Polarimetric SAR Interferometry (PolInSAR) and Inversion Modelling

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Polarimetric SAR Interferometry (PolInSAR) is an advanced technique (Cloude and Papathanassiou, 1998) of Radar remote sensing that combines the advantages of Polarimetry and Interferometry. Using SAR Polarimetry target characteristics such as its orientation, material constituents (Boerner, 2006, 2004), shape and dielectric properties (Krieger et al., 2005), permittivity as well as ensemble average entropy (Lee et al., 2002; Neumann et al., 2010) can be estimated. SAR Interferometry provides information on the coherence of the scattering mechanisms (Hellmann and Cloude, 2007) and the object’s spatial (range/in-depth) structure (Boerner, 2004) and estimates the location of the scatterer in vertical plane through the phase difference in the images acquired from spatially separated apertures at either ends of a baseline (Krieger et al., 2005). Combination of polarimetry and interferometry leads to separation of scattering mechanisms within a resolution cell. For complex scattering media such as forests, various types of scatterers are present below the canopy. The underlying scattering mechanisms can be interpreted using PolInSAR (Hellmann and Cloude, 2007) as the scattering media physical properties are closely related to the polarimetric features observed. The polarimetric and interferometric information are complementary to each other which leads to the combination of both approaches in Polarimetric SAR Interferometry (PolInSAR). Cloude and Papathanassiou formulated the PolInSAR theory (Cloude and Papathanassiou, 1998) and demonstrated its applications using single-baseline PolInSAR data (Papathanassiou and Cloude, 2001) and its extension to multi-baseline data is presented in (Neumann et al., 2010).

PolInSAR data is studied in a number of application areas such as forest-stand/tree height retrieval (Li et al., 2013; Luo et al., 2010; Minh and Zou, 2013; Minh et al., 2012; Nghia et al., 2012; Tan and Yang, 2008), agricultural height estimation (Lopez-Sanchez and Ballester-Berman, 2009; Lopez-Sanchez et al., 2012), crop parameter estimation (Ballester-Berman et al., 2005), building parameter (Cai et al., 2011; Zou et al., 2013) and building height estimation (Colin-Koeniguer and Trouve, 2014), forest biomass estimation (Mette, 2006), forest parameter estimation (Frey et al., 2012; Lee, 2012) and ground topography estimation (Lopez-Martinez and Papathanassiou, 2013; Zou et al., 2011), among others. Forest parameters such as height, extinction and ground topography (Lopez-Martinez et al., 2009) can also be estimated using PolSAR and PolInSAR data. However, the present work exclusively focuses on forest-stand retrieval using PolInSAR techniques.

Two PolSAR acquisitions are carried out using the exact same geometric configuration viz. Beam mode, Incidence angle, and Polarization mode. The scattering matrix for each pixel can be derived for both the acquisitions. \([S_1]\) and \([S_2]\) are the scattering matrices for the two acquisitions and the vectorized form can be represented by the scattering vectors \(\mathbf{k}_1\) and \(\mathbf{k}_2\) respectively (Schuler et al., 1996). The 6x6 coherence matrix \([T_6]\) is the main observable in PolInSAR. The Hermitian
positive semidefinite matrix \([T_6]\) is generated from the outer product formed from the scattering vector \(k_1\) and \(k_2\) in Pauli Basis (Cloude and Papathanassiou, 1998)

\[
[T_6] := \begin{pmatrix} k_1 \  k_2^T \end{pmatrix} = \begin{bmatrix} [T_{11}] & [\Omega_{12}] \\ [\Omega_{12}]^T & [T_{22}] \end{bmatrix}
\]

\[k_1 = [S_{HH}^1 + S_{VV}^1 \  S_{HH}^1 - S_{VV}^1 \  2S_{HV}^1] \quad \text{and} \quad k_2 = [S_{HH}^2 + S_{VV}^2 \  S_{HH}^2 - S_{VV}^2 \  2S_{HV}^2]^T \]

Where the superscripts 1 and 2 represent the acquisitions from two ends of the baseline.

\[
[T_6] = \begin{pmatrix} S_{HH}^1 + S_{VV}^1 \ S_{HH}^1 - S_{VV}^1 \ 2S_{HV}^1 \\ S_{HH}^2 + S_{VV}^2 \ S_{HH}^2 - S_{VV}^2 \ 2S_{HV}^2 \end{pmatrix}
\]

\[T_6 = \begin{bmatrix} T_{11} \\ \Omega_{12} \\ T_{22} \end{bmatrix} \]

In Eq. 1 - Eq. 2, \([T_{11}]\) and \([T_{22}]\) are the Hermitian coherence matrices for the two acquisitions and describe the polarimetric properties of each acquisition while \([\Omega_{12}]\) is a non-hermitian complex matrix which contains both polarimetric and interferometric information.

