UAVSAR Tomography for Vertical Profile Generation of Tropical Forest of Mondah National Park, Gabon

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Abstract Polarmetric synthetic-aperture radar (SAR) remote sensing has been widely used for structural and biophysical parameters retrieval of forest vegetation. It has been found that the combination of polarimetric properties and interferometric characteristics of SAR remote sensing provides the capacity to retrieve forest height. The prime objective of this research was to investigate the potential of Polarmetric Synthetic Aperture Radar Tomography (PolTomSAR) for the forested and river region of Mondah National Park, Gabon. SAR tomography is an improved method for acquiring the height of geographical features. UAVSAR L-band fully polarimetric multibaseline data have been used in this research (1.275 GHz). SAR data and ground data over the area have been collected in the year 2016. With the superresolution-based Capon algorithm, multiple scatterers located at a different vertical position in the same azimuth range cell has been resolved and reconstructed. This work provides a framework for Capon-based tomographic processing of multibaseline UAVSAR data for vertical profile retrieval of forest vegetation. The height profile of the forest patch having sparse, as well as dense vegetation, were retrieved. The vertical profile for a single azimuthal bin was obtained in range direction. The tomographic profile obtained was cross-checked with the field-measured forest height for the 16 locations in Mondah National Park, Gabon. To check the accuracy of the applied method, the statistical method of \( R^2 \) and root-mean-square error (RMSE) is employed. The obtained RMSE of the result is 4.21 m and \( R^2 \) is 0.92. The obtained results were concluded to find the potential of the Capon algorithm for the tomographic reconstruction of UAVSAR data.

1. Introduction

The importance of microwave remote sensing in the field of estimation of parameters of forest and natural vegetation has been increasing with the time being. Several spaceborne and airborne SAR missions (T. Fatoyinbo et al., 2016; Labriere et al., 2018) have already been launched by various space agencies and in the near future, several other missions are also planned (Rosen & Kumar, 2019; Williams, 2015). Using the technique of synthetic-aperture radar (SAR) tomography, the global forest structure in 3-D can be imaged by estimating the height of forest; thus, developing and checking the applicability of the algorithms of tomography is very important. The estimation of aboveground biomass (AGB), can be done using the forest height parameter (Valbuena et al., 2016). Many studies have been done to link SAR tomography and AGB (Blomberg et al., 2018; El Moussawi et al., 2019; Ho Tong Minh et al., 2016; Zhang et al., 2018).

The SAR is a modality of the acquisition of the backscattering of transmitted microwave from the terrain. The amount of backscattering from the geographical features depends upon the size, shape, and dielectric constant of the feature (Tebaldini et al., 2019). There are many techniques developed by processing SAR data for (a) estimation of various parameters such as for estimation of movement in the terrain of any feature the technique of DInSAR (Differential Interferometric Synthetic Aperture Radar) (Gupta et al., 2019; Radhi et al., 2015), PSInSAR (Persistent Scatterer Interferometric Synthetic Aperture Radar) (Asopa et al., 2018); (b) differentiating between various geographical features using the technique of PolSAR and PolInSAR (Budillon et al., 2019; Shafai & Kumar, 2020); (c) to find the height of any geographical feature using the technique of SAR tomography (S. Kumar et al., 2017), and so forth. UAVSAR L-band has a wavelength of 23.84 cm with a frequency of 1257.5 MHz. L-band microwaves can penetrate through the canopy of the forest, getting backscattered from the ground surface and other areas such as snow and sand is a case where it is opaque at the optical spectrum (Tebaldini et al., 2019). Due to the penetration of the L-band microwave into the forest canopy, the vertical profile of a forest cover can also be mapped. The studies have shown the capability of SAR tomography to map the subcanopy features of the forest (Tebaldini & Rocca, 2012). However, microwave remote sensing encounters a problem because of the complex type of backscattering due to the...
involvement of multiple scatterers in the path having various scattering mechanisms. The radar signal in the forest is determined by direct scattering from elements within the vegetation canopy, from the underlying terrain, as well as from multiple scattering resulting from the waves bouncing off the ground in the direction of the radar after being scattered downward by the tree canopy and trunks (Treuhaft & Siqueira, 2000).

Apart from SAR tomography, three-stage PolInSAR inversion is also a method for estimating the parameter like forest height profile estimation (Babu & Kumar, 2018; Joshi et al., 2016) of a forest. SAR tomography is an extension of 2-D SAR imaging (range and azimuth plane) to 3-D by forming an additional aperture (synthetic) in the direction of elevation utilizing the stack of multibaseline InSAR data sets resulting in a profile of height of target as a third dimension in the data (Reigber & Moreira, 2000). SAR tomography is an advanced tool to estimate the vertical profile of geographical feature, that is, arrangement of various kinds of scatterers at different height or altitude from the ground. The tomographic SAR data are acquired by making continuous imaging of the area with multiple trajectories in such a way that they have a minimum horizontal and fixed vertical baseline (Nannini et al., 2008). The L-band microwave having a low frequency and large wavelength can penetrate through the canopy to the ground beneath. Electromagnetic wave interacts with the canopy, branch and leaf, stem, and then ground in the path.

SAR tomography was first demonstrated by Reigber and Moreira (2000) using the airborne L-band data. Mostly, L-band SAR tomography has been performed in the boreal forest (Tebaldini & Rocca, 2012) or temperate forest (Tello et al., 2018) regions with an assumption that L-band microwaves barely penetrate through the dense forest canopy to the ground. But recent studies carried out on tropical forests of Gabon country by L-band UAVSAR for retrieval of forest height have yielded a good result (Marco Lavalle et al., 2017; El Moussawi, Tong Minh, et al., 2019).

