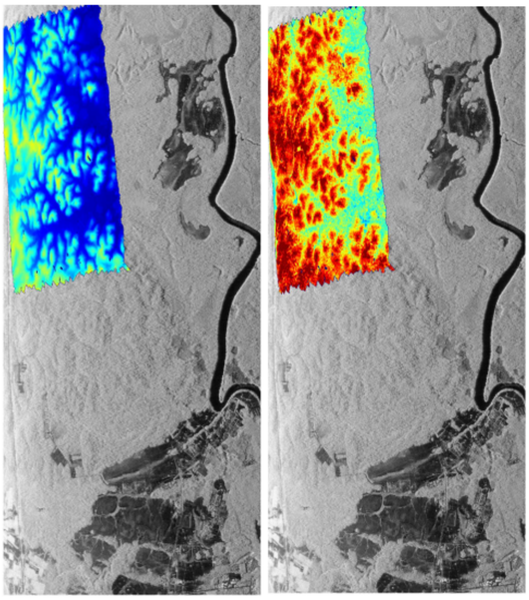
### 4.1 BIOMASS data simulation

BIOMASS data are simulated from airborne acquisitions by applying adequate spectral filters in the radar geometry, in order



(a) Optical image (Google maps)

(b) PolSAR image



(c) DTM

(d) DSM

Figure 4. SAR images, DTM and DSM over the Paracou test site

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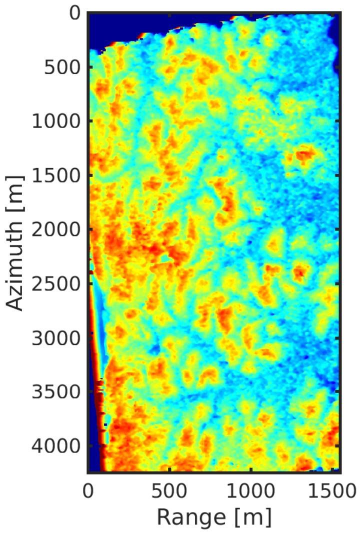
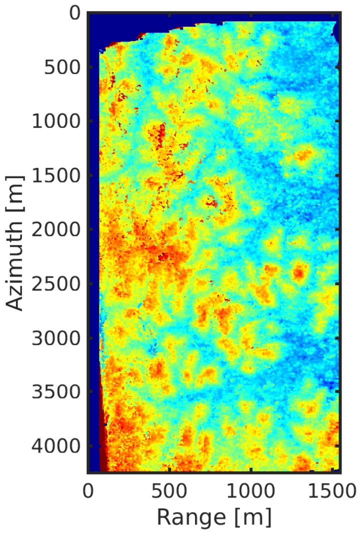
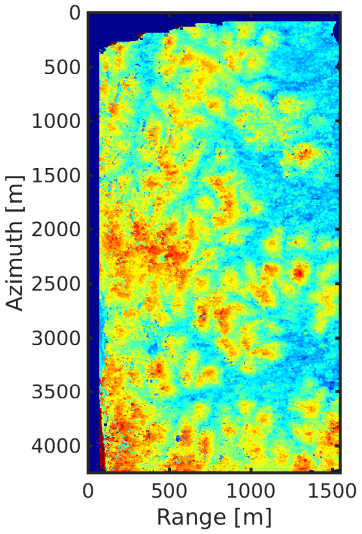


(a) Lidar



(b) Using parametric SAR tomography



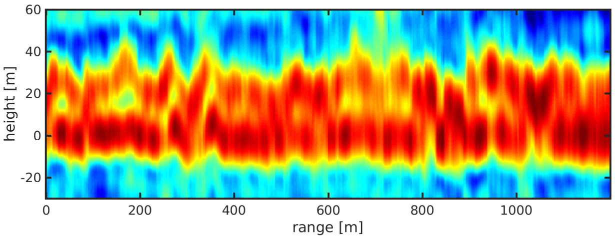
(c) Using SKP-based tomographic decomposition

Figure 5. Tropical forest Digital Surface Models (tree top elevation) estimated over Paracou using high-resolution airborne SAR data