SAR measurements are not directly related to the physical parameters of the targets, hence extraction of bio- and geo-physical parameters require the inversion of scattering models (Krieger et al., 2005). These scattering models relate the physical parameters of the scattering processes to the observables from the SAR data. Complex structures such as forests act as a group of multiple scatterers – the tree trunk and ground acts as a dihedral surface leading to double-bounce scattering; ground near the tree acts as specular surface leading to surface scattering; leaves, twigs and branches lead to volume scattering in the higher canopy (S. Cloude and K. P. Papathanassiou, 2003; Tebaldini, 2010) (Figure 1). The scattering phase center is the location at which a particular scattering mechanism is dominant in the media. Using PolInSAR techniques, it becomes possible to identify the locations of the different scattering mechanism occurring in the target. This becomes possible as the SAR Polarimetry identifies the scattering mechanism and SAR Interferometry can locate it in vertical space (in-depth). In Figure 1, a pictorial representation is provided for the different scattering mechanisms occurring at different locations of a forest-stand.

This vegetation/forest structure can be modelled using the Random Volume over Ground (RVoG) scattering model (S. Cloude and K. P. Papathanassiou, 2003; Cloude, 2008, 2006; Mette, 2006; Papathanassiou and Cloude, 2001) which considers a vegetation layer of thickness \(h\), containing randomly oriented dipoles, located over a surface scattering media presented by a ground layer, positioned at height \(Z=Z_0\) as depicted in Figure 1.
\[ [T_{21}] = \begin{bmatrix}
\langle S^+_{HH} + S^+_{HV} \rangle^2 \\
\langle S^+_{HH} - S^+_{HV} \rangle (S^+_{HH} + S^+_{HV}) \\
2(S^+_{HV} (S^+_{HH} + S^+_{HV})) \\
\end{bmatrix}
\]

\[ [T_{22}] = \begin{bmatrix}
\langle |S^+_H + S^+_V|^2 \rangle \\
\langle |S^+_H - S^+_V|^2 \rangle \\
\end{bmatrix}
\]

\[ [T_{21}] = \begin{bmatrix}
\langle S^+_{HH} + S^+_{HV} \rangle (S^+_{HH} - S^+_{HV}) \rangle^* \\
\langle S^+_{HH} - S^+_{HV} \rangle (S^+_{HH} + S^+_{HV}) \rangle^* \\
2(S^+_{HV} (S^+_{HH} - S^+_{HV}) \rangle^* \\
\end{bmatrix}
\]

\[ [T_{22}] = \begin{bmatrix}
\langle |S^+_H + S^+_V|^2 \rangle \\
\langle |S^+_H - S^+_V|^2 \rangle \\
\end{bmatrix}
\]

\[ [\Omega_{21}] = \begin{bmatrix}
\langle |S^+_H + S^+_V|^2 \rangle \\
\langle |S^+_H - S^+_V|^2 \rangle \\
\end{bmatrix}
\]

\[ [\Omega_{22}] = \begin{bmatrix}
\langle |S^+_H + S^+_V|^2 \rangle \\
\langle |S^+_H - S^+_V|^2 \rangle \\
\end{bmatrix}
\]

\[ [T_{22}] = \begin{bmatrix}
\langle |S^+_H + S^+_V|^2 \rangle \\
\langle |S^+_H - S^+_V|^2 \rangle \\
\end{bmatrix}
\]

\[ [\Omega_{21}] = \begin{bmatrix}
\langle |S^+_H + S^+_V|^2 \rangle \\
\langle |S^+_H - S^+_V|^2 \rangle \\
\end{bmatrix}
\]

\[ [\Omega_{22}] = \begin{bmatrix}
\langle |S^+_H + S^+_V|^2 \rangle \\
\langle |S^+_H - S^+_V|^2 \rangle \\
\end{bmatrix}
\]
PolInSAR coherence ($\gamma$) is a complex vector quantity described in (S. Cloude and K. P. Papathanassiou, 2003) Eq. 4.

