COMPARISON OF METHODS TO DERIVE FOREST HEIGHT FROM POLARIMETRIC SAR INTERFEROMETRY

E. X. Chen (1), Z. Y. Li(1), S. R. Cloude(2), K. P. Papathanassiou(3), E. Pottier(4)

(1) Institute of Forest Resources Information Techniques of Chinese Academy of Forestry, Dong Xiao Fu 1 Hao, Haidian District, Beijing, China, 100091; chenerx@caf.ac.cn, zy@caf.ac.cn
(2) AEL Consultants, Cupar, Scotland, United Kingdom; scloude@ieee.org
(3) Microwaves and Radar Institute, German Aerospace Center (DLR), Oberpfaffenhofen, Germany; Kostas.Papathanassiou@dlr.de
(4) IETR UMR CNRS 6164, University of Rennes 1, Rennes, France; eric.pottier@yahoo.fr

ABSTRACT

Six forest tree height inversion methods of polarimetric SAR interferometry were validated using repeat pass E-SAR datasets and the corresponding ground measured forest stand height. We show that SINC, three stage full model and three stage SINC inversions have good performance, and the SINC inversion with the first optimum coherence (OPT1) produces the best result among the eleven coherence types validated. Taking SINC inversion as one example, two inversion correction methods were investigated, RMSE can be reduced below 4.0m after correction. The phase and coherence inversion method achieved the second lowest RMSE among the six inversion methods validated, but the estimated tree height of it has very low correlation with ground truth, and this drawback was found caused by the poor performance of RVoG phase inversion method involved.

1. INTRODUCTION

Several forest mean tree height inversion methods with polarimetric SAR interferometric (POLinSAR) data have been developed in the past 10 years. With the development of the polarimetric optimization technique in radar interferometry [1], the phase difference of interferograms formed by different polarization combinations was found to be correlated with vegetation height [2], the simplest method involved is just to take the height difference of two digital elevation model (DEM) as the tree height. In 2001, a polarimetric coherent scattering model for vegetation cover suitable for the estimation of forest parameters from interferometric observables was introduced. Based on this model, a general inversion algorithm which allows the estimation of tree height, average extinction and underlying topography from single-baseline POLinSAR data is addressed [3]. A new geometrical approach for the inversion of a two-layer coherent scattering model was clearly defined and demonstrated with simulated POLinSAR data [4], this method is the well-known three-stage inversion process for POLinSAR with one 2D lookup table computed from the most complex form of the 2-layer model (full model) for the inversion of tree height and average extinction.

In order to stimulate the application and education of these already established techniques, some POLinSAR tree height inversion methods have been coded in the POLinSAR tree height inversion module of the PolsarPro software developed through ESA funding [5], and the corresponding tutorial document published the algorithms implemented by each tree height inversion functions[6]. Except for the simplest DEM difference method and the most complex three stage full model method mentioned previously, the coherence amplitude inversion, the phase and coherence inversion (PCI) were firstly introduced. Coherence amplitude inversion refers to these methods to extract height from coherence amplitude only. It will become SINC inversion (SI) when
extinction is set to zero [6]. In PolSarPro v-3.0, the coherence amplitude inversion was programmed as SINC inversion. The performance of these tree height inversion methods were successfully demonstrated with one simulated POLinSAR dataset generated from a coherent polarimetric interferometric SAR data simulation model.

However, there is still very few comparative validation work carried out for all the established tree height inversion methods using the same real POLinSAR data. This paper is just to investigate and validate the performance of these tree height inversion algorithms using one real airborne (E-SAR) POLinSAR dataset and some ground truth data in forest stand scale.

2. TEST SITE AND DATA

The test site Traunstein is located in the pre-alpine moraine landscape of southeast Bavaria near the city of Traunstein, Germany. It forms a mosaic of agricultural fields and forests. The topography varies from 600-650 m above sea level with only few steep slopes. The climatic condition of 7.8°C mean annual temperature and precipitation of 1600 mm/a favor mixed mountainous forests, dominated by spruce (*Picea abies*), beech (*Fagus sylvatica*) and fir (*Abies alba*). The test site forest includes the two forest districts “Bürgerwald” and “Heilig-Geist” and covers a total area of 218 ha [7].