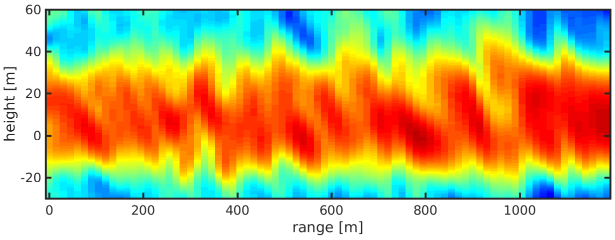
| DTM | bias [m] | sdev [m] |
|---|---|---|
| Cov fit | 0.1 | 1.26 |
| SKP | 0 | 1.67 |

| CHM | bias [m] | sdev [m] |
|---|---|---|
| Cov fit | -0.18 | 2.40 |
| SKP | -0.02 | 2.83 |

Table 1. Bias and standard deviation, with respect to lidar reference, for the DTM and CHM estimates in the airborne SAR case



(a) Using airborne SAR data



(b) using simulated BIOMASS SAR data

Figure 6. Tomograms computed along a profile over Paracou from SAR data having different resolutions

to synthesize 2D SAR images with a resolution of 12 m in azimuth and 25 m in slant range, i.e. 50 m in ground range. The influence of this loss of horizontal resolution on tomographic features is illustrated in Fig. 6. The vertical resolution is significantly affected, due to the well known range decorrelation effect (Gatelli et al., 1994).

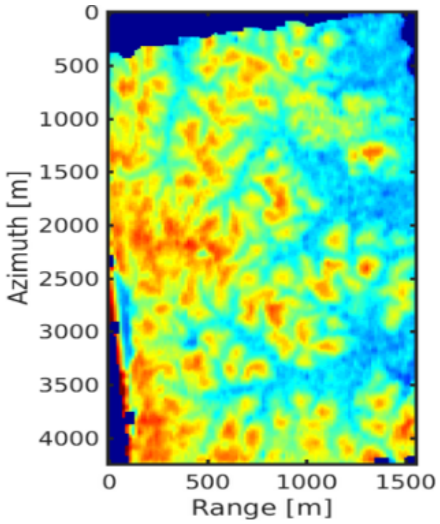
### 4.2 DTM and forest height estimation

The estimated DSM displayed in Fig. 7 indicate coarser errors and features with respect to the high-resolution airborne case. Both method give usable estimate maps, but as one may see in Table 2, the SKP method is more sensitive to the loss of resolution and shows larger errors features, mainly due to the ambiguous estimation of ground and volume coomponents.

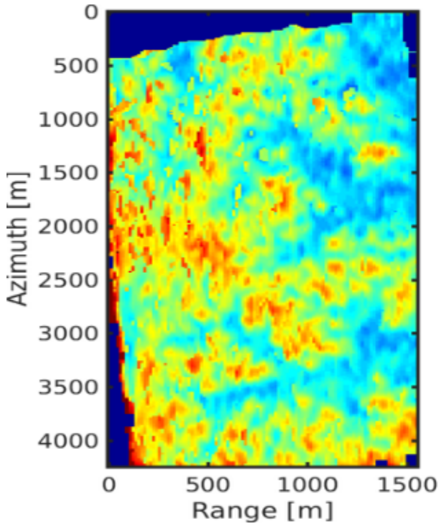
The performance summary given in Table 1 depicts a very good agreement with lidar estimates for both methods.

## 5. Conclusion

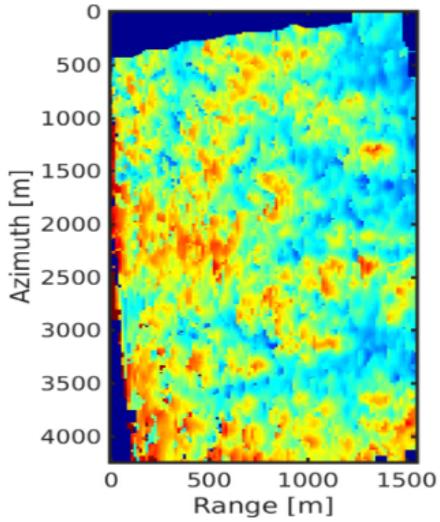
This paper proposed a validation of a parametric tomographic SAR focusing technique, aiming at characterizing tropical forest at lower frequencies, i.e. P band. Results show that a low dimensionality model allows to robustely estimate the vertical density of reflectivity through a simple optimization procedure. A comparison of the proposed method with a well-established fully polarimetric technique indicates that both approaches can



(a) Lidar



(b) Using parametric SAR tomography



(c) Using SKP-based tomographic decomposition

Figure 7. Tropical forest Digital Surface Models (tree top elevation) estimated over Paracou using simulated BIOMASS SAR data

| DTM | bias [m] | sdev [m] |
|---|---|---|
| Cov fit | 0.33 | 2.67 |
| SKP | 1.10 | 3.63 |

| CHM | bias [m] | sdev [m] |
|---|---|---|
| Cov fit | -0.2 | 3.31 |
| SKP | -1.42 | 4.21 |

Table 2. Bias and standard deviation, with respect to lidar reference, for the DTM and CHM estimates in the BIOMASS case

accurately estimate the DTM and DSM of a forest in the airborne case and that the presented techniques outperforms the one in the more challenging case of spaceborne BIOMASS SAR data characterized by a very coarse horizontal resolution.

## References

Aghababaei, H., Ferraioli, G., Ferro-Famil, L., Huang, Y., Mariotti D’Alessandro, M., Pascazio, V., Schirinzi, G., Tebaldini, S., 2020. Forest SAR Tomography: Principles and Applications. *IEEE Geoscience and Remote Sensing Magazine*, 8(2), 30-45.

Bamler, R., Hartl, P., 1998. Synthetic aperture radar interferometry. *Inverse problems*, 14(4), R1.

Berenger, Z., Denis, L., Tupin, F., Ferro-Famil, L., Huang, Y., 2023. A Deep-Learning Approach for SAR Tomographic Imaging of Forested Areas. *IEEE Geoscience and Remote Sensing Letters*, 20, 1-5.

Dubois-Fernandez, P. C., Le Toan, T., Daniel, S., Oriot, H., Chave, J., Blanc, L., Villard, L., Davidson, M. W. J., Petit, M., 2012. The TropiSAR Airborne Campaign in French Guiana: Objectives, Description, and Observed Temporal Behavior of the Backscatter Signal. *IEEE Transactions on Geoscience and Remote Sensing*, 50(8), 3228-3241.

Ferro-Famil, L., Huang, Y., Ge, N., 2022. Forest structure characterization using sar tomography and an adaptive estimation technique. *EUSAR 2022; 14th European Conference on Synthetic Aperture Radar*, 1–4.

Ferro-Famil, L., Huang, Y., Pottier, E., n.d. Principles and Applications of Polarimetric SAR Tomography for the Characterization of Complex Environments. *Springer Berlin Heidelberg*, 1-13.

Ferro-Famil, L., Huang, Y., Villard, L., Toan, T. L., Koleck, T., 2021. Comparison of biomass acquisition modes for the characterization of forests. *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*, 1545–1548.

Gatelli, F., Monti Guamieri, A., Parizzi, F., Pasquali, P., Prati, C., Rocca, F., 1994. The wavenumber shift in SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, 32(4), 855-865.

Gini, F., Lombardini, F., 2005. Multibaseline cross-track SAR interferometry: A signal processing perspective. *IEEE Aerospace and Electronic Systems Magazine*, 20(8), 71–93.

Huang, Y., Ferro-Famil, L., Reigber, A., 2012. Under-Foliage Object Imaging Using SAR Tomography and Polarimetric Spectral Estimators. *IEEE Transactions on Geoscience and Remote Sensing*, 50(6), 2213-2225.

Reigber, A., Moreira, A., 2000. First demonstration of airborne SAR tomography using multibaseline L-band data. *IEEE Transactions on Geoscience and Remote Sensing*, 38(5), 2142–2152.

Tebaldini, S., 2009. Algebraic synthesis of forest scenarios from multibaseline PolInSAR data. *IEEE Transactions on Geoscience and Remote Sensing*, 47(12), 4132–4142.

Tebaldini, S., 2010. Single and Multipolarimetric SAR Tomography of Forested Areas: A Parametric Approach. *IEEE Transactions on Geoscience and Remote Sensing*, 48(5), 2375-2387.

Tebaldini, S., Rocca, F., 2012. Multibaseline Polarimetric SAR Tomography of a Boreal Forest at P- and L-Bands. *IEEE Transactions on Geoscience and Remote Sensing*, 50(1), 232-246.