# Potential of forest height estimation using X band by means of two different inversion scenarios

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***Abstract*** —Polarimetric SAR Interferometry (Pol-InSAR) is a powerful remote sensing method for forest height estimation by using the random volume over ground model (RVoG). At higher frequencies implementation of forest height estimation in X band is limited to less dense and low forest types where X band is able to penetrate through the volume to the ground. However, the penetration depth at X band is insufficient to cover all forest types. In the paper, forest height inversion at X band using two different approaches is demonstrated with focus on the impact of extinction on forest height estimation.

***Keywords: PolInSAR, Forest Height, X band,***

## I. INTRODUCTION

Forest height estimation based on Polarimetric SAR Interferometry (Pol-InSAR) has recently been successfully demonstrated using low frequency SAR at P- and L-band. Validated results for forest height were shown for different forest types. In [6,7,8] height estimates for tropical forests based on the INDREX-II (Indonesian Radar experiment) data set were presented. Forest height estimates for temperate forests were discussed in [9,11], while results over boreal forest have been reported in [10].

As one of the main parameters that limit the performance of Pol-InSAR inversion at longer wavelengths is temporal decorretation that is intrinsic in repeat-pass systems even at small temporal baselines. This, combined with the fact that interferometry indicated clearly that forest extinction values have been significantly overestimated in the past, increases the interest on forest parameter estimation at higher frequencies - where single pass interferometry can be realized easier. At higher frequencies (e.g. C- and X band), inversion is limited to forest types characterized by low(er) extinctions that allow the wave to penetrate through the whole forest volume and "see" the underlying ground. Boreal forest and tropical peat swamp forest are less dense and less high forest types. First inversion results at X band using a simplified inversion approach have been demonstrated in [8,10]. Nevertheless, the inversion performance at X band in terms of penetration depth and extinction still needs to be evaluated. In this paper forest height estimation assigning different inversion assumptions/scenarios is discussed and validated by means of selected test sites.

## II. INVERSION SCENARIOS

Forest height inversion is based on the random volume over ground (RVoG) model, [1,2,3]

$$\tilde{\gamma}_V = exp(i\kappa_z z_0)\frac{\tilde{\gamma}_{V0}+m}{1+m} \qquad \text{-1)}$$

$\varphi_0 = \kappa_z z_0$ is the phase related to the ground topography z0, where $\kappa_z$ is the vertical wavenumber and *m* the effective ground-to-volume amplitude ratio accounting for the attenuation through the volume. $\tilde{\gamma}_{V0}$ is the volume decorrelation caused in the absence of the ground layer and corresponds to:

$$\tilde{\gamma}_V = exp(i\kappa_z z_0)\frac{\int_0^{h_V} exp(i\kappa_z z')\,exp\left(\frac{2\ \sigma\ z'}{cos\,\theta_0}\right)dz'}{\int_0^{h_V} exp\left(\frac{2\ \sigma\ z'}{cos\,\theta_0}\right)dz'} \qquad \text{-2)}$$

where $\sigma$ is the mean extinction coefficient and $\theta$ the angle of incidence.

At higher frequencies the mean extinction increases attenuating more and more the ground scattering contribution. At high extinction levels, the effective phase center moves towards the top increasing the interferometric coherence values, weakening its dependency on polarization is rather limited as the strongly polarized ground scattering get lost. One possible approximation towards a simplified inversion scenario is to ignore completely the ground scattering component (by assuming *m=0* in Eq. 1) in all polarizations. Using the interferometric coherence at a single polarization channel leads to an underdetermined inversion problem with 3 unknowns and only 1 (complex) observable. Fixing the ground phase allows to obtain a determined problem

$$\min_{h_V,\phi_0} \left\| \tilde{\gamma}(\vec{w}) - \tilde{\gamma}_V(h_V,\sigma \mid \phi_0 = \phi_{DEM}) \right\| \cdot \qquad \text{-3)}$$

A second possibility proposed is to fix the extinction value reducing further the inversion problem to a single parameter (height) problem by neglecting the ground phase.

$$\min_{h_V} \left\| \ |\tilde{\gamma}(\vec{w})| - |\tilde{\gamma}_V(h_V,\varphi_0 \mid \sigma = \sigma_0)| \ \right\| \qquad \text{-4)}$$

III. DESCRIPTION OF TEST SITES

Two test sites have been used for the investigations in this paper. The first site is the Mawas test site, a tropical peat swamp forest located in Kalimantan, Indonesia. SAR and ground data have been acquired during the INDREX II campaign in 2005 [4]. The second site is "Ebersberger Forst", a temperate forest located in the vicinity of Munich.

