# Two-Level Forest Model Inversion of Interferometric TanDEM-X Data

Maciej Jerzy Soja, Chalmers University of Technology, soja@chalmers.se, Sweden
Lars M. H. Ulander, Swedish Defence Research Agency, lars.ulander@foi.se, Sweden

## Abstract

In this work, a two-level model is inverted and estimates of ground-to-vegetation ratio and level distance are obtained. Interferometric TanDEM-X data acquired over Remningstorp, a hemi-boreal test site situated in southern Sweden are used. Interferograms are flattened through the removal of ground phase, computed from a high-resolution digital terrain model. 32 circular, 40-metre radius field plots are used to show that the two estimated model parameters are well-correlated with the lidar-derived parameters vegetation ratio (VR, a canopy density measure) and 95$^{th}$-percentile forest height (H95), with the respective Pearson correlation coefficients -0.83 and 0.99. Two new quantitites, IVR and IFH95, are introduced as interferometry-based estimates of VR and H95, with RMSE values 0.68 m and 4.50 percentage points, respectively.

## 1 Introduction

Forest height and canopy density are two of the most important forest parameters used in biomass mapping based on small-footprint lidar. While they can be easily derived from high-resolution lidar images, their estimation from spaceborne SAR imagery is much more difficult due to different acquisition geometry, lower resolution, different imaging technique, etc.

TanDEM-X (TDM) is an X-band, single-pass interferometric sensor consisting of two almost identical SAR satellites flying in a tight tandem formation [1]. The main purpose of TDM is the acquisition of a first, global, high-resolution DEM. If an accurate DTM is available, ground topography can be subtracted from the TDM DEM and an estimate for scattering centre position can be produced. This estimate is often well-correlated with forest height [2-4], but in some cases it can be biased due to imaging geometry [5] or weather conditions [4, 6].

The main scope of this paper is to show that the inversion of a proposed two-level model produces two parameters, which can be used as accurate forest height and canopy density estimates, and which are less sensitive to baseline-related effects, such as the bias effect occurring for layered stands at relatively low height-of-ambiguity values and described in [5].

## 2 Two-Level Model

Complex correlation coefficient $\tilde{\gamma}(k_z)$ can be written as a normalized Fourier transform of radar cross section $\sigma(z)$ in the vertical direction at the spatial frequency $k_z$:

$$\tilde{\gamma}(k_z) = \frac{\int_V \sigma(z) e^{ik_z z} \mathrm{d}z}{\int_V \sigma(z) \mathrm{d}z}. \quad (1)$$

For a two-level model with areafill factor η (the fraction of the total area covered by the top level), radar cross section can be written as:

$$\sigma(z) = \sigma_{gr}^0 (1-\eta)\delta(z) + \sigma_{veg}^0 \eta \delta(z - \Delta h), \quad (2)$$

where $\sigma_{gr}^0$ is the bottom (ground) level backscattering coefficient, $\sigma_{veg}^0$ is the top (vegetation) level backscattering coefficient, and $\Delta h$ is the level distance.

With this assumption, and with ground-to-vegetation ratio $\mu = \frac{\sigma_{gr}^0}{\sigma_{veg}^0}\frac{1-\eta}{\eta}$, (1) can be simplified to:

$$\tilde{\gamma}(k_z) = \frac{e^{ik_z \Delta h} + \mu}{1+\mu}. \quad (3)$$

This formulation uses two parameters to model one complex value for a certain value of $k_z$. The model is a one-to-one mapping for all ground-corrected correlation coefficients except unity, unambiguous within one $2\pi$-interval. There exists therefore one single combination of $\mu$ and $\Delta h$ for each measured ground-corrected complex correlation coefficient.

The two-level model is a simplified version of the interferometric water cloud model (IWCM) [4] with infinite extinction coefficient and zero ground phase, or, when μ is treated as an independent parameter, the random volume over ground (RVoG) model [7] with infinite extinction coefficient and zero ground phase. Instead of having a distributed volume, an effective scattering height is employed, and all interaction between top and bottom level is modelled by one parameter, the ground-to-vegetation ratio.

