Tree Height Retrieval Using Single Baseline Polarimetric Interferometry

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ABSTRACT
This work, carried out as part of the ESA-ESRIN project “Applications of SAR Polarimetry”, concerns a review of algorithms available for the quantitative inversion of polarimetric interferometric SAR data and validation of the algorithms using simulated SAR data for forest scattering. It has been shown in several recent publications that by using interferograms in multiple polarisation channels, estimation of vegetation height, underlying ground topography and mean extinction is possible. Furthermore this can be achieved with a single frequency sensor without the need for a separate reference DEM, other a priori information or the use of data specific regression formulae. Here we concentrate on forest height as a single parameter and consider the impact of temporal decorrelation and vertical structure on height estimation. This leads to three classes of height retrieval algorithm and we show quantitative comparisons between the different methods.

1. INTRODUCTION
Polarimetric SAR Interferometry (POLInSAR) was first developed in 1997 using SIRC L-Band data [1,2]. Originally it involved generating phase differences between interferograms formed using different polarization combinations. These phase differences were observed to be correlated with vegetation height [2]. However, it was quickly realized that more accurate estimates of height could be obtained by correcting the phase differences using coherent wave scattering models [3,4]. Since then there have been several groups working on the development and inversion of suitable models for the interpretation of POLInSAR data. A particularly useful model, which presents a good compromise between physical structure and model complexity is a variant of that first developed by Treuhaft et al [3,4,6]. The basic radar observable in POLInSAR is the 6x6 coherency matrix of a pixel, defined as shown in equation 1

\[ \begin{pmatrix} k_{ij}^T \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12}^T \\ T_{12} & T_{22} \end{pmatrix} \]

where superscripts 1 and 2 denote measurements at the two ends of the baseline and \(<,>\) represents ensemble averaging. We have further partitioned the matrix into 3 x 3 polarimetric coherency matrices \(T_{ij}\) and polarimetric interferometry \(\oplus_{ij}\). Generally this matrix must be estimated by multi-look processing of the data using a local window centred on the pixel of interest. Consequently, full matrix estimation follows a complex Wishart distribution and this enables characterisation of the fluctuation statistics in POLInSAR data [5].

According to the 2-layer vegetation model, first derived in [3] and extended for fully polarimetric interpretation in [6], the complex interferometric coherence for a random volume over a ground can be derived as shown in equation 3 and shown schematically in figure 1, where \(w\) is a 3 component unitary complex vector defining the choice of polarization [2], \(\overline{w}\) is the mean wave extinction in the medium, \(k\), the vertical wavenumber of the interferometer (following spectral range filtering) and \(\overline{\theta}\) the mean angle of incidence. The random canopy assumption has been supported by 3-D SAR imaging experiments at L-band [7,8]. Under this assumption, \(T_v\) is the 3 x 3 diagonal coherency matrix for the volume scattering and \(T_g\) the reflection symmetric ground scattering coherency matrix, defined as shown in equation 2 [2].

\[ T_v = \begin{pmatrix} 1 & t_{12} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0.5 \end{pmatrix} \]

\[ T_g = \begin{pmatrix} 1 & t_{12}^* & 0 \\ 0 & 1 & 0 \\ 0 & 0 & t_{33} \end{pmatrix} \]

By assuming that the canopy extends from crown to ground then we can simplify equation 3 by setting \(\oplus_{ii} = \overline{\omega}\). Later we shall examine the consequences of this assumption in the presence of vertical forest structure, but for the moment we assume the bottom of the canopy corresponds to the ground surface.
\[
d(z) = \exp\left(\int_{z_0}^{z} h(z)\,dz\right) + m(z)\,z_0\quad k = \frac{4\cos\theta}{\sin\theta}\quad z = z_0 + h
\]