Based on aerial photography, forest inventory, and the forest management plan, 20 homogeneous stands between 1 ha and 23 ha size were selected for the validation. Most of the stands were dominated by spruce, only few by beech or maple. Heights reach up to 40 m and biomass levels up to 450 t/ha. The height data were estimated from forest inventory data (1 plot/ ha). Height was defined as upper canopy height and calculated as the mid height of the highest inventory layer [7].

The radar data were acquired on the morning of Oct. 11, 2003 with the E-SAR system of DLR. The validation has focused upon an interferometric fully polarized L-band data set with a spatial baseline of 5m (horizontal) at a flight altitude of 3000 m above ground, the temporal baseline 20 minutes. The data were processed for 1.5 m range resolution and 3.0 m resolution in azimuth (4 looks). The incidence angle ranges from 25° in near range to 60° in far range.

The master and slave quad-polarization complex data were already co-registered precisely to each other, the flat earth phase image and effective wave number image were also provided. These images are all of size 1414 pixels and 4642 lines. After multi-look processing (6 looks azimuth and 2 looks range) and extracting the region covered by ground truth data, the window images of master and slave data of size 707 pixels and 773 lines were generated. The resulting master polarimetric data is shown in Pauli-basis as Fig.1. The corresponding ground truth image is shown in Fig.2. The minimum forest stand height is 13.0m and the maximum is 36.1m.

![Figure 1. The master polarimetric SAR data extracted from original data after multi-looking and subset processing, shown in Pauli-basis with HH-VV as red, HV+VH as green and HH+VV as blue](image)

3. FOREST HEIGHT INVERSION METHODS

3.1. DEM difference

Assuming the polarization channel for the top forest canopy was separated from that for the ground surface
under the canopy, the canopy height \( h_v \) can be extracted simply from equation (1) \[6\].

\[
h_v = \frac{\arg(\gamma_{w_v}) - \arg(\gamma_{w_v})}{k_z}
\]  

(1)

Figure 2. The ground truth data with each polygon standing for one forest stand and all the pixels fallen into one polygon were assigned with one tree height number shown in different color

where \( w_v \) is a user selected polarization, assumed to be located at the top of the vegetation, \( \gamma_{w_v} \) is its complex coherence; \( w_s \) is assumed to be located near the ground surface under the vegetation canopy. Here, HV is chosen as \( w_v \), and HH minus VV is set as \( w_s \). \( k_z \) is the effective wave number, which can be computed from the interferometric geometry using equation (2).

\[
k_z = \frac{4\pi\Delta\theta}{\lambda\sin\theta} \approx \frac{4\pi B_n}{\lambda R \sin\theta}
\]  

(2)

Where \( \lambda \) is the radar wave length in meter, \( \theta \) is the SAR incidence angle corresponding to the master track, and \( \Delta\theta \) is the incidence angle difference between the two tracks, \( B_n \) is the normal baseline length and \( R \) is the slant range distance from the master to the target.

### 3.2. RVoG phase inversion

Instead of simply taking the phase of surface coherence \( \gamma_{w_s} \) as ground phase, one two layers backscattering model called random volume over ground (RVoG) can be used for tree height inversion. One simple way to compute ground phase with two known coherences \( \gamma_{w_v} \), and \( \gamma_{w_s} \), was suggested as equation (3) \[6\],

\[
\phi = \arg(\gamma_{w_s} - \gamma_{w_v} (1 - L_{w_v}))
\]  

(3)

where \( L_{w_v} \) is the normal baseline length and \( R \) is the slant range distance from the master to the target.

Then tree height can be extracted with (4) \[6\].

\[
h_v = \frac{\arg(\gamma_{w_v}) - \phi}{k_z}
\]  

(4)

This method is named as RVoG phase inversion (RPI). Here, coherence of HV (symbolized as HV-HV) is considered as \( \gamma_{w_v} \) and coherence of HH minus VV (symbolized as (HV-HV)-(HH-VV)) is taken as \( \gamma_{w_s} \).