This research paper provides an understanding of SAR tomography through the superresolution-based Capon algorithm for vertical structure retrieval of forest in Mondah National Park of Gabon. Capon algorithm was introduced in the year 1969 for the study for complex signals (Capon, 1969). The SAR tomography has been implemented with the help of various experiments done in the years on both airborne and spaceborne SAR data in experiments (Gini et al., 2002; Guillasio & Reigber, 2005a; Lombardini & Reigber, 2003). SAR tomographic algorithms are basically of two types: parametric (root MUSIC, M-RELAX, etc.) and non-parametric (Beamforming, Capon, etc.). It is observed via various studies done for retrieval of the vertical profile of the geographical features, the nonparametric algorithm of Capon yields a better estimation (Gini et al., 2002).

The potential of the application of a superresolution based Capon spectral estimation method, on the L-band UAVSAR data set is investigated through this experiment and ground observation. The SAR tomography of tropical forest has been studied in this research. The first section of the paper is dedicated to the introduction of the technique and importance of the study, section 2 is dedicated to introducing the study and providing the information about the location and terrain type of the area. The data set utilized in the study and steps involved to perform the tomography is provided in section 3. The results obtained and inferences made through the results are given in section 4. Section 5 includes the analysis of results and discussion of the same. Section 6 concludes the research.

2. Study Area

The site of study selected for this research is located in the Mondah National Park of Gabon country in the African Continent. The National Park is located between 0°36′ and 0°24′N latitude and 9°18′ to 9°50′E longitude in the “Estuaire” Province of the country. This park was established in 2002. This lower altitude zone is populated by 35,000 ha of relatively untouched marine mangroves, swamp forests, and grassy savannas. Figure 1 shows the location of the study area (displayed by the SAR data) over the true color composite made by the Sentinel-2 data set. The elevation in the park varies up to 250 m which is derived from the SRTM 1 arcsec data.

The Mondah National has the forest which is almost undisturbed and contains large number of marine mangroves, swampy forest, and grassy savanna forest, which is a home for migratory birds such as Palearctic waders. This area serves as an important place for many species as a feeding area. Some of these species are “endangered marine turtles” (Lepidochelys olivacea and Dermochelys coriacea), This area also provides
sanctuary for birds like “little stint” (Calidris minuta), “gray plover” (Pluvialis squatarola), “endemic yellow-breasted apalis” (Apalis flavida), and “swamp boubou” (Laniarius bicolor), also this area is a major habitat and breeding ground for crustaceans and fish-like “bonga shad” (Ethmalosa fimbriata) and “flathead mullet” (Mugil cephalus).

3. Materials and Methods

3.1. Data Set

The data set belongs to the L-band wavelength range of the microwave spectrum. The data set was acquired with the sensor heading in direction 160°. A total of nine data sets was utilized in this study. The data set was having a fixed vertical baseline which is 20 m with a minimum horizontal baseline. The properties of the data set are provided in Table 1 along with the baseline distribution of the data set. Figure 2 represents the stack of data set arranged according to the spatial baseline of the data set.

These data sets were acquired by NASA under the mission of AfriSAR. This mission was initiated to support the upcoming NISAR, GEDI, and BIOMASS missions. This UAVSAR data set was acquired with the aircraft “Gulfstream-III jet”. This aircraft has been modified to incorporate an MAU-12 ejector rack on the bottom of the fuselage. At the time of data acquisition, four crew members stayed on the aircraft to pilot and monitor the autopilot of the aircraft. The Platform Precision Autopilot (PPA) accurately maintains the flight of the plane while the radar collects the data. It also controls the airplane so that it can fly a similar flight path within a tube of diameter 10 m (33 ft.), for very long distance at a time, which is an essential step for the tomographic data set processing.

3.2. Field Data

The field data set was collected by the team from 1 March 2016 to 23 March 2016. The forest area chosen for the data collection was located in the western part of the Mondah Forest. Spatially, the plots made were of different sizes such as 0.0625, 0.25, and 1 ha, which is given

Table 1

| Parameters                   | Description                  |
|------------------------------|------------------------------|
| Date of acquisition          | 6 March 2016                 |
| Stack name                   | Mondah_TM270_04              |
| Flight line ID               |                              |
| No. of data set              | 9                            |
| Heading angle                | 160                          |
| Antenna angle                | 90                           |
| Look direction               | Left                         |
| Look angle range (degree)    | 25–65                        |
| Polarizations                | Quad Pol (HH, HV, VH, VV)    |
| Pulse length (μs)            | 40.0                         |
| Center frequency (MHz)       | 1257.5                       |
| Wavelength (cm)              | 23.8403545                   |
| Intrinsic resolution         | 1.8 m slant range            |
|                             | 0.8 m azimuth                |
| Band                         | L                            |
| Data type                    | SLC                          |
| Data dimension               | 47,825 × 9,900               |
| Aircraft speed (m/s)         | 220                          |
| Baseline (m)                 | 0–160                        |
| Chirp bandwidth (MHz)        | 80                           |
| Aircraft altitude (m)        | 13,800                       |
| Swath width (m)              | 16,000                       |
in T. Fatoyinbo et al. (2016). The measurements were taken once in the study area. Overall, 92 plots were made to collect data such as GPS location of the field points, DBH of the trees, tree height (canopy), basal area, vegetation type, and others. Roughly, around 6,700 trees were measured (L. Fatoyinbo et al., 2017; T. Fatoyinbo et al., 2016; Marco Lavalle et al., 2017). The area was scanned with the aerial LiDAR during the period of February to March, 2016. The LiDAR was mounted on LVIS (land, vegetation, and ice sensor) (Blair et al., 1999). The forest of Gabon was sensed as a part of NASA/ESA/DLR/AGEOS AfriSAR Campaign. It produced two level products (Level 1B and Level 2). In this research, Level 2 data sets were utilized as the reference for forest height as well as the ground survey data. The level 2 LiDAR data files contained canopy top and ground elevation. The LiDAR data were downloaded from the portal of National Snow and Ice Data Center (NSIDC) (Blair & Hofton, 2018).

The field visit was done by the team of NASA under the mission AfriSAR and TropiSAR for the estimation of various biophysical parameters of the forest of Mondah and other chosen locations as Lope, Mabounie, and Rabi in Gabon Country (Labriere et al., 2018). The location of ground survey points is displayed in Figure 3, which provides the location of 16 plots in the selected region of study. Plot points have been placed onto the Pauli RGB of the data set. The plot ID of these survey locations provided as MND05, MND01, MND13, and MND20 are A, B, C, and D locations, respectively. Out of all the locations for the ground survey done by the team of mission in Mondah National Park, these locations (A, B, C, and D) have been taken into study. The locations provided in Figure 3 are 1-ha locations, these are further divided into four parts as the 0.25-ha plot. For the simplicity in representation, 1-ha plots are displayed (A, B, C, and D). These 0.25-ha plots have plot ID as MND01q1, MND01q2, and so forth. as provided in Table 2 (Labriere et al., 2018).

### 3.3. Methodology and Background of Technique

The methodology employed in this study is provided in Figure 4. The steps adopted into processing for tomographic spectral estimation includes various steps such as creating the stack of SAR data, calculating the covariance matrix, and so forth. The covariance matrix has been used to estimate the power spectrum of selected resolution cells according to the elevation or position of scatterer in the elevation direction. The SAR data provided by the agency is in the format of a single look complex which is in slant range x azimuth plane, in the image plane of satellite data. Every pixel of the data set is in complex format, that is, containing a real and imaginary value (I and Q) (ESA, 2018).

PolInSAR images are multiple fully polarimetric data sets having interferometric properties, that is, small spatial as well as a temporal baseline. In this section the method of estimating the tomogram is discussed. The tomography is of two types: Multibaseline InSAR-based tomography, that is, only single polarization is used to estimate the tomograms, the other one is Multibaseline PolInSAR-based tomography, which employs all the four polarimetric channels. For estimating the tomograms following steps were performed which are covariance matrix generation and estimating the tomograms using the beamforming method. Here the Capon beamforming method is employed. The signal model representing the acquired signal from the parallel flight tracks can be expressed by (Bamler & Hartl, 1998; Tebaldini et al., 2019).

\[
I_i = \int s(y, z) * \exp \left( \frac{4\pi}{\lambda} R_i(y, z) \right) dydz
\]  

(1)

Here, \( I_i \) is the complex-valued pixel of the SAR image acquired along the ith track; \( s(y, z) \) represents the individual scattering element in the height/ground range plane; \( R_i \) is the representation of the distance between
the scattering element and the sensor. This integral provided in Equation 1 is limited to the resolution cell in-ground range and height plane. The radius of the resolution cell is $R$ and centered for the $i$th track. Expanding Equation 1 to a reference point by projecting the scene reflectivity on to the elevation axis and taking baseline as $b_n$ (as from Tebaldini et al., 2016):

$$I_i = \int P(e) \exp \left( \frac{-4 \pi b_n}{\lambda R} e \right) de$$

(2)

Here, $e$ is the representation of the elevation of the scatterer, $R$ is the slant range distance of the scatterer and the sensor. From Equation 2, the vertical wave number for $n$th acquisition track can be defined as

$$K_n = \frac{4 \pi b_n}{\lambda R}$$

(3)

For this study, the vertical wave number file is provided along with the data set. The $k_z$ file is the height vector of every resolution cell interlinking the distance of the target from the sensor, wavelength employed, and the baseline distance of the data set along with the master. Vertical wavenumber file is very important in the studies of height and other parameters of a geographical feature. The sensitivity of the phase to the height variation is well described by the vertical wave number (Bamler & Hartl, 1998). It is denoted by the “$k_z$.”

Reviewing Equation 3 for vertical wave number through Equation 4

Figure 3. Location of the survey plots in the region of study.
Vertical wave number is estimated between the master and slave images. So, here \( \Delta \theta = \theta_1 - \theta_2 \) is the change in the incidence angle induced by the spatial baseline \( B_{\perp} \), \( \theta_1 \) represents the incident angle of the pixel l of master image and \( \theta_2 \) represents the incident angle of the slave image; \( \lambda \) is the wavelength, \( R \) is the slant range distance. The factor \( m \) accounts for the acquisition mode: \( m = 2 \) for monostatic acquisitions and \( m = 1 \) for bistatic acquisitions. In conventional interferometric applications, \( k_z \) expresses the sensitivity of the interferometric phase to (terrain) height variations (Bamler & Hartl, 1998). For a constant forest height, the volume coherence decreases with increasing \( k_z \). Decreasing extinctions also lead to a constant height and a fixed \( k_z \) to lower coherence levels (Kugler et al., 2015). Since the value of \( k_z \) is dependent on the sine of incidence angle inversely, that is why for increasing incidence angle, \( k_z \) is decreasing, which means that for near range the value of \( k_z \) is high, and for far range the value of \( k_z \) is small.

The factors affecting the quality of reconstruction are the baseline, vertical wave number, and height of ambiguity. Height of ambiguity is the “distance from a target along the vertical direction at which artifacts appear due to the finite sampling in the wave number domain,” that is, the height interval in which objects may appear during the reconstruction. If the baseline interval is assumed to be uniform between the set of images then the total baseline span of distribution for \( x \) number of images can be given as \( b_x = x' \Delta b \), and thus the wave number \( k_z \) can be written as

\[
k_z = \frac{2^*m^*\pi^*\Delta \theta}{\lambda^*\sin(\theta)} \approx \frac{2^*m^*\pi^*B_{\perp}}{\lambda^*R^*\sin(\theta)} \tag{4}
\]

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\[
\Delta K = \frac{4^*\pi^*\Delta b}{\lambda^*R} \tag{5}
\]

Here, \( \Delta b \) is the common spatial baseline difference and \( R \) is the slant range distance of the resolution cell and sensor. The height of ambiguity can be provided as

\[
z_{ambi} = \frac{\lambda^*R}{2^*\Delta b^*\sin(\theta)} \tag{6}
\]