\[ \frac{|\langle \omega_1^T [\Omega_{12}] \omega_2 \rangle|}{\sqrt{\langle \omega_1^T [T_{11}] \omega_1 \rangle \langle \omega_2^T [T_{22}] \omega_2 \rangle}} \]

The two normalized complex vectors $\omega_1$ and $\omega_2$ represent different polarization basis. Coherence maps in different polarizations depict the scattering contributions of different scatterers (Cloude and Papathanassiou, 1998). Coherences in different polarizations such as HH, HV, VH and VV can be obtained for H, V-polarization basis. Basis transformations are applied for estimation of coherence in different polarization basis such as Linear, Pauli, Circular and Optimal. Each coherence represents a dominant scattering mechanism. For e.g., the cross-polarized HV coherence generally represents the dominant volume scattering. Separation of underlying scattering mechanisms require coherence optimization as proposed in (Cloude and Papathanassiou, 1998) for Gaussian distribution of PolInSAR data. Yong and Mercer (Yong Bian and Mercer, 2010) have generalized the optimization process which also applies to non-Gaussian PolInSAR data. Various alternative approaches for coherence optimization are proposed in (Yong Bian and Mercer, 2010) while (Binghuang and Bing, 2007) presents a comparative study of optimization techniques. The coherence optimization approach of (Cloude and Papathanassiou, 1998) has been utilized in the present work for estimation of three optimum coherences.

The present work utilizes the acquired PolInSAR data for estimation of forest-stand height and vertical structure. It utilizes the techniques developed in (S. Cloude and K. P. Papathanassiou, 2003; Cloude and Papathanassiou, 1998; Cloude, 2006) for the study. The next section details the forest stand height estimation techniques.

**Vegetation height estimation using PolInSAR**

The training course on PolInSAR (Cloude, 2005) provides an insight into techniques and algorithms developed for forest-stand height estimation. A very simple technique for vegetation height estimation is to generate DEM’s corresponding to two polarizations representing the scattering at top and bottom of the vegetation layer, and to differentiate them to find the height of the vegetation layer (Cloude, 2006, 2005). However, the scattering phase center was found to lie (Cloude, 2006, 2005) anywhere between the top of the canopy and half the tree height and the location depended on the wave extinction in the scattering media and the structure of the vertical canopy. Various techniques (S. Cloude and K. P. Papathanassiou, 2003; Mette, 2006; Neumann et al., 2010; Papathanassiou and Cloude, 2001) have been proposed to factor the effects of wave extinction and vertical canopy structure. A second technique applied in this work is the
‘Coherence Amplitude Inversion’ (CAI) technique. The coherence is inversely related to the volume density or density of vegetation/forest layer. As the density of forests increases, the volume decorrelation also increases leading to decrease in coherence. CAI applies this phenomenon to estimate the height of the vegetation layer. Two polarization channels are selected much the same as for DEM differencing height, one dominated by surface scattering and the other by volume scattering. CAI can be applied to estimate the height using estimates for extinction in the volume layer. The present work investigates the ‘Three-stage inversion” technique (S. Cloude and K. P. Papathanassiou, 2003). The ‘Three-stage inversion’ (TSI) technique uses the two-layer model for vegetation (S. Cloude and K. P. Papathanassiou, 2003). TSI technique observes the complex coherence in different polarizations and predicts the ground topography and polarization-independent volume coherence using least squares technique. The technique considers the effects of temporal decorrelation on estimation of height of the vegetation layer. (Lee et al., 2006) presents a detailed study on the effects of temporal decorrelation on PolInSAR data.

**Estimation of Forest Stand Height**

This section shows the result for PolInSAR based tree height for Barkot and Thano forest area of Dehradun Valley, Uttarakhand, India. In this study two datasets of RADARSAT-2 were used and both were collected in polarimetric interferometry mode. The forest stand height is estimated using three techniques – DEM Differencing, Coherence Amplitude Inversion and Three Stage Inversion.