### 3.3. SINC inversion

It’s assumed that the relationship between canopy height \( h_v \) and volumetric coherence amplitude follows a SINC function, so if we know the volumetric coherence \( \gamma_{w_v} \), the forest height can be estimated with equation (5) \[6\].

\[
h_v = \frac{2 \cdot \text{sinc}^{-1}(\gamma_{w_v})}{k_z}
\]  

(5)

In order to do comparisons with the other method, coherence of HV is also considered as \( \gamma_{w_v} \).

For the further analysis, 11 coherence images were inputted to (5) separately, these images includes the 1st optimization coherence (OPT1), the 2nd optimization coherence (OPT2), and the 3rd optimization
coherence (OPT3) [2], HH-HH, HV-HV, VV-VV, LL-LL, 
LR-LR, RR-RR, Pauli-1 and Pauli-2. Pauli-1 is the 
coherence of polarization (HH-VV) and Pauli-2 is the 
coherence of polarization (HH+VV).

3.4. Phase and coherence inversion

Combining RVoG phase inversion equation (4) and 
SINC inversion equation (5) we get equation (6), which 
is the so called phase and coherence inversion (PCI). The 
inputs to (6) include two coherence images: volume 
coherence $\gamma_{w}$, and surface coherence $\gamma_{s}$ [6].

$$h_i = \frac{\arg(\gamma_w) - \hat{\phi}}{k_z} + \varepsilon \frac{2 \cdot \text{sinc}^{-1}(\{\gamma_s\})}{k_z}$$  (6)

Again coherence of HV is considered as $\gamma_{w}$, coherence 
of HH minus VV is used as $\gamma_{s}$, and $\varepsilon = 0.4$.

3.5. Three stages full model inversion

The three stage full model inversion algorithm (FMI) 
applied here was the same as described in [4] with one 
characteristic of using 2D Look up table (LUT). The 
same 11 coherence images as introduced for the SINC 
inversion were taken as inputs to the FMI. There three 
stages can be defined as the follows:

Stage 1: Line fitting and find the intersection point 
P1 and P2;

Stage 2: Find out the ground phase point (P1 or P2) 
and compute the ground phase $\hat{\phi}$ and select the 
volumetric coherence $\gamma_{w}$ through coherence ranking 
order algorithm;

Stage 3: Extract tree height $h_i$ using 2D LUT.

3.6. Three stages SINC inversion

The three stages SINC inversion (TSS) algorithm has no 
difference with FMI in the 1st and 2nd stage. The only 
difference is in the 3rd stage, where the volumetric 
coherence $\gamma_{w}$, derived from the stage 2 is inputted into 
the SINC inversion function (5) for computing the tree 
height instead of using the 2D LUT.

3.7. Criteria for inversion methods validation

The squared correlation coefficient ($R^2$) and the root 
mean square error (RMSE) were selected as statistic 
criterion for validating the tree height inversion accuracy 
of the six methods involved.

The tree height estimation accuracy was validated in 
forest stand scale. 20 forest stands have been measured 
through field plot work. The mean dominate tree height 
($h_{100}$) was computed from ground measured tree height 
(Fig. 2). The $h_{100}$ for the forest stand $i$ is defined as $H_i(i)$, 
i = 1, 2, ... , N. N=20.

The tree height was inversed in pixel scale, although the 
coherence information used for each pixel is in reality 
the mean value computed from all the pixels of a 
window around it (window size is 7*7). In order to 
estimate the model inversed tree height in forest stand 
sele, the mean tree height of all the pixels fallen into 
each forest stand polygon was calculated and defined as 
$H_e(i)$, i = 1, 2, ... , N. N=20.

Then, the $R^2$ and RMSE between the estimated vector 
$H_e$ and the true value vector $H_i$ were computed as validation 
criterions.