Basically, for the forest area, the height of ambiguity should be larger than the height of the ambiguity of the data set for the tomographic reconstruction. Thus, for aerial survey planning, the height of ambiguity should be kept in check by maintaining the baseline difference such that the height of ambiguity should be at least twice the height of the forest. There are many studies on the tomographic reconstruction using Fourier transform (Guillaso & Reigber, 2005a; S. Kumar & Joshi, 2017). The problem with the Fourier transform-

| Plot no. | Area code | Plot ID | Longitude | Latitude | Height recorded in ground survey (m) | Height derived with the PolInSAR inversion (m) | LiDAR height (m) | Height profile achieved in the tomographic processing (m) |
|---------|-----------|---------|-----------|----------|-------------------------------------|-----------------------------------------------|-----------------|-------------------------------------------------|
| 1       | MND01q1   | MND01   | 9.356666  | 0.549284 | 43.45                               | 43.31                                         | 47.68           | 47                                             |
| 2       | MND01q2   | MND01   | 9.356695  | 0.550654 | 46.06                               | 42.59                                         | 49.38           | 48                                             |
| 3       | MND01q3   | MND01   | 9.356685  | 0.549711 | 44.54                               | 53.49                                         | 48.86           | 45                                             |
| 4       | MND01q4   | MND01   | 9.356682  | 0.550171 | 45.67                               | 43.31                                         | 48.83           | 50                                             |
| 5       | MON05q1   | MON05   | 9.342178  | 0.563019 | 11.22                               | 13.07                                         | 20.11           | 15                                             |
| 6       | MON05q2   | MON05   | 9.34217  | 0.563436 | 15.64                               | 20.29                                         | 20.8505         | 21                                             |
| 7       | MON05q3   | MON05   | 9.342611 | 0.563049 | 5.81                                | 10.81                                         | 9.09            | 7                                              |
| 8       | MON05q4   | MON05   | 9.342573 | 0.563478 | 6.26                                | 18.71                                         | 13.2375         | 15                                             |
| 9       | MON13q1   | MON13   | 9.357092 | 0.576632 | 26.77                               | 21.73                                         | 34.669          | 30                                             |
| 10      | MON13q2   | MON13   | 9.357111 | 0.577082 | 21.62                               | 19.17                                         | 27.11           | 15                                             |
| 11      | MON13q3   | MON13   | 9.357555 | 0.576604 | 16.14                               | 16.25                                         | 19.61           | 18                                             |
| 12      | MON13q4   | MON13   | 9.357552 | 0.577069 | 15.28                               | 17.01                                         | 19.9            | 10                                             |
| 13      | MON20q1   | MON20   | 9.36768  | 0.573033 | 20.4                                | 16.42                                         | 20.92           | 16                                             |
| 14      | MON20q2   | MON20   | 9.367708 | 0.573483 | 23.97                               | 15.64                                         | 26.55           | 25                                             |
| 15      | MON20q3   | MON20   | 9.368118 | 0.573018 | 6.8                                 | 8.94                                          | 8.15            | 9                                              |
| 16      | MON20q4   | MON20   | 9.36814  | 0.573451 | 23.59                               | 9.31                                          | 10.641          | 26                                             |
based tomographic reconstruction is that the vertical resolution of the reconstruction is limited to the verti-
cal resolution defined by the Rayleigh limit (Equation 7):

$$\Delta z \approx \frac{\lambda r}{2 b_{\text{max}} \sin(\theta)} \quad (7)$$

Here, $b_{\text{max}}$ is the representation of the maximum baseline span of the data set. The vertical resolution achieved by the Fourier transform for the height profile retrieval is limited to the vertical resolution achieved making the output coarser (Ho & Minh, 2013; S. Kumar et al., 2017). To study the objects smaller than the vertical resolution or Rayleigh limit, superresolution algorithms are required which can successfully map the features of size smaller than the resolution. Superresolution algorithms allow data-dependent side lobes cancelation by rejecting interference coming from other elevation directions than the selected as sensed through the information in the spatial covariance matrix (Ho & Minh, 2013). Upon considering $N$ backscatter-
ing sources in a single-resolution cell, the vector $Y(k)$ denotes the noise-compensated signal of additive and multiplicative noise, denoted by Equation 7:

$$Y(k) = c(k) + n(k) \quad (8)$$

Here, $c(k)$ contains the multiplicative noise due to speckle, and $n(k)$ is the additive noise; $x_n(k)$ is the backscattering; $b(\theta_n)$ is the steering vector; $\tau$ represents the radar reflectivity which is mean intensity of the resolution cell (Lopès et al., 2010), that is, the SPAN which is given in (Equation 10)

$$\text{SPAN} = |S_{HH}|^2 + |S_{HV}|^2 + |S_{VH}|^2 + |S_{VV}|^2 \quad (10)$$

For each resolution cell and single polarization channel, the steering vector is defined as follows (Equation 11), having the dimension of $N \times 1$ for each elevation point $z$:
For the fully polarimetric data set, the steering vector can be written as (Equation 12) (S. Kumar, Joshi, & Govil, 2017)

$$\mathbf{b}(z) = \begin{bmatrix} a(z) & 0 & 0 & 0 \\ 0 & a(z) & 0 & 0 \\ 0 & 0 & a(z) & 0 \\ 0 & 0 & 0 & a(z) \end{bmatrix}$$

The covariance matrix can be calculated by averaging all interferograms of noise-cancelled signals over the estimation window (Equation 13):

$$\hat{\mathbf{R}} = \frac{1}{N} \sum_{n=1}^{N} \mathbf{Y}(n)\mathbf{Y}^\dagger(n)$$