**DEM Differencing height**

This is the simplest technique to estimate the height of the vegetation layer. Interferograms in different polarizations are selected and their Digital Elevation Models (DEM) are generated. The heights derived from these interferograms depend upon the scattering center for the polarization channels. Hence, differences in the DEM provide the difference in the heights of the scattering centers. If accurate phase centers representing top and bottom canopy are selected, the vegetation height can be accurately estimated. Cross-polarized SAR waves, generally have the scattering center in the canopy and hence are used for canopy height estimation. The difference between the DEM derived using the cross- and co-polarized SAR waves provide the height of the canopy.
Figure 2 shows the DEM difference height obtained using HV and VV polarization channels selected for generating top and bottom DEM’s. The DEM obtained using HV polarization provides DEM corresponding to top of canopy while the VV polarized DEM provides the near-ground DEM. The height obtained using this technique varies between 0 meters and 14.17 meters. Field data collected for Barkot and Thano forest ranges has a mean height of 23.90 meters. But the height estimated using DEM Difference technique has a maximum height of 14.17 meters and mean height of 4.06 meters. Similar results are obtained in previous studies (Cloude, 2006, 2005). The DEM Difference heights with different combinations of polarizations for top and bottom DEM are analyzed. However similar results are obtained. The maximum derived height does not exceed 14.5 meters. One important observation of this technique is that it estimates the height of dry riverbed regions accurately. As seen in Figure 2, the height estimated for dry river channels is in the range of 0-2 meters. This technique accurately estimates the height in the dry-river bed regions. The height is underestimated for forest regions. The technique overestimates the height of water surface and urban regions.

5.3.2 Coherence Amplitude Inversion Height

The second technique applied to the PolInSAR data is the coherence amplitude inversion technique explained in (Cloude, 2005). It is an alternative to the DEM differencing approach. It requires selection of two polarization channels. One channel is selected which represents only volume scattering while the other is believed to represent the surface scattering. The polarization channels are selected from the analysis
carried out in previous sections. HH+VV best represents ground layer and HV+VH best represents the volume layer.

Figure 3 shows a forest height map with the two polarizations selected from Pauli basis. Using these two polarization channels the forest canopy height is estimated. It is observed that the height is over-estimated for urban and dry riverbed with the height in these regions in the range of 15-20m. Ideally, the estimated height in these regions should be near 0 m for dry riverbed and <10 meters for urban areas as very tall structures are not present in Rishikesh city. The Thano and Barkot forest range canopy height ranges from 16 to 28 meters. The distribution of canopy height is shown in the histogram in Figure 4. The mean height is 23.11 meters with standard deviation of 2.41 meters.

Figure 4 Coherence Amplitude Inversion height histogram. The descriptive statistics are provided on the right side.

Descriptive Statistics
Minimum Height : 6.05 meters
Maximum Height: 28.34 meters
Mean Height: 23.11 meters
Standard Deviation: 2.41 meters
Table. Accuracy assessment results for coherence amplitude inversion height

<table>
<thead>
<tr>
<th>Forest Height Derived Using</th>
<th>Mean height</th>
<th>Variance</th>
<th>RMSE</th>
<th>Correlation</th>
<th>Average Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherence Inversion Amplitude Height</td>
<td>23.61 m</td>
<td>2.922</td>
<td>2.77 m</td>
<td>0.34</td>
<td>90.10%</td>
</tr>
</tbody>
</table>

It is observed that though the accuracy of tree height estimation is high, but the correlation is very low at 34%. The scatter plot is shown in Figure 5. The plot shows the comparison of the field measured height data with the derived data.

![Figure 5 Scatter plot for the height derived using the Coherence Amplitude Inversion Technique. The solid line is the line at 45° and the dotted line is the best fit line through the plots. The \( R^2 \) value is low at 0.1159 corresponding to a correlation of 0.34.]

5.3.3 Three Stage Inversion Technique

Three Stage Inversion’ technique

The ‘Three Stage Inversion’ technique is applied to the PolInSAR data using the derived coherences in various polarization basis. The height of the forest stand is estimated and the height map is shown in 29. This technique utilizes the complex coherences computed for different polarization basis. The complex coherences are plotted on complex plane and using the technique described in (S. Cloude and K. P. Papathanassiou, 2003) the forest stand height is estimated for each resolution cell. The estimated tree height ranges from 8 – 27m. The different colors in Figure 6 denote the height range. It is observed that the ‘Three Stage Inversion’ technique overestimates the height of the urban and dry riverbed regions. The height in these regions is in the range of 12 - 16m. The agricultural areas to the south of the Jolly Grant Airport, in
the center of the image, also presents with high vegetation height of around 17 – 20m. The derived forest height varies between 18 -27m.

