Mapping Topography and Forest Parameters in a Boreal Forest with Dual-Baseline TanDEM-X Data and the Two-Level Model

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Abstract

In this paper, two-level model (TLM) inversion is used for unsupervised mapping of ground topography, forest height, and canopy density in boreal forests from dual-baseline, alternating bistatic mode TanDEM-X data. The TLM models forest as two discrete scattering levels, ground and vegetation, the latter with gaps. It is here shown using two alternating bistatic-mode TanDEM-X acquisitions made over the Swedish boreal test site Krycklan in September 2011 that the inverted TLM parameters can be used for mapping of ground topography and forest parameters.

1 Introduction

Since its launch in June 2010, the twin-satellite, X-band (9.65 GHz) synthetic-aperture radar (SAR) interferometer TanDEM-X [1] has provided vast amounts of data, supporting both the creation of the first fully-global digital elevation model (DEM) [2] as well as many scientific studies in various fields [3].

In forestry, many studies have shown promising results for forest parameter estimation from TanDEM-X [4–10]. However, many of these studies rely on the use of an external high-resolution digital terrain model (DTM), which is used as ground reference when canopy height is estimated from a TanDEM-X DEM. The availability of such DTMs is limited to a few European countries and some test sites around the world. This severely restricts the areas of application of the proposed methods.

The scope of this paper is to propose a method for ground topography and forest parameter mapping from TanDEM-X using the alternating bistatic-mode data. The proposed approach is based on the two-level model (TLM), which has previously been successfully used in [8–10]. The proposed method is evaluated on TanDEM-X data acquired over the boreal test site Krycklan, situated in northern Sweden.

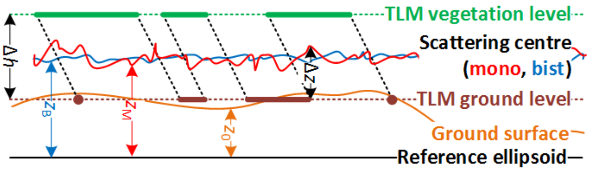


Figure 1: A sketch summarising height nomenclature used in this paper.

2 Two-Level Model (TLM)

The two-level model (TLM) models forest as two discrete scattering levels, ground and vegetation, the latter with gaps. The complex correlation coefficient is modelled as:

$$\tilde{\gamma} = e^{ik_z z_0} \frac{\mu + e^{ik_z \Delta h}}{\mu + 1} \tag{1}$$

where k_z is the vertical wavenumber, z_0 is the ground surface height over reference ellipsoid, μ is the area-weighted backscatter ratio, and Δh is the level distance [8, 9], see also Fig. 1, where the different heights are visualised. The vertical wavenumber is computed from acquisition geometry using

$$k_z = \frac{4\pi B_{eff}}{\lambda R \sin\theta} \tag{2}$$

where B_{eff} is the effective baseline between the satellites, λ is the wavelength, R is the average range between the satellites and the ground, and θ is the average incidence angle. The height offset corresponding to a 2π phase shift in the interferogram is called height-of-ambiguity (HOA) and it is related to k_z through:

$$\mathrm{HOA} = \frac{2\pi}{k_z}. \tag{3}$$

2.1 Single-Baseline Inversion with External DTM

In previous studies of the TLM [8–10], z_0 was assumed known from an external digital terrain model (DTM), which made the inversion of μ and Δh from single-baseline, single-polarized TanDEM-X data possible. Moreover, Δh was then found to be a good estimate of the lidar-based forest height metric H50, which is the median of all lidar returns above 1 m. Also, it was found that

$$\eta_0 = \frac{1}{1 + \mu} \tag{4}$$

is a good estimate of the lidar-based canopy density metric vegetation ratio (VR), which is the fraction of all lidar returns that originate from above 1 m. However, the proposed approach strictly relies on the availability of a high-resolution DTM, which effectively limits its use for global applications.

2.2 Dual-Baseline Inversion without external DTM

The TanDEM-X system features an alternating bistatic mode, in which dual-baseline InSAR data are acquired near-simultaneously by alternate switching of the transmitting satellite. In fact, three image pairs are created: one image pair consisting of two monostatic acquisitions and hereafter referred to as "monostatic pair", and two image pairs consisting of one monostatic acquisition and one bistatic acquisition and hereafter referred to as "bistatic pairs".

For the monostatic pair, the effective baseline B_{eff} is equal to the actual distance between the two satellites in the direction perpendicular to the broadside of the antennas. For the bistatic pairs, however, the effective baseline B_{eff} is equal to one half of the perpendicular distance between the satellites [11]. The alternating bistatic mode provides thus dual-baseline data due to different acquisition modes, and