**Phase Reference**

Figure 1: Schematic representation of a 2-Layer Coherence Model for Vegetated Land Surfaces

\[
\mathcal{I} = \frac{w^T}{w} \mathcal{I}_{12} \frac{w}{w}
\]

\[
T_{11} = I_1^V + e^{\frac{2\pi i}{\cos\theta}} I_1^G
\]

\[
I_1^V = \int_0^0 \cos\theta T_v \,dz'
I_1^G = \int_0^0 \left(z' \right) e^{\frac{2\pi i}{\cos\theta}} T_g \,dz' = T
\]

\[
I_2^V = \int_0^0 \frac{\sin\theta}{\cos\theta} e^{2\pi i z'} T_v \,dz'
I_2^G = T_g e^{2\pi i z}
\]

By combining equations 2 and 3 we obtain the following explicit equation for the complex coherence, which can be rewritten as the equation of a straight line in the complex plane as shown in equation 4

\[
\mathcal{I}(w) = e^{i\theta} \left[ \frac{1 + \mathcal{I}(w)}{1 + \mathcal{I}(w)} \right] = e^{i\theta} \frac{\mathcal{I}(w)}{1 + \mathcal{I}(w)} \quad (1 \quad 1) = e^{i\theta} \frac{1}{T_g} \quad (1 \quad 1)
\]

The ground-to-volume scattering ratio \(\mathcal{I}\) includes the effects of wave extinction in the medium and is defined as

\[
\mathcal{I}(w) = \frac{2\mathcal{I}}{2\mathcal{I} + \cos(\theta \cos G) \mathcal{I} (1 \quad 1)} = \frac{w^T}{w} T_g \frac{w}{w} \geq 0
\]

Note that \(\mathcal{I}\) is positive semi-definite and that the max/min values of this function versus polarization are given by the eigenvalues of a contrast optimization problem since

\[
\max_{\mathbb{w}} \frac{w^T}{w} T_{\mathbb{w}} \frac{w}{w} \quad T_{\mathbb{w}}^T \frac{w_{opt}}{w_{opt}} = \mathcal{I}(w_{opt})
\]

The eigenvalues \(\mathcal{I}\) are non-degenerate, due to the strong polarization dependence of ground scattering, and this lends support to the variation of coherence with polarization in equation 4. We note that the three eigenvectors of this problem are not mutually orthogonal. This is in contrast to the situation when differential propagation effects are important, when the optimum \(w\) vectors are related to the propagation eigenpolarisations, which for a single vegetation layer are
mutually orthogonal [10,11]. In equation 4 only $\bar{\Gamma}$ is a function of polarisation. This arises since $\Gamma$, is a polarization independent volume integral as shown in equation 7.

$$
\bar{\Gamma} = \frac{w^T}{w^T} \int_{0}^{2\pi} e^{i\bar{\Gamma}z} dz' \frac{2\pi e^{i\bar{\Gamma}z} dz'}{m} = \frac{2\pi}{m} \int_{0}^{2\pi} e^{i\bar{\Gamma}z} dz' \cos\left(e^{2\pi i \bar{\Gamma}z} \right) \left( \frac{h}{h} \right) \frac{2\pi e^{i\bar{\Gamma}z} dz'}{m} \right)
$$

In the limit that the wave extinction is zero this reduces to an elementary sinc function. As well as the coherence amplitude, consideration must also be given to variation of the phase of the observed interferogram. According to equation 7, the presence of vegetation causes an offset in the estimation of the interferometric phase of the ground topography given by half the vegetation height (or more as the extinction increases). This offset decreases with increasing ground component but is always present, biasing the estimation of ground topography.

Inversion of equation 4 is greatly facilitated by employing a geometrical interpretation inside the unit circle of the complex coherence plane [9]. Figure 2 shows how the model maps coherence points from equation 5 onto a line in the complex plane. This line has three important features:

1) The line intersects the circle at 2 points. One of these is the underlying topography related phase (shown as the point Q in figure 4). The other is a false solution and must be rejected by the inversion process.

2) The volume coherence $\bar{\Gamma}$ lies at one end of the line ($\bar{\Gamma} = 0$). It is shown as the point P in figure 2. This point is central to the estimation of height and extinction and needs to be estimated from the data.