4. RESULTS AND ANALYSIS

4.1. Comparison of the six inversion methods

The tree height inversion performance of the six methods 
was summarized in Tab.1. The $R^2$ shows the relationship 
between the estimated and the true forest stand tree 
height, apparently, the DD, RPI and PCI are of very low 
$R^2$ value (below 0.2), while the other three methods (SI, 
FMI and TSS) show $R^2$ bigger than 0.75. So the six 
methods were naturally separated into two categories 
according to their $R^2$ values.

Although the RMSE of SI, FMI and TSS are all bigger 
than 7.0m, which maybe possibly caused by temporal 
de-correlation, their high $R^2$ values show that these errors 
can be corrected in some degrees if ground measured 
forest stand tree height can be used for the correction of 
the inversion model or the inversion results, see section 
4.2 for further analysis.
The consistent linear changing trend of estimated tree height with ground measurement shown in Fig.3-(c), (e) and (f) for SI, FMI and TSS respectively tell us that one acceptable inversion method should produce results with $R^2$ not less than 0.75 for this POLinSAR dataset. One inversion method of $R^2$ as low as 0.2 could not be considered as revealing the general relationship between $H_e$ and $H_t$ discovered by SI, FMI and TSS.

Among the three inversion methods (SI, FMI and TSS), the $RMSE$ of TSS is the smallest (Tab. 1), the SI method is of the largest $RMSE$, while FMI method is in the middle. As the most complex model, FMI achieving better result is reasonable. However, it is interesting to find that the simple SI method can produce good correlation result with ground truth ($R^2=0.78$).

Furthermore, TSS achieved better result ($RMSE=7.12m$, $R^2=0.86$) than FMI method ($RMSE=10.98m$, $R^2=0.85$) through replacing 2D LUT solution by SINC function in the 3$^{rd}$ stage of FMI. This means the volumetric coherence selected through ranking order algorithm was inputted to SINC inversion by TSS. Therefore, it is possible to improve the performance of SINC inversion if the optimal volumetric only coherence can be found out and supplied to SI. In order to validate the other possibility to improve the result of the SINC inversion, the performance of the other arbitrary chosen volumetric coherence for different polarizations will be analyzed in the next section.

**Table 1. The performance of the six tree height inversion methods**

<table>
<thead>
<tr>
<th>Inversion Method used</th>
<th>$R^2$</th>
<th>$RMSE$</th>
</tr>
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<tbody>
<tr>
<td>DEM difference (DD)</td>
<td>0.12</td>
<td>26.00</td>
</tr>
<tr>
<td>RVoG phase inversion (RPI)</td>
<td>0.02</td>
<td>21.28</td>
</tr>
<tr>
<td>SINC inversion (SI)</td>
<td>0.78</td>
<td>13.76</td>
</tr>
<tr>
<td>Phase &amp; coherence inversion (PCI)</td>
<td>0.15</td>
<td>7.99</td>
</tr>
<tr>
<td>Full model inversion (FMI)</td>
<td>0.85</td>
<td>10.98</td>
</tr>
<tr>
<td>Three stage SINC (TSS)</td>
<td>0.86</td>
<td>7.12</td>
</tr>
</tbody>
</table>
Figure 3. Scattering plot of estimated forest stand tree height with ground measured, plate (a), (b), (c), (d), (e) and (f) corresponds to method DD, RPI, SI, PCI, FMI and TSS

4.2. SINC inversion with different coherences

The amplitude of the 11 kinds of complex coherence images were evaluated with the SI method, their performances are shown in Tab. 2. There is not so much difference between $R^2$, while the best result is from OPT1 with lowest RMSE of 6.84m. OPT3 is of the largest RMSE. Normally OPT1 stands for the surface coherence component and maybe of lowest $R^2$ with tree height. But OPT1 is not always the surface component. It can be the volume-only component according to the location of the coherence in the line model.

Because of the $R^2$ is always around 0.8 in Tab. 2, so the RMSE can be corrected with one simple function. The function $H_e=a+b*H_t$ can be fitted between $H_e$ and $H_t$ using Least Mean Square Error (LMS) method, then it was used to estimate tree height. Applying this correction method to the model inversion result of the 11 coherence respectively, it was found that the RMSE were successfully reduced to 3-4m. The OPT1 was still the best with one RMSE of 3.65m, and OPT3 the worst with one RMSE of 4.30m, while the RMSE of HV-HV is 3.84m.

Table 2. Comparison of the performance of SI with different kind of coherences

<table>
<thead>
<tr>
<th>Coherence types</th>
<th>$R^2$</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPT1</td>
<td>0.81</td>
<td>6.84</td>
</tr>
<tr>
<td>OPT2</td>
<td>0.79</td>
<td>12.75</td>
</tr>
<tr>
<td>OPT3</td>
<td>0.72</td>
<td>19.80</td>
</tr>
<tr>
<td>HH-HH</td>
<td>0.80</td>
<td>13.59</td>
</tr>
<tr>
<td>HV-HV</td>
<td>0.78</td>
<td>13.76</td>
</tr>
<tr>
<td>VV-VV</td>
<td>0.73</td>
<td>13.78</td>
</tr>
<tr>
<td>LL-LL</td>
<td>0.78</td>
<td>14.21</td>
</tr>
<tr>
<td>RR-RR</td>
<td>0.80</td>
<td>14.18</td>
</tr>
<tr>
<td>(HH+VV)-(HH+VV)</td>
<td>0.77</td>
<td>13.30</td>
</tr>
<tr>
<td>(HH-VV)-(HH-VV)</td>
<td>0.77</td>
<td>14.07</td>
</tr>
</tbody>
</table>

Here, we just use this empirical correction method to show that it is possible to correct the inversion result when $R^2$ between $H_e$ and $H_t$ is high enough. In fact, it is easy to do the correction through incorporating one de-correlation factor $k$ into (5) to compensate all the none-volumetric de-correlation.

$$h_e = \frac{2 \cdot \text{sinc}^{-1}(\frac{\nu_{wc}}{k})}{k}$$

As one example, if OPT1 is chosen as the volumetric coherence and $k$ is set to 0.98, the RMSE can be reduced to 3.16m and $R^2$ is as high as 0.84. So the overestimated problem maybe caused by temporal de-correlation and the other factors can be solved in some degree by this way. Fig. 4 shows the relationship between estimated tree height and the ground truth.

4.3. Phase and coherence inversion’s performance

The performance of PCI is very different from the other methods (Tab.1). Although PCI has the second smallest RMSE (7.99m), just a little bit larger than TSS, its $R^2$ is
too low (0.15), this means the estimated tree height has no significant relationship with ground measurement. However, PCI was found to be robust and of best performance among all the inversion methods through theory analysis and experiences learned from simulation and real POLinSAR datasets [6]. If we compare the result of RPI, SI and PCI, it is easy to understand that the poor performance observed in this case study is really caused by the very poor performance of the RPI method. So combining the poor result of RPI with SI should lead to very poor result. However, on other conditions when the result of RPI is of high accuracy, the robust and of best performance feature of PCI may be observed as in shown in [6].

Taking SINC inversion as one example, the inversion result correction method and the model correction method were investigated with ground truth data, the \( \text{RMSE} \) can be reduced below 4.0 m by these corrections.

The phase and coherence inversion method achieved the second lowest \( \text{RMSE} \), but the estimated tree height has very low correlation with ground truth, this drawback was found caused by the poor performance of the phase inversion method involved.

5. CONCLUSIONS

It has been observed that SINC inversion, full model inversion and the three stage SINC inversion have good performance: the estimated tree height in forest stand level correlates very well with ground measured forest height.

The performances of the first four methods depend on the selected or assumed volumetric coherence and surface coherence (SINC inversion only need volumetric coherence). There are many possible combinations if the two types of coherence should be chosen manually. SINC inversion test shows that the first optimum coherence (OPT1) can produce best result among the eleven different coherence types.

REFERENCES