## 3 Experimental Data

The test site used in this study is Remningstorp, situated in southern Sweden. It is a hemi-boreal test site featuring a mixture of Norway spruce, Scots pine, and birch.

The test site is flat, with stand-level slopes very rarely exceeding 5 degrees [8].

Interferometric TDM image pairs are processed using a Matlab algorithm based on [9] and described in [4, 10]. Ground contribution is removed using a 2 m x 2 m grid DTM provided by Swedish Land Survey [11]. This new national height model has a maximal height error lower than 0.5 m. By 2015, it will be available for the whole country. Interferometric forest height (IFH) maps are computed from the phase of the flattened interferogram through a scaling with $1/k_z$ and constant offset removal using ground control points.

Additionally, 32 circular, 40-metre radius plots are used. $95^{th}$-percentile forest height (H95) and vegetation ratio (VR, the ratio between all lidar returns above 1 m to the total number of lidar returns) are computed from 10 m x 10 m maps provided within the BioSAR 2010 campaign [12]. TDM IFH and coherence values are estimated at plot level from SLC images using all pixels within each region of interest, giving very large number of looks (around 330 for the image used here). Six of the plots were measured during autumn 2010 and the rest during spring 2011.

In this work, results from one TDM acquisition made in 2011-06-04 are shown, but seven other images were studied as well, all giving similar results. They were acquired in the summers of 2011, 2012, and 2013, at VV polarisation, and in the ascending mode. The incident angle was of 41 degrees. For the image from 2011-06-04, the effective perpendicular baseline was 140 m, leading to a vertical wavenumber of 0.13 $m^{-1}$ and a mean coherence over forest of 0.65. Corresponding height-of-ambiguity (HOA) was 49 m.

# 4 Results

In **Figure 1**, the derived IFH and coherence maps are compared to H95 and VR maps. It can be observed, that the TDM-derived height map underestimates H95.

In **Figure 2**, a scatter plot for the TDM-based and lidar-based height estimates is shown. Good correlation can be observed with Pearson correlation coefficient equal to 0.95, but an underestimation of approximately 5 meters can be seen. This is caused by the penetration of the electromagnetic wave into the canopy and through the openings between and within tree crowns. Also, it was earlier observed in [5] that the estimated forest height is sensitive to HOA, especially at low HOA and for layered pine stands, where the bottom level contribution is relatively large. It can be observed in Figure 3, that four pine plots show slightly lower values than expected from the general trend.

In **Figure 3**, the results of two-level model inversion are shown. For each plot, the two-level model was inverted from the estimated coherence and flattened phase values, giving estimates of level distance $\Delta h$ and ground-to-vegetation ratio $\mu$.

The inverted $\Delta h$ is almost perfectly correlated with H95 (Pearson r=0.99), but there is still a bias. To create an unbiased estimate, a new measure called interferometric H95 estimate (IH95) is defined as:

$$IH95 = \mathrm{a} \cdot \Delta\mathrm{h}, \quad (4)$$

where $a$ is estimated to 1.25 using linear regression. This means, that $\Delta h$ is 20% lower than H95. In the left-hand-side plot in **Figure 4**, IH95 is plotted against H95. The RMSE is 0.68 m.