3) The visible length of the line in the data may only be a fraction of PQ and neither P nor Q may be directly observed. The visible length depends on baseline, operating frequency and vegetation density [6]. However the line can be extrapolated to enable parameter estimation as we now show.

$$
\Gamma = \left\{ \begin{array}{c}
\Gamma_1 \\
\Gamma_2 \\
\Gamma_3
\end{array} \right\}
$$

$$
\left\{ \begin{array}{c}
\Gamma P \\
\Gamma_{HV} \\
\Gamma_{HHHV} \\
\Gamma_{HHVV}
\end{array} \right\} = \left\{ \begin{array}{c}
P \\
Q
\end{array} \right\} e^{i\bar{\Gamma}_1}
$$

Figure 2: Coherence Line Structure in the Complex Plane

2. POLINSAR MODEL INVERSION

We can clarify the requirements of the inversion of equation 4 by breaking the process down into three separate stages as follows:

**Stage 1: Least Squares Line Fit**

The first stage is to find the best-fit straight line inside the unit circle of interferometric coherence. To do this we vary two phase variable $\bar{\Gamma}$ and $\bar{\Gamma}$. Each pair defines a line and we choose the pair that minimises the MSE between the line and set of coherence points. One way to do this is to use a total least squares line fit to the real and imaginary components of the data and then use the line parameter estimates to secure the intersection points. Alternatively a faster least squares line fit in the real and/or imaginary parts can secure an estimate of the minimum error solution [14]. An alternative method based on a maximum likelihood approach using the complex Wishart distribution has recently been outlined in [16]. Phase centre estimation based on the ESPRIT processing technique has also been employed for this purpose [17].

**Stage 2: Vegetation Bias Removal**
In the second stage we must choose one of the pair $[\hat{\beta}, \bar{\beta}]$ as the underlying ground topographic phase for each pixel. To do this we mark the polarization states in rank order as shown schematically in figure 2. It follows from equation 5 that the ground-to-volume ratio $[\hat{\beta}]$ is given by the distance along the line as shown in figure 2. We see that the nearer a coherence point is to $Q$, the higher is the corresponding ground-to-volume ratio $[\hat{\beta}]$. It is reasonable to expect that the HV coherence channel will be ranked furthest away in distance from the true ground phase point $Q$. This gives us a systematic way of breaking the symmetry between the two points $[\hat{\beta}, \bar{\beta}]$.

**Stage 3 : Height and Extinction estimation**

To estimate the two remaining parameters, height and extinction, we use the estimate of ground phase $[\hat{\beta}]$ together with equation 7 to find the intersection point between the coherence line and the curve corresponding to the height/extinction variations. This process requires regularization, as there exists a family of possible solutions [9]. This whole inversion process requires some care as it relies on complex coherence estimation. Problems can arise with:

1) Phase and Coherence fluctuations. The Cramer-Rao bounds on variance of these two parameters can be approximated as [12] shown in equation 8, where $N$ is the number of looks. These expressions can be used to assess the variance of height estimates.

$$ \var_{\hat{\beta}} > \frac{1}{2N} \left( \frac{\hat{\beta}}{\bar{\beta}} \right)^2 $$

$$ \var_{\bar{\beta}} > \frac{1}{2N} \left( \frac{\bar{\beta}}{\hat{\beta}} \right)^2 $$

2) Coherence bias for low coherence values. Standard boxcar methods overestimate low coherence values and hence distort the line parameters [13]. The bias reduces with increasing coherence and with increasing $N$.

3) Temporal decorrelation and vertical structure. In repeat-pass systems, coherence can fall due to changes in the scene between passes. To avoid this, single pass polarimetric interferometry is preferred. We note from equation 4 that volume temporal decorrelation effects will not necessarily destroy the line structure, only lower the coherence so causing additional problems through 1) and 2) above. The effect of an elevated canopy further separates the volume and ground phase centres ($[\hat{\beta}]$ and $[\bar{\beta}]$ are different in equation 1). Consequently, in the presence of wind driven vegetation decorrelation and canopy elevation, equation 4 is modified as shown in equation 9

$$ \bar{\beta} = e^{i\bar{\beta}} e^{i\bar{\beta}} \frac{1}{1+e^{i\bar{\beta}}} $$