Here, $\hat{\mathbf{R}}$ the covariance matrix, $\mathbf{Y}$ denotes the noise-cancelled signal, the symbol $\dagger$ denotes the complex conjugate, and $N$ is the number of images. Capon algorithm is a non-model-based, nonparametric algorithm. Accuracy in vertical profile estimation can be achieved by implementing the Capon algorithm, but the achieved radiometric accuracy gets comparatively low (Lombardini & Reigber, 2003). The inverse of the covariance matrix ($\hat{\mathbf{R}}^{-1}$) can be derived only if the adaptive noise has positive definite covariance matrix. As provided in Equation 11, the steering vector depends on the elevation of the point scatterer ($z$). As the application of the SAR Tomography is the retrieval of the elevation of scatterer and its reflectivity (Khati et al., 2019). The final power estimation of fully polarimetric SAR data using Capon spectral estimator is given as

$$\hat{P}_{\text{pol}}^\text{C} = \frac{1}{B^\dagger(w)\hat{\mathbf{R}}^{-1}B(w)}$$

The fully polarimetric Capon estimator executes more averaging which reduces the azimuthal range resolution (S. Kumar, Joshi, & Govil, 2017). Capon estimator reduces the possibility of sidelobes in the power backscattering function and thus makes it possible to get a higher resolution for continuous vertical profile of forest vegetation (El Moussawi, Tong Minh, et al., 2019; Guillasso & Reigber, 2005b; Lin, 2017). In the case of tropical forest, identifying the vertical structure of the tree can be a little ambiguous because of the structure. Thus, in this case, SAR tomography has been very promising as it can locate the position of dominant backscatterer in the vertical domain. Capon beamformer provides the power distribution of a ground pixel in the vertical domain. In a vertical structure of a tree, the dominant scatterer position is the position where the canopy density is relatively high.

The height of the effective/dominant scattering center or phase center from the Capon-based 3-D backscatter profile of multiple SLC data was measured from the location which shows the maximum concentration of backscatter energy. The effective phase center height is a point located somewhere between the TCH and the ground. Equation 15 represents the effective phase center height ($H_{C}$) in vertical direction $z$ at slant range location $r$ and azimuth location $x$.

$$H_{C}(r, x) = \arg\max \left\{ \hat{P}_{\text{pol}}^\text{C} (z, r, x) \right\}$$

where $\hat{P}_{\text{pol}}^\text{C} (z, r, x)]$ is the maximum backscatter in vertical direction $z$ at a given range and azimuth locations.

The forest top height is different than the height of the effective scattering center. To measure the TomoSAR-based top canopy height, we implemented the procedure for measuring the power loss value from the effective phase center along the vertical direction in the upper envelope of the profile (El Moussawi et al., 2019; El
Equation 16 shows the formula to measure the TomoSAR-based top canopy height.

\[
H(r, x) = \arg\min \{P(z', r, x) - P(H_C, r, x) - K\}
\]  

(16)

where \(P(H_C, r, x)\) is the backscatter at effective scattering center, \(K\) is the power loss value, and the envelope of the profile is represented by \(z'\). To measure an approximate power loss a PolInSAR canopy height model (Lavalle et al., 2018) was used.

4. Results

Tomographic results obtained through the study of the airborne UAVSAR data set are mentioned in this section. The tomographic outputs of the UAVSAR data set of site Mondah National Park, Gabon is validated with the ground data acquired over the area. The tomographic reconstruction was done using the Capon beamforming algorithm as explained in the previous section. The tomographic results can be provided in the manner of power (dB) as well as in normalized form. The power from the dominant scatterers is displayed in the tomogram. For a homogeneous patch of vegetation, the vertical profile obtained is of linear type, that is, maintaining a similar height level.

The Pauli RGB image derived from the data set of UAVSAR itself is provided in Figure 5a, for comparing the SAR data set with the optical data set, Figure 5b has been provided alongside. For the tomogram provided in Figure 5c, the vertical profile is homogeneous and power estimated at various locations has some spatial leakage, which is the indication of the other scatterer present at that location, and thus it is the indicator of the presence of the subcanopy features lying beneath the main top canopy of the forest. For bin numbers 300 to 500 and at the rightmost part after bin 800 (green ellipses), there is further subcanopy feature present which provides a good amount of power scattering.

In the tomogram (Figure 6), it can be seen that the intensity or the power estimated in the initial part of the tomogram is relatively very low (almost no tree stands), which is the indication of the presence of smooth surface features that continue till the bin number ~780. The transect for the above image covers the part...
of the land (river bank), river body, and then some of the land body which is also giving backscattering corresponding to the smooth surface feature. From bin 780, the algorithm detects the presence of tall canopy, which appears to be sparsely vegetated. This sparseness can be verified by the LiDAR signal (white line in tomogram Figure 6c). Due to their sparseness, the LiDAR height profile shows a little variation. The algorithm estimated the presence of tall canopy with height corresponding to 55 m–60 m at the end of the transect and shown by the high intensity in the tomogram. The bin from 750 onward is located away from the river bank and the dense forest area starts afterward. The presence of tree canopy at the end of the transect can also be seen in the optical image (as it is a true-color composite made from the high-resolution satellite data from Google Earth satellite) provided in Figure 6b. Figure 6a shows the area and transects for which the tomogram has been made in the Pauli RGB image produced from UAVSAR data. The land area covered in the bin provides a good vertical profile and has dominant power backscattering from the top canopy height.

In Table 2 (provided below), the height recorded during the ground survey is provided in Column 6 (forest canopy height) (L. Fatoyinbo et al., 2017) and the tree height achieved with the tomographic processing of available data sets in Column 9. The height profile of the whole Mondah region is generated by authors (Lavalle et al., 2018), with which the height map derived with the PolInSAR method is provided (mondah_polinsar_canopy_height.tif). For reference, the height derived from the PolInSAR inversion method is taken into comparison at the ground survey sites. The height profile at the ground survey point is mentioned in Column 7 and LiDAR height is provided in Column 8 of Table 2.