For ground-to-vegetation ratio, high negative correlation with vegetation ratio is observed (Pearson r=-0.83). Note that pine plots seem to have the lowest vegetation ratio and the highest ground-to-vegetation ratio. This agrees with the previous observations made about the canopy structure in these plots [5]. Note also, that the estimated ground-to-vegetation ratio and vegetation ratio are related, but they measure different things and with different techniques. A new measure called interferometric vegetation ratio estimate (IVR) is created as:

$$IVR = 100\%/(1+\mu)^b, \quad (5)$$

where $b$ is estimated to 1.18 using linear regression. This measure is reasonable in the limits (thick canopy gives low $\mu$ and high vegetation ratio, and vice versa), but it is based on the assumption that lidar and X-band radar measure similar things. The relation between IVR and lidar-measured vegetation ratio are shown to the right in Figure 4. The RMSE is 4.50 percentage points. Note, that the IVR is closely related to η: if $b = 1$ and $\frac{\sigma_{gr}^0}{\sigma_{veg}^0} = 1$, then $IVR = \eta$.

# 5 Discussion

The promising results of the two-level model inversion lead to the conclusion that the removal of the extinction parameter is beneficial in TanDEM-X applications. It has been previously reported [4, 13], that the classical RVoG extinction coefficient was lower than expected. In this work, it is argued that by choosing an infinite extinction and letting all decorrelation be modelled through ground contribution, inversion can be done from one single complex value with promising results, without the need of additional information (multiple baselines, multiple polarizations, other assumptions).


# Acknowledgements

The authors would like to thank SNSB for the funding of this work, DLR for TDM data, SLU for field data, and ESA for lidar data.


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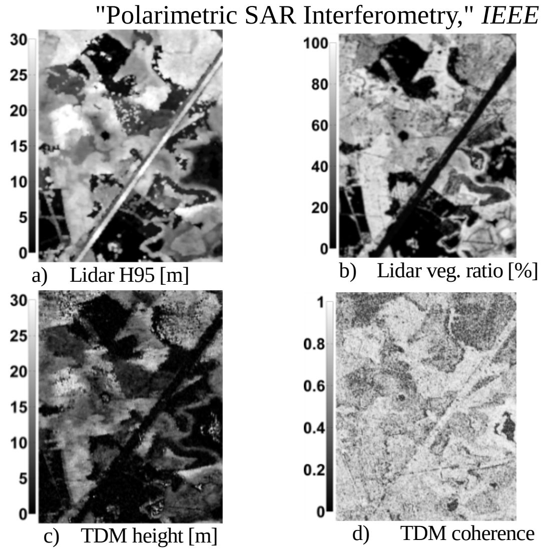