**Figure 3 : The effect of temporal decorrelation on the coherence line model**

Equation 9 shows that the line model is still valid and hence the line fit and ground phase estimation procedures are unchanged. However, the effect of temporal decorrelation is to make the coherence amplitude too small for the observed vegetation bias $[\hat{\beta}]$. This is shown as the dotted line in figure 3. The true volume coherence is shifted radially to the origin by the temporal decorrelation and so the geometrical effect is to rotate and stretch the line about the unit circle ground phase point as shown in figure 3. To secure a solution we must therefore move the observed volume coherence point radially in the coherence plane to compensate. The problem is we have no indication from the data itself how much temporal decorrelation has occurred. Hence the required radial scale factor is unknown. However, we can increase the coherence until we secure a first unique solution as intersection with a height/extinction curve. This will occur first for zero extinction but will then also be valid for a whole family of increasing extinction values as shown in the double line region of figure 3. This line region will extend out to the unit circle. Hence we conclude that extinction estima-
tion becomes ambiguous in the presence of temporal decorrelation. A sensible regularization strategy is to set the extinction to zero or some other pre-determined value. In the zero extinction case, we resort to the simple sinc function model for volume coherence and the tree height is then simply related to the maximum vegetation bias [1], as shown in figure 3.

Geometrically the effect of canopy elevation represents a rotation of the volume coherence point about the origin. Again the line model is still valid but the observed volume coherence is now phase shifted away from its true position. Hence for a given height, the volume coherence is higher than expected based on the simple two-layer model. Nonetheless, this can be accommodated in the model by artificially increasing the extinction. Hence the effect of higher thinner canopies is to increase the extinction estimate with only a small error in the height. For this reason vertical structure is not too serious a limitation for single pass SBPI if only tree height and ground topography are the important parameters of interest. The extinction however becomes an unreliable measure of tree canopy density.

The worst situation arises when we have vertical structure combined with temporal decorrelation when only the ground topography estimation becomes a reliable parameter. However, if information is available about the canopy extent of the trees in the scene based on species or age information for example, then we can use the following simplified algorithm to estimate tree height

\[
\text{temporal decorrelation} + \text{canopy fill } F \quad \mathcal{G} = \mathcal{G}, \quad h_v = \frac{\mathcal{G}}{k_c(1 \mathcal{G} F)^2}, \quad \mathcal{G} = 0 \quad - 10)
\]

where \( F = (h_v - z) / h_v \) is the fractional canopy fill of the trees.

4) Even if all other factors 1-3 are minimised, the line model assumption may not be correct. This can arise for several reasons, such as when the vegetation becomes oriented and we have differential extinction and propagation phase [10,11]. In this case the volume coherence itself becomes a function of polarisation. A suitable statistical confidence test for the line can be applied as shown in [14]. Oriented volume effects can also be identified through the presence of orthogonal eigenvectors and the rank order of the coherence values. [10,11]. Recently a technique for determining the coherence region shape has been developed [15] although in its current form it takes no account of the intrinsic statistical fluctuations in interferometric coherence and phase data.

3. SUMMARY OF POLINSAR SOFTWARE DEVELOPMENT

In line with the above discussion, we implemented the above algorithms in IDL 5.5 using a two stage processing structure as shown in figure 4. In Stage I, complex coherence estimates are made based on multi-looking of projected complex scattering matrix data. This coherence data is then used as input into stage 2 modules for quantitative parameter estimation. In addition to the parameter estimates themselves, the output from stage 2 includes a metric for the assessment of the quality of the model fit and also parameter variance estimates.

![Figure 4: POLINSAR Software Development Structure](image)

Stage I Modules: The following modules have been developed

- Linear polarisation interferometric coherence triplet HH, HV and VV
- Circular polarisation interferometric coherence triplet LL, LR and RR
- Pauli channel interferometric complex coherence triplet HH+VV, HH-VV and 2HV
- Polarimetric Coherence Evaluation between any 2 of the above channels
• Local angle of incidence estimation based on flight geometry
• Vertical wavenumber k, estimation from flight track data

Stage II Modules: The following have been implemented for the 2-layer coherence model:

• Model Based Parameter estimation: vegetation height/ground topography/mean extinction

Having selected the number of channels and data source, the GUI shown in figure 5 is then displayed. Here the user can make the choice of 3 different methods of selecting sub-sets of the data for processing. In the first case, the linear transect, an arbitrary line through the coherence data can be selected by using the mouse. Users click the start and stop points of the line in the displayed coherence window. The parameter estimation is then applied along this line and the results plotted on the screen and saved to file. Also stored are the integer co-ordinates in the original data set of the selected linear transect and parameter variance estimates.