Figure 7a represents the achieved value of $R^2$ for the analysis of accuracy in the processing. The obtained value of $R^2$ for this experiment is 0.92. Here from the regression line, we can easily see that most of the points of the graph are located near to the trend line in the graph. The more points are near to the line, the better the model of processing. Some of the points at the location (47, 43.45), (48, 46.06), (45, 44.54), and (50, 45.67) are located at a very small distance from the trend line, which is an indication of the good fit of the model in obtaining the vertical profile. The height of larger trees can be reliably estimated with the data of shorter...
baseline, and for smaller trees, longer baseline provides reliable estimation (Denbina et al., 2018). The equation of the trendline derived from the values of the model is

$$y = 0.99x + 1.52$$  \hspace{1cm} (15)

This equation is the best fit line in this model with the value of $R^2$ to be 0.92 which is the indication of fitting of the model to obtain the output, that is, vertical profile through tomography. The deviation in the vertical profile of the feature has been statistically analyzed with the help of RMSE (root mean square error) also.

Figure 7b displays the comparative height derived with the Capon beamforming-based tomographic processing and the PolInSAR inversion-based height profile. The experimental values obtained with the PolInSAR based inversion model provide the RMSE of 6.279 m in comparison with the height obtained from ground survey whereas the output from the Capon beamforming-based tomographic processing yields 4.21 m RMSE which is 2.06 m less than the previously mentioned method.

The output derived by the Capon beamforming algorithm for retrieval of the vertical profile of the forest vegetation in the area of Mondah National Park at the Gabon country is found to be having RMSE value of 4.21 m, that is, the mean error or variation found in the processed output is 4.21 m deviated from the original value of features as observed in the ground survey.

5. Discussion

The output generated through the process of tomographic reconstruction is provided in the previous section. Such a location where the tree canopy is dense, the microwaves get backscattered from the upper layer of the canopy itself that causes a problem in mapping the subcanopy features present underneath. But these features can be mapped if the higher wavelength is employed in the process. Thus, in this research, $L$-band microwave data are used for this purpose. The UAVSAR $L$-band has a wavelength of 23.84 cm and this wavelength is sufficient to penetrate through the canopy cover of moderately dense forest. Figure 5c provides the tomogram of the slice through a densely populated forest area and $L$-band microwave could penetrate through the tree crown in bins 300–500; there is high power distribution below the continuous power distribution map; this is because of the presence of a large number of scatterers present at that elevation value. The mapping of these features is possible with the superresolution-based Capon beamforming. Similarly, in Figure 6c the tomogram presented is from the location where there is a water body (stream), the land having grass patch (surface scattering), and then tree canopy. It can be seen in the subsequent Figure 6b, which is high-resolution optical data taken from Google Earth top to down, the tall trees are located in the rightmost part of the bin, while from bin 0–750, the present features do not contribute much to the elevation, thus they represent the surface-like scattering. Figure 7a represents the comparative analysis of the height derived with the ground survey and from Capon beamforming-based tomography. The figure provides the value of $R^2$ which turns out to be 0.92, Figure 7b provides the comparative analysis of four methods of height derivation (ground survey, PolInSAR-based inversion, LiDAR height, and Capon beamforming-based tomographic method). It is clear from Figure 7 and its analysis mentioned above that the tomographic methods provide the height profile with less variation in both sparsely as well as densely populated forest areas.

Figure 7. (a) Regression analysis of the output generated to an observation made in the ground survey. (b) Comparison of the height profile recorded via (i) Ground Survey, (ii) PolInSAR Inversion (Lavalle et al., 2018), (iii) LiDAR Height (Blair & Hofton, 2018), and (iv) Capon beamforming Tomographic Processing.
6. Conclusions

In this research paper, the potential of SAR tomography on UAVSAR L-band data has been mapped. This paper provides research findings of tomographic processing on the MBFP UAVSAR L-band data on natural features. Initially, the Capon beamforming algorithm is applied to the data stack to obtain the elevation values at locations of the ground survey. This application of the TomoSAR algorithm has yielded the vertical profile of an area having dense forest canopy cover as well as relatively sparse vegetation. The output obtained on these locations are found to be having 4.21 m RMSE and R² to be 0.92. These values indicate a good correlation between the estimated vertical profile and ground observation. These values indicate the potential of L-band UAVSAR data for tomographic reconstruction. Both ground data collection and SAR data acquisition were done in 2016. Mondah National Park has tropical forests both dense and sparse, which were mapped successfully using the Capon estimator. This opens various other research sectors such as estimating the total biomass stored in the national park and other tropical forests available all around the globe.

Data Availability Statement

The following are the link to the web portals from where the data set used can be downloaded for free. The UAVSAR data could be downloaded from the following link (https://uavsar.jpl.nasa.gov/cgi-bin/data.pl). The field data are available on the following link (https://daac.ornl.gov/AFRISAR/guides/AfrisAR_Mondah_Field_Data.html). The Reference data (PolInSAR Inversion) are available on the following link (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1601). The LiDAR height data can be downloaded from the following link (https://lvis.gsfc.nasa.gov/Data/Maps/Gabon2016Map.html).

Conflict of Interest

The authors declare no conflict of interest.

References

Asopa, U., Kumar, S., & Thakur, P. K. (2018). PSInSAR study of Lyngenfjord Norway, using TerraSAR – X data. In A. S. Kumar, S. Saran, H. Padaliya (Eds.), ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences (Vol. IV-5, pp. 245–251).