In both sites InSAR data were acquired by DLR's (German Aerospace Center) E-SAR System in a quad-pol repeat-pass mode at L- (and P-band only in Mavas) and a single-pol (VV) single-pass InSAR mode at X band. At X band the vertical wavenumber varies from 0.07rad/m at near to 0.13rad/m at far range.

Both sites are characterized by flat topography, which facilitates the determination of ground phase by means of non-vegetated areas within and or beside the forest.

*A. Ground Measurements and Description: Mawas area*

The Mawas test site is situated in Southern Borneo it is a largely flat peat swamp area, covered by tropical peat swamp forest. The forest imaged in the scene is disturbed by logging activities. Therefore, the area is pervaded by a net of logging trails which can be also recognized in the radar images. Beside the logging trails the forest is uniformly structured in terms of tree composition and forest height.

For Validation, tree heights along two transect, each 100m in length and 10m wide, broken down to squares of 10m by 10m were measured. As reference height a top height, the so called "h100" [5], was calculated for each square individually (see Figure 1). Forest heights deduced from the measurements range between 18m and 39m, mean forest height is 26m. An X band amplitude and coherence image of the scene is displayed in Figure 2 the upper part of the image is completely covered with forest while the lower part is filled with extensive areas of bare surface (burned forest) and a river. In the forested part of the coherence image appear several strips of high coherence. This strips show the logging trails within the forest.

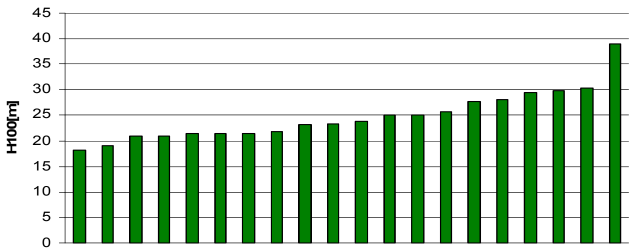


Figure 1: Ground measurements Mawas top height h100 for each 10m x 10m subplot.

Due to low vegetation density along the logging trails there is a high probability of a ground contribution in the signal leading to high coherence values. Along azimuth coherence is disturbed by a strip of low coherence which is due to an antenna defect during the acquisition.

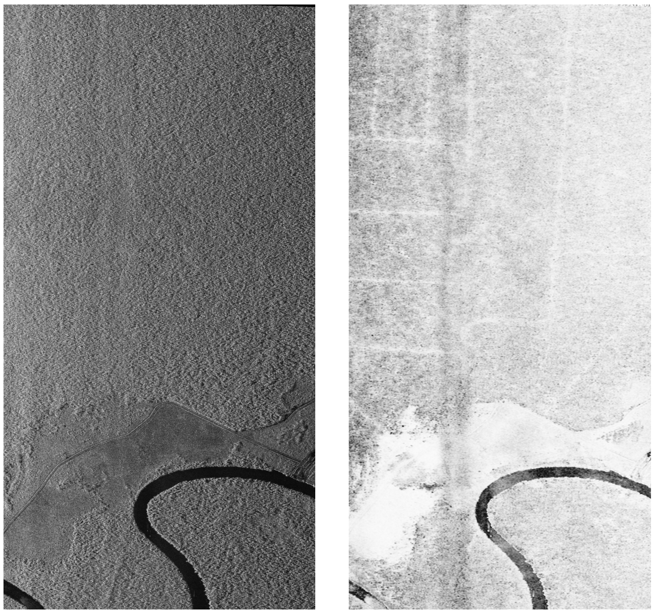

Figure 2: X band (VV) amplitude (left) and InSAR coherence (right) of the Mawas Test site.

*B. Description "Ebersberger Forst"*

The test site "Ebersberger Forst" is a managed forest dominated by coniferous trees, whereas the forested area is divided into several even aged stands.