![GUI for Data Sub-Sampling Selection](image)

Figure 5: GUI for Data Sub-Sampling Selection

If the 2-D region is selected then by clicking with the mouse a zoom window is displayed, centred on the selected pixel. The size and location of the window can be changed by mouse operations as explained on-line in the text window. In this way the parameter estimation can be applied to a region of the image as selected by the user. By selecting the unit circle loci, no parameter estimation is carried out but the mouse is used to select a pixel in the scene and for that pixel the full set of selected coherence values is plotted inside the unit circle, together with the least squares line fit. Displayed in the text window is the chi-square metric for the quality of the line fit. In this way the user can investigate the coherence structure in detail for a desired region. The next stage of processing is to select the algorithm to be used for parameter estimation. If the linear transect or 2-D modes have been chosen in figure 5 then the GUI shown in figure 6 appears.

![GUI for Algorithm Selection in Linear Transect Mode](image)

Figure 6: GUI for Algorithm Selection in Linear Transect Mode

The user then has a choice from 3 height estimation algorithms:

• Max DEM difference: This is a phase based technique which ignores the coherence amplitude and estimates the vegetation height from the maximum phase difference between selected polarisation channels. This will generally underestimate height and provides no estimate of ground topography. It is provided primarily as a reference for comparison with the other two methods.

• Vegetation Bias removal: This too is a phase based method which ignores the coherence amplitude but unlike the max DEM difference, employs vegetation bias removal by fitting a least squares straight line through the coherence values. In this way it provides estimates of two parameters, vegetation height and ground topography. It also provides a measure of the goodness of the line fit. This mode should be used
when temporal decorrelation is present in the data. It requires the user to input an estimate of the canopy fill factor F.

- Full model inversion: This inverts the full two layer coherence model to estimate vegetation height and ground phase. It does not require a user value for the canopy fill F. In addition to the line fit metric it also provides a second measure of accuracy, namely the coherence error residue (CER) which is the distance in the coherence plane between the estimated volume coherence in the model and the volume coherence in the data. It is defined as

\[
CER = \left| \frac{\mathbf{I}_1 \cdot \mathbf{I}_2}{\mathbf{I}_1 \cdot \mathbf{I}_2_{\text{true}}} \right| = \left| \frac{\sum_{i=1}^{n} e^{j2\pi i \lambda (z_i)}}{\cos \theta_i \sum_{i=1}^{n} e^{j2\pi i \lambda (z_i)}} \right|
\]

This should be zero for a good solution and can be used as a measure of confidence in the parameters obtained from the full model inversion.

### 4. Algorithm Validation Using Simulated SAR Data

In order to illustrate application of the above algorithm to POLInSAR data, we employ a forest scattering model with predetermined structure and attempt reconstruction of the height and ground topography from complex coherence data. Note that this model is not the same one used for the algorithm development. To generate a fair test of algorithm performance, a full Maxwell equation based wave propagation and scattering model is used to generate the test data. DSTL Malvern have developed such a capability to model forest scattering in detail, employing a 3-D voxel based vector wave propagation and scattering model tied to a detailed description of branch, leaf and trunk distributions [18,19]. Penetration and scattering are calculated as a function of wavelength and polarisation. The underlying surface scattering is modeled as a tilted Bragg surface and mutual interactions such as ground-trunk and canopy-ground are incorporated in the model. The technique is fully coherent and so can be used to model volume decorrelation effects in polarimetric radar interferometry.