**Figure 1:** TDM and lidar maps for a central part of Remningstorp.

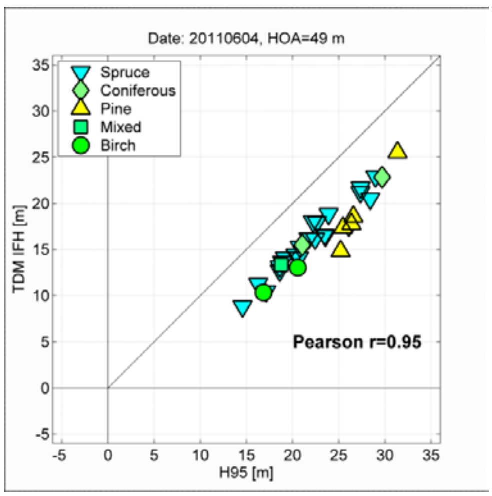


**Figure 2:** Scatter plot for interferometric height vs. lidar height.

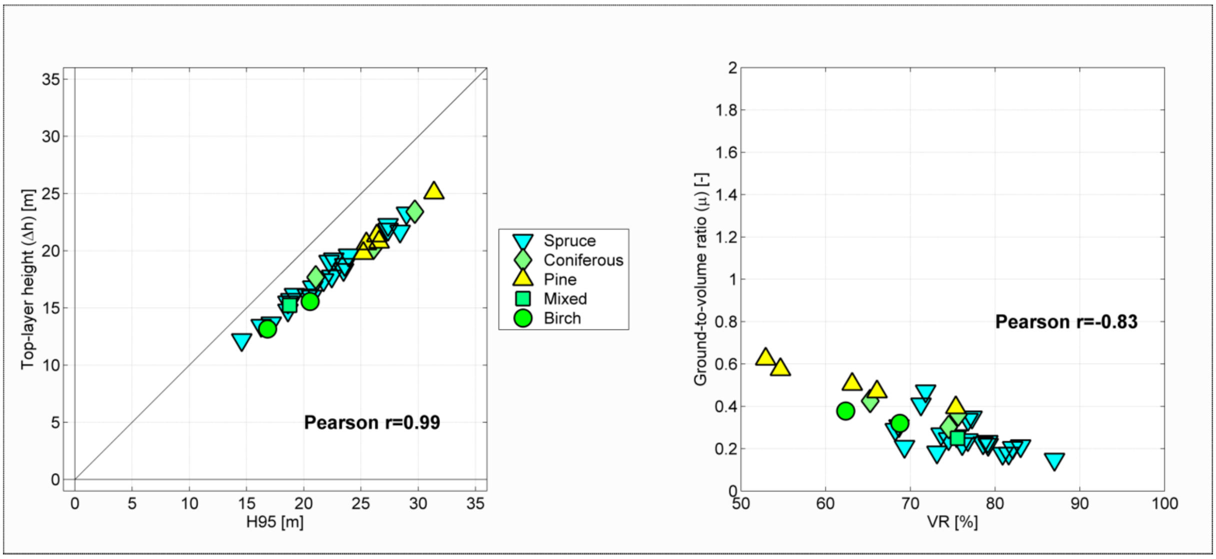


**Figure 3:** Scatter plots for top-level height and ground-to-vegetation ratio vs. lidar measures for forest height and canopy density.

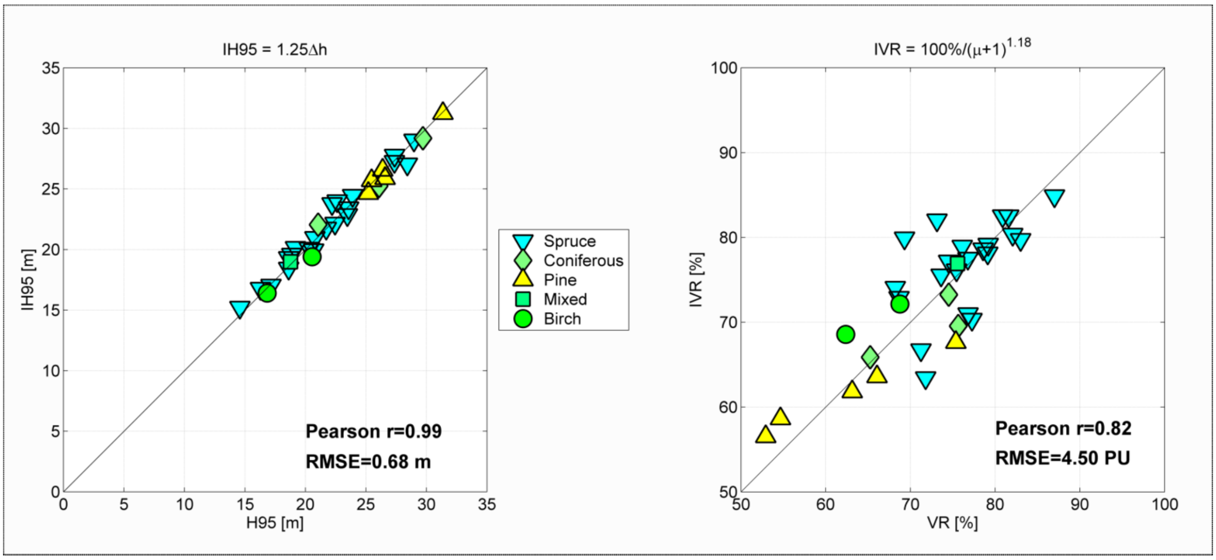


**Figure 4:** Scatter plot for interferometric estimates of forest height and canopy density vs. their lidar-derived counterparts.