Dehdasht, ISPRS. https://doi.org/10.5194/isprs-annals-iv-5-245-2018

Baba, A., & Kumar, S. (2018). Tree canopy height estimation using multi baseline RVOG inversion technique. In ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (Vol. XLII-5, pp. 605–611). https://doi.org/10.5194/isprs-archives-xlii-5-605-2018

Bamber, R., & Hartl, P. (1998). Synthetic aperture radar interferometry. *Inverse Problems*, 14(4), R1–R54. https://doi.org/10.1088/0266-5611/14/4/001

Blair, J. B., & Hofton, M. A. (2018). AfrisAR LIVIS L2 geolocated surface elevation product, version 1. Boulder, Colorado, USA: NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/AOPMUXVUVYNH

Blair, J. B., Babine, D. L., & Hofton, M. A. (1999). The laser vegetation imaging sensor: A medium-altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography. *ISPRS Journal of Photogrammetry and Remote Sensing*, 54(2–3), 115–122. https://doi.org/10.1016/S0924-2716(99)00002-7

Blommberg, E., Ferro-Famil, L., Soja, M. J., Ulander, L. M. H., & Tehuldini, S. (2018). Forest biomass retrieval from L-band SAR using tomographic ground backscatter removal. *IEEE Geoscience and Remote Sensing Letters*, 15(7), 1030–1034. https://doi.org/10.1109/LGRS.2018.2819684

Budillon, A., Johnsny, A. C., & Schirzini, G. (2019). Urban tomographic imaging using polarimetric SAR data. *Remote Sensing*, 11, 132. https://doi.org/10.3390/rs11020132

Capon, J. (1969). High-resolution frequency-wavenumber Spectrum analysis. In *IEEE*, 57, 1408–1418. https://doi.org/10.1109/PROC.1969.7278

Denbina, M., Simard, M., & Hawkins, B. (2018). Forest height estimation using multibaseline PolInSAR and sparse Lidar data fusion. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 11(10), 3415–3433. https://doi.org/10.1109/JSTARS.2018.2841388

El Moussiawi, I., Minh, D. H. T., Baghdadi, N., Abdallah, C., Jomaah, J., Strauss, O., et al. (2019). Monitoring tropical forest structure using SAR tomography at L- and P-band. *Remote Sensing*, 11, 1934. https://doi.org/10.3390/rs11161934

El Moussiawi, I., Tong Minh, D. H., Baghdadi, N., Abdallah, C., Jomaah, J., Strauss, O., & Lavalle, M. (2019). L-band UAVSAR tomographic imaging in dense forest: Gabon forests. *Remote Sensing*, 11, 475. https://doi.org/10.3390/rs11050475

ESA. (2018). Single look complex—Level-1 SLC product guide. Retrieved May 27, 2019, from https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-1-slc-product-guide

Fatoyinbo, L., Pinto, N., Hofton, M., Simards, M., Blair, B., Saatchi, S., et al. (2017). The 2016 NASA AfriSAR campaign: Airborne SAR and lidar measurements of tropical forest structure and biomass in support of future satellite missions. In *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (pp. 4286–4287). Fort Worth, TX, IEEE. https://doi.org/10.1109/IGARSS.2017.8127949

Fatoyinbo, T., Saatchi, S. S., Armstrong, J., Poulsen, J. R., Marsels, S., Pinto, N., et al. (2018). AfriSAR: Mondah forest tree species, biophysical, and biomass data, Gabon, 2016. Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1580

Gini, F., Lombardini, F., & Montanari, M. (2002). Layover solution in multibaseline SAR interferometry. *IEEE Transactions on Aerospace and Electronic Systems*, 38(4), 1344–1356. https://doi.org/10.1109/TAES.2002.1145755
Guillao, S., & Reigber, A. (2005a). Polarimetric SAR tomography. European Space Agency. (Special Publication) ESA SP, (586), 19–24.

Guillao, S., & Reigber, A. (2005b). Scatterer characterisation using polarimetric SAR tomography. International Geoscience and Remote Sensing Symposium (IGARSS). 4, 2685–2688. https://doi.org/10.1109/IGARSS.2005.1525619

Gupta, A., Asopa, U., & Bhattacharjee, R. (2019). Land subsidence monitoring in Jagadhri City using Sentinel 1 data and DInSAR processing. Proceedings, 24(1), 1–9. https://doi.org/10.3390/eic2019-06230

Ho, D., & Minh, T. (2013). Tomographic imaging of the tropical forest in P-band. Politecnico di Milano. Retrieved from https://www.politeisti.polimi.it/bitstream/10589/74343/1/2013_02_PhD_HoTongMinh.pdf

Ho Tong Minh, D., Le Toan, T., Rocca, F., Tebaldini, S., Villard, L., Réjou-Méchain, M., et al. (2016). SAR tomography for the retrieval of forest biomass and height: Cross-validation at two tropical forest sites in French Guiana. Remote Sensing of Environment, 175, 136–147. https://doi.org/10.1016/j.rse.2015.12.037

Joshi, S. K., Kumar, S., Agrawal, S., & Dinh, H. T. M. (2016). PolInSAR tomography for vertical profile retrieval of forest vegetation using spaceborne SAR data. Land Surface and Cryosphere Remote Sensing III, 9877, 987709. https://doi.org/10.1117/12.2228068

Khati, U., Lavalle, M., & Singh, G. (2019). Spaceborne tomography of multi-species Indian tropical forests. Remote Sensing of Environment, 229, 193–212. https://doi.org/10.1016/j.rse.2019.04.017

Kugler, F., Lee, S. K., Hajnsek, I., & Papathanassiou, K. P. (2015). Forest height estimation by means of poI-InSAR data inversion: The role of the vertical wavenumber. IEEE Transactions on Geoscience and Remote Sensing, 53, 5294–5311. https://doi.org/10.1109/TGRS.2015.2420996

Kumar, S., & Joshi, S. K. (2017). SAR tomography for forest structure investigation. In 2016 Asia-Pacific Microwave Conference (APMC) (pp. 1–4). New Delhi, India: IEEE. https://doi.org/10.1109/APMC.2016.7931452

Kumar, S., Joshi, S. K., & Gowi, H. (2017). Spaceborne PoliSAR tomography for forest height retrieval. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 10(12), 5175–5185. https://doi.org/10.1109/JSTARS.2017.2741723

Kumar, S., Joshi, S. K., Tomar, K. S., Aggarwal, N., Khati, U. G., Chandola, S., et al. (2017). PoliSAR based modelling for scattering characterization and forest parameter retrieval. In The 38th Asian Conference on Remote Sensing, ACRS 2017. Space Applications: Touching Human Lives, 119 (May 2018) (pp. 1-10). New Delhi: Asian Association on Remote Sensing (AARS). Retrieved from https://a-ar-s.org/proceeding/ACRS2017/ID_753_1652_1076.pdf

Labrière, N., Tao, S., Chave, J., Scipal, K., Le Toan, T., Abernethy, K., et al. (2018). In situ reference datasets from the TropiSAR and AfrisAR campaigns in support of upcoming Spaceborne biomass missions. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 11, 3637–3637. https://doi.org/10.1002/2019JSTARS.2851606

Lavalle, M., Hawkins, B., & Hensley, S. (2017). Tomographic imaging with UAVSAR: Current status and new results from the 2016 AfrisAR campaign. In 2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) (pp. 2485–2488). Fort Worth, TX: IEEE. https://doi.org/10.1109/IGARSS.2017.8127498

Lavalle, M., Riel, B. V., Shiroma, G., & Hawkins, B. P. (2018). AfriSAR: Canopy structure derived from PoliSAR and coherence TomoSAR NISAR tools. ORNL Distributed Active Archive Center. https://doi.org/10.3334/ORNLDAAC/1601

Lin, Q. (2017). Spaceborne multibaseline SAR tomography for retrieving forest heights. Stanford University.

Lombardini, F., & Reigber, A. (2003). Adaptive spectral estimation for multibaseline SAR tomography with airborne L-band data. In IGARSS 2003. 2003 IEEE International Geoscience and Remote Sensing Symposium. Proceedings (IEEE Cat. No.03CH37477) (Vol. 3, pp. 2014–2016). Toulouse, France: IEEE. https://doi.org/10.1109/igars.2003.1294324

Lopéz, A., Tupin, F., & Le Hégarat-Mascle, S. (2010). Reflectivity estimation and SAR image filtering. In H. Maitre (Ed.), Processing of Synthetic Aperture Radar Images (1st ed., pp. 143–173). Hoboken, NJ, USA: John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470611111.ch6

Mannini, M., Scheiber, R., & Moreira, A. (2008). On the minimum number of tracks for SAR tomography. In IGARSS 2008–2008 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2008) (Vol. 2, pp. II–441–II–444). Boston, MA, USA: IEEE. https://doi.org/10.1109/IGARSS.2008.4779023

Radli, A. A. M., Sarker, M. L. R., & Ishak, N. (2015). Monitoring of surface deformation due to earthquake using dInSAR technique and PALSAR-2 data: A case study of the Gorkha earthquake in Nepal, 2015. ACRS 2015 36th Asian Conference on Remote Sensing: Fostering Resilient Growth in Asia, Proceedings, 2–9.

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. https://doi.org/10.1109/36.868873

Rosen, P., & Kumar, R. (2019). The NISAR mission – An NASA/ISRO space partnership supporting global research and applications. 2019 URSI Asia-Pacific Radio Science Conference (AP-RASC) (pp. 1–1). New Delhi, India: IEEE. https://doi.org/10.23919/URSIAP-RASC.2019.8738639

Saatchi, S. S., Chave, J., Labrière, N., Réjou-Méchain, M., Ferraz, A., & Tao, S. (2019). AfriSAR: Aboveground biomass for lope, Mabounie, Mondah, and Rabi Sites. Gabon. https://doi.org/10.3334/ORNLDAAC/1683

Shafai, S. S., & Kumar, S. (2020). PolInSAR coherence and entropy-based hybrid decomposition model. Earth and Space Science, 7, e2020EA001279. https://doi.org/10.1029/2020EA001279

Tebaldini, S., Ho Tong Minh, D., Mariotti d’Alessandro, M., Villard, L., Le Toan, T., & Chave, J. (2019). The status of technologies to measure Forest biomass and structural properties: State of the art in SAR tomography of tropical forests. Surveys in Geophysics, 40(4), 779–801. https://doi.org/10.1007/s10712-019-09539-7

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. https://doi.org/10.1109/TGRS.2011.2159614

Tebaldini, S., Rocca, F., Mariotti D’Alessandro, M., & Ferro-Famil, L. (2016). Phase calibration of airborne tomographic SAR data via phase center double localization. IEEE Transactions on Geoscience and Remote Sensing, 54, 1775–1792. https://doi.org/10.1109/TGRS.2015.2488358

Tello, M., Cazcarra-Bes, V., Pardini, M., & Papathanassiou, K. (2018). Forest structure characterization from SAR tomography at L-band. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 11(10), 3402–3414. https://doi.org/10.1109/JSTARS.2018.2859050

Treuhaft, R. N., & Siqueira, P. R. (2000). Vertical structure of vegetated land surfaces from interferometric and polarimetric radar. Radio Science, 35(1), 141–177. https://doi.org/10.1029/1999RS900108

Valbuena, R., Heiskanen, J., Aynekulu, E., Pitkänen, S., & Packalen, P. (2016). Sensitivity of above-ground biomass estimates to height-diameter modelling in mixed-species West African woodlands. PLoS ONE, 11(7), e0158198. https://doi.org/10.1371/journal.pone.0158198
Williams, M. (2015). The BIOMASS mission: Science and background. In 1st BIOMASS Science Workshop, ESA/ESRIN (pp. 1–21). Frascati, Italy: European Space Research Institute. Retrieved from http://seom.esa.int/polinsar-biomass2015/files/D2S1_Opening_2.pdf

Zhang, H., Wang, C., Zhu, J., Fu, H., Xie, Q., & Shen, P. (2018). Forest above-ground biomass estimation using single-baseline polarization coherence tomography with P-band PolInSAR data. Forests, 9, 163. https://doi.org/10.3390/f9040163