The SAR simulator was initialised using a point spread function matched to the airborne DLR E-SAR system with 0.69m azimuthal and 1.38m ground range resolution. Simulations were carried out at L band (23cm wavelength) and at 45 degrees angle of incidence from 3km altitude with 10m and 20m horizontal baselines. To test the algorithms, the SAR simulator was first employed to simulate L-band coherent backscatter from a random canopy above a flat ground. The canopy has a uniform height of 10m and the branch distribution inside the canopy is Gaussian with mean length 1.5 m and standard deviation 0.2m. The branches have a random orientation distribution and constitute a mean volume fraction of 0.2%. From the model output the mean canopy extinction is calculated as 0.28 dB/m one way. Hence we know that the three primary parameters of interest should be \( h = 10 \text{m}, \theta = 0.28 \text{ dB/m} \) and \( \theta = 0^\circ \). This provides a convenient check of the algorithm performance.

In figure 7 we show the HH intensity for the data. Also shown is a linear transect through the middle of the data. The tree height retrieval results for this transect using the 10m baseline and each of the 3 algorithms are shown in figure 8. Here we used the five channels HH,HV,VV,HH+VV, and HH-VV for parameter estimation. The full model gives the best estimate of the true height value of 10m. In figure 9 we show the corresponding CER for this transect. Note that the CER is generally small, showing a good match between model and data. However at the edges of the stand the CER is larger. This edge effect is caused by the boxcar coherence estimation approach and has been studied in [20].

As a second test of algorithm performance, the SAR simulator was next employed with a full 3-D structural model of a Scots Pine forest. Here no assumptions about the canopy statistics were made and a detailed biologically correct branch distribution was employed. Also, vertical structure was modeled through the presence of an elevated canopy. Figure 10 shows an optical image of the simulated test scene, together with an HH intensity image from the L band SAR simulator. The mean tree height of the stand is 17.5m and the underlying ground topography has also been modeled through provision of a reference DEM.

Although such simulations can be used in a wide range of POLInSAR validation studies, here we concentrate on the effect of vertical structure on height retrieval. Figure 11 shows a coherence diagram obtained for a sample inside the forest stand. The interferograms have been corrected for the topography and the ground phase point lies at 0 degrees. We see the large vegetation bias and limited line visibility for this forest. Nonetheless we see that the line fit shows a unit circle intersection close to the true ground phase point. On closer inspection we see that it is the HH-VV channel which is vital in stretching the visible line length. This is due to the presence of dihedral ground/trunk interactions in the data. Using the unit circle point as a reference, we then apply the full model to estimate the height/extinction. The results obtained are shown in table 1. Note that the height estimate is good, within 10% accuracy, but the extinction is too large by a factor of nearly 3. This confirms the predictions of the model (equation 7). In the presence of an elevated canopy, the mean extinction is increased to compensate the offset phase.
### Table I: Comparison of Estimated vs True Forest Parameters for Scots Pine

<table>
<thead>
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<th>Estimate</th>
<th>True Value</th>
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</thead>
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<td>Scots Pine</td>
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<td></td>
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<tr>
<td>Height (m)</td>
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<td>18.23</td>
</tr>
<tr>
<td>Extinction (dB/m)</td>
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<td>Ground Phase (degrees)</td>
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<tr>
<td>CER (dB)</td>
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</tr>
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Figure 7: L-Band HH Intensity for simulated 10m Canopy Data with linear azimuth transect AA’

Figure 8: Height estimates for AA’ using full model inversion (top), vegetation bias removal (center) and Dem difference (lower)
Figure 9: CER in dB for the AA’ transect

Figure 10: Scots Pine Forest Model (left) and simulated HV SAR Image (right)

Figure 11: 10m baseline Coherence Loci for sample point in Scots Pine Forest
5. CONCLUSIONS

In this paper we have developed three algorithms for height retrieval using single baseline POLInSAR. We have shown that a simple difference of DEMs approach is poor, consistently underestimating height, while retrieval using inversion of a 2-layer coherence model is the most accurate. However this requires zero temporal decorrelation and hence is better suited to single pass systems. In the presence of temporal effects, the extinction becomes unknown and height retrieval is only possible by using a prior estimates of mean extinction and vertical canopy offset. In this case, better results are obtained by first using the line model to find the ground phase point and then using a phase algorithm to determine height. We have validated the algorithms using a Monte Carlo coherent SAR simulator for a random canopy and structural pine tree model.

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7. REFERENCES