IV. INVERSION RESULTS AND VALIDATION

*A. Mawas region*

Forest Height inversion from the X band (VV polarisation) single-pass InSAR data has been performed using the two inversion approaches addressed in Section I. The first approach is the one-dimensional inversion based on the interferometric coherence amplitude (see Eq.4, further referred as Inversion II) while extinction was fixed first to 0.1dB/m and then to 0.3dB/m

The second approach is the two dimensional inversion based on the complex interferometric coherence values that allows the estimation of height and extinction at the same time. For this the ground phase term has to be accounted (see Eq 3, further referred as Inversion I). Therefore ground phase was estimated from the interferometric phase of non-vegetated areas within the scene. Due to the flat topography, the ground phase is assumed to be constant in the whole image. By assuming also no ground contribution in the signal one polarization is sufficient to make a full inversion as described by Eq. 3.

Inversion results of Inversion I are shown in Figure 3 left side. As no forest / non-forest mask has been used even the bare surfaces next to the river are related to a forest height. However these values have no real meaning as in this case the decorrelation is caused by SNR rather than volume decorrelation leading to a miss-interpretation of the model.

Estimated forest height ranges between 13m and 38m. The logging tracks on the left side appear correctly in the height map as lower forest. Around the logging tracks more patches of lower forest can be recognized than in the rest of the image indicating a higher disturbance due to the logging activities. In the upper left part of the image forest height increases, probably because the topography changes and the assumption of a constant ground phase becomes erroneous. On strip of lower coherence along azimuth (see Figure 2 right) - caused by an antenna gain error - forest height is - off course - overestimated.

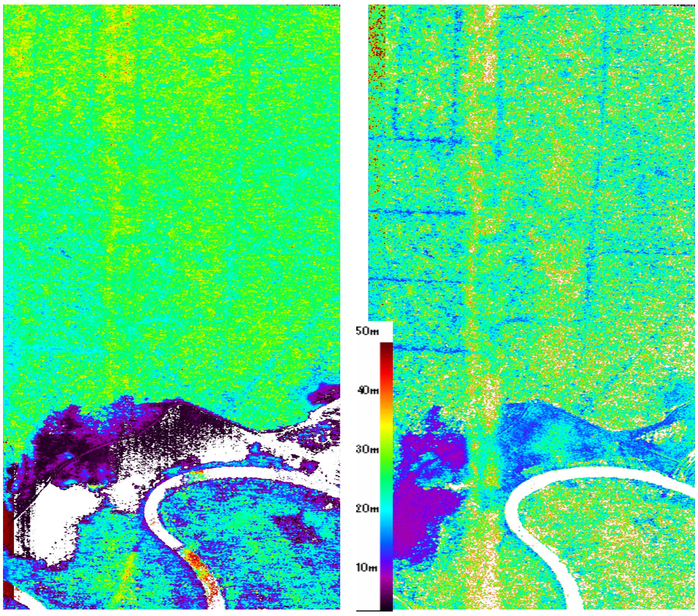


Figure 3: Forest Height image, left: Inversion I, right: Inversion II 0.3dB/m extinction;

As mentioned, Inversion II was performed for two extinction values: 0.1dB/m and 0.3dB/m. The results for the 0.3dB/m case are shown on the right side of Figure 3. Compared to Inversion I, forest height is in general overestimated; locally the estimated heights reach up to 60m. However, the trend of forest overestimation in the upper left corner as appearing in the results of Inversion II is here not present. On the other hand, the heights along the logging tracks are much lower than the ones obtained from Inversion I.

For validation, an area of about 400m x 400m including the ground measurement plots is used to validate the ground measured forest height to the obtained estimates. The validation is based on the assumption that the forest is homogeneous in this area and the measured plots are representative.

Forest height from Inversion I ranges from 14m to 38m with a mean value of 25m (see blue line in Figure 4 left) which fits well the ground measurements. The height of the phase center (red line in Figure 4 left) ranges from 7m to 22m with a mean level of 17m. This indicates a mean penetration depth on the order of about 10m (40% of the mean forest height).

Inversion I provides beside to forest height also extinction estimates. Figure 4 right shows the histogram of the obtained extinction values over the validation area. Extinction ranges up to 1.0dB/m with a mean value of 0.3dB/m.

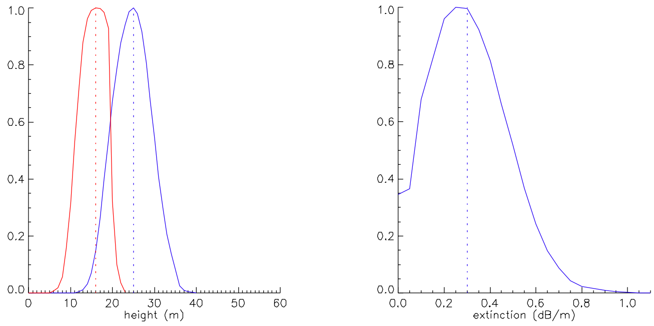


Figure 4 left: histogram of forest height estimates for Inversion I (blue) and height of phase center (red); right: histogram of extinction estimates Inversion I

For Inversion II assuming 0.3dB/m extinction (see red line in Figure 5 right) the range of values goes from 9m to 60m with a mean value of 27m. The mean value fits well the ground measurements, while the range of height values is too wide, characterized by a clear overestimation of forest heights. Assuming an extinction value of about 0.1dB/m (see red histogram in Figure 5 left), mean forest height drops to 22m with a range of values from 9m to 40m. Compared to the 0.3dB/m inversion results range of values became smaller and less overestimationed.

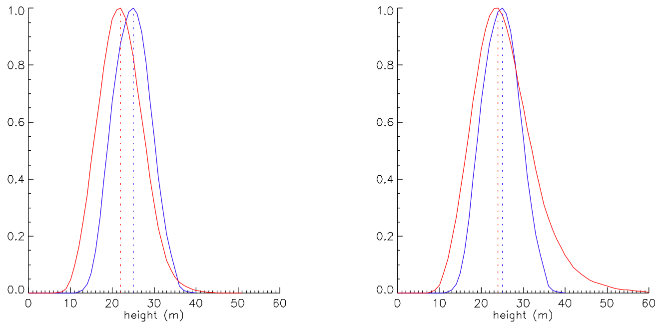


Figure 5 left: histogram of forest height estimates Inversion I (blue) and forest height estimates Inversion II 0.1db/m extinction; right: histogram of forest height estimates Inversion I (blue) and forest height estimates Inversion II 0.3db/m extinction

### B. *Ebersberger Forst*

In the Ebersberger Forst test site the inversion was done in the opposite direction, i.e., forest height and ground phase were used as input parameter in order to estimate extinction and ground to volume ratio in X band (VV polarization). The characteristics of the scene that consist of uniform single species even aged stands, the availability of actual forest inventory data and the relative flat terrain allow the implementation of this method.

On a small scale the terrain can be assumed constant while on a large scale elevation changes on the order of about 100m have to be compensated. Therefore extinction and ground to volume ratio was estimated locally on five test stands. As ground phase $\varphi_0$ the interferometric phase from a bare surface next to the stand was used. Forest height was obtained from the forest inventory data.

The inversion results are summarized in Table 1. Forest height in the selected plots with 1 sample of 22m and 4 samples around 30m are in the order the Mawas forest heights. Nevertheless vegetation density here is higher than in the Mawas region, which accounts in higher extinction estimates, up to 0.8dB/m. Also here the phase center height lies clearly under the forest canopy. Another important result is that the ground contribution for all five plots is indeed negligible low.

Table 1: Inversion Results „Ebersberger Forst“

| | Stand I | Stand II | Stand III | Stand IV | Stand V |
|---|---|---|---|---|---|
| Forest Height [m] | 30 | 29 | 32 | 31 | 22 |
| Phase Center [m] | 23 | 21 | 21 | 25 | 17 |
| Extinction [dB/m] | 0.4 | 0.4 | 0.5 | 0.5 | 0.8 |
| Ground to Volume ratio | 0 | 0.05 | 0 | 0 | 0.05 |

## V. Discussion

The comparison of the estimated phase centers with the ground measurements - in both test sites - makes obvious that the scattering center of X band is located clearly below the forest canopy. This is a clear indication that X band penetrates into the forest volume and the decorrelation in the interferometric coherence is caused by volume decorrelation. This allows on the one side to investigate forest volumes by means of conventional Pol-InSAR techniques even at X band while on the other side indicates the insufficiency of approaches based on the assumption that X band interferometric phase is located on the top of the canopy.

The feasibility of forest height inversion in X band using a single polarization was demonstrated. Best results were received for a full inversion using an estimate of the ground phase as input information (Inversion I). The mean value of the estimated forest height (~25m) was very close to mean value of ground measurements (~26m) and the range of forest height obtained corresponded well to the range of heights of the ground measurements. The inversions also show that the corresponding extinction values depend strongly on the local forest conditions and vary up to 1db/m values.

Inversion II was performed by using a mean extinction value (obtained from inversion II 0.3dB/m) and ignoring the ground phase. In this case, while the mean value of the obtained height estimates (~27m) fits quite well to the reference height (~26m) the range of heights obtained is unrealistic wide, induced caused by the variation of extinction within the forest. On a large scale over- and underestimation compensates each other leading to the right mean value. In this sense this approach can be valuable on a large scale (low resolution) context while on a small scale (high resolution) context locally large deviations have to be expected.

Inversion II is limited to low extinction forest conditions, where X band penetrates through the vegetation layer until the ground while Inversion I works also for higher extinctions when the required information for the ground phase is given.

## Acknowledgment

The authors would like to thank Marcela Quinones and Dirk Hoekman for their invaluable work in providing the ground measurements for the Mawas test site. We would also like to express our gratitude to the Indonesian Ministry of Forestry for their help throughout the INDREX II campaign.

Funding for the INDREX II campaign was provided by ESA under contract 18602/04/NLCB. The investigation in this paper where supported in the frame of ESA 3-11536/06/I-EC

## References

[1] K.P. Papathanassiou and S.R. Cloude, ‘‘Single base-line Polarimetric SAR Interferometry’’, IEEE Transactions on Geoscience and Remote Sensing, vol. 39, no. 11, pp. 2352-2363, 2001.

[2] S.R. Cloude and K.P., Papathanassiou, “Three-stage inversion process for polarimetric SAR interferometry”, IEE Proceedings - Radar Sonar and Navigation, vol. 150, no. 3, pp. 125-134, 2003.

[3] S.R. Cloude and K.P. Papathanassiou 1998, "Polarimetric SAR Interferometry", IEEE Transactions on Geoscience and Remote Sensing, vol. 36, no. 5, pp. 1551-1565, September 1998.

[4] I. Hajnsek, et al INDREX – Indonesian Airborne Radar Experiment Campaign over tropical forest in L- and P-band, Workshop PolinSAR, ESA, ESRIN, Italy, January 2005, http://earth.esa.int/cgi-bin/confpol.pl?abstract=193

[5] T. Mette, K. P. Papathanassiou, I. Hajnsek, “Biomass estimation from polarimetric SAR interferometry over heterogeneous forest terrain”, Proceeding of IEEE Geoscience and Remote Sensing Symposium (IGARSS 2004), 20. - 24. September, Anchorage, Alaska, 2004

[6] F. Kugler, K. P. Papathanassiou, I. Hajnsek, D. Hoekman, “Forest Height Estimation in Tropical Rain Forest using Pol-InSAR Techniques”,Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 31 July -04 August, Denver, USA, 2006.

[7] F. Kugler, K.P. Papathanassiou, I. Hajnsek, and D. Hoekman, “INDREX-II – Tropical Forest Height Estimation with L- and P-Band Polarimetric Interferometric SAR”, Proceedings of European Conference on Synthetic Aperture Radar, EUSAR 06, Dresden, Germany, May 16-18, 2006.

[8] F. Kugler, I. Hajnsek, K. P. Papathanssiou, D. Hoekman, “INDREXII – Indonesian Ariborne Radar Experiment Campaign over Tropical Forest In L- and P-Band Polarimetric interferometric SAR”, Proc. 3D Remote Sensing in Forestry, Vienna, 14.2 – 15.2.2005

[9] F. Kugler, F.N. Koudogbo, K.P. Papathanassiou and K. Gutjahr , “Frequency Effects in Pol-InSAR Forest Height Estimation”, Proceedings of European Conference on Synthetic Aperture Radar, EUSAR'06, Dresden, Germany, May 16-18, 2006.

[10] J. Praks, F. Kugler, K.P. Papathanssiou, I. Hajnsek, M. Hallikainen, “Treeheight estimation for boreal forest by means of L and X band POLInSAR and HUTSCAT scatterometer”, IEEE Transactions on Geoscience and Remote Sensing letters, submitted

[11] F. Garestier, P. Dubois-Fernandez, K. P. Papathansssiou, “Pine forest Height inversion using single-pass X-band Pol-InSAR data”, Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS), accepted