5.3.3.1 Validation and Accuracy Assessment

‘Three Stage Inversion’ technique derived height is validated and its accuracy assessed. The tree height is collected during the field survey. This estimated tree height is validated against the field data. The descriptive statistics for the ‘Three Stage Inversion’ technique derived height and the field height is presented in Table 6.

![Figure 6 Forest Stand Height estimated using ‘Three Stage Inversion’ technique.](image)

Table 6 Statistics – Three Stage inversion height and Field height (H_avg)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Derived Height</th>
<th>Field Height (H_avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>18 m</td>
<td>15 m</td>
</tr>
<tr>
<td>Mean</td>
<td>22.98 m</td>
<td>23.44 m</td>
</tr>
<tr>
<td>Maximum</td>
<td>27 m</td>
<td>29 m</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.122</td>
<td>2.87</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.4</td>
<td>-0.277</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>-0.563</td>
<td>-0.078</td>
</tr>
</tbody>
</table>

The Figure 7 shows the histogram of the tree height estimated using the three stage inversion method. The black line in the histogram is the ideal normal distribution line. It is observed from the histogram that the derived height is skewed towards higher tree heights. The test of normality is applied to the estimated forest height. The Shapiro-Wilk test results are presented in Table 7. The p-value for the derived height is 0.001. For a confidence interval of 95%, the threshold p-value for passing the test of normality is 0.05. The derived
height samples do not belong to a normally distributed data. The box plot of the derived height and the field height is shown in Figure 8.

![Figure 7 Histogram of ‘Three Stage Inversion’ technique derived Forest Height](image)

![Figure 8 Box plot of the ‘Three Stage Inversion’ technique derived Forest height and the field measured tree height](image)

Table 7 Test of Normality of Data for Three Stage Inversion height and Field Height (H_avg)

<table>
<thead>
<tr>
<th>Height Type</th>
<th>Samples (N)</th>
<th>Significance (p-value)</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Measured Height</td>
<td>100</td>
<td>0.107</td>
<td>24.01</td>
</tr>
<tr>
<td>Three Stage Inversion Height</td>
<td>100</td>
<td>0.001</td>
<td>23.42</td>
</tr>
</tbody>
</table>

The results for the accuracy assessment for the ‘Three Stage Inversion’ technique derived forest height is tabulated in Table 8. For the 100 samples collected the RMSE calculated is 2.28m for a mean height of 23m. The correlation is higher than the coherence amplitude inversion technique at 0.62. The average accuracy for this technique is high at 91.56%.

Table 8 Accuracy Assessment Results for ‘Three Stage Inversion’ technique height

<table>
<thead>
<tr>
<th>Forest Height Derived using</th>
<th>Mean height</th>
<th>Variance</th>
<th>RMSE</th>
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</thead>
<tbody>
<tr>
<td>‘Three Stage Inversion’ technique</td>
<td>23 m</td>
<td>4.505</td>
<td>2.28 m</td>
<td>0.62</td>
<td>91.56%</td>
</tr>
<tr>
<td>Coherence Amplitude Inversion Technique</td>
<td>23.61 m</td>
<td>2.922</td>
<td>2.76 m</td>
<td>0.34</td>
<td>90.10%</td>
</tr>
</tbody>
</table>

The Figure 9 shows the scatter plot for the field measured height and the three stage inversion derived height. The R^2 value for 100 plots is 0.3877. It is observed from Table Error! No text of specified style in document. and Table 8 that the ‘Three Stage Inversion’ technique produces accurate results as compared with the coherence amplitude inversion technique. The correlation of the field and derived height using the ‘Three Stage Inversion’ technique is superior to that obtained from the coherence amplitude inversion technique.
Figure 9 Scatter Plot - Three Stage Inversion Height vs Field Measured Average height (H-avg). The solid line is the line at 45° and the dotted line is the best fit line through the plots. The R² value is 0.3877 corresponding to a correlation of 0.623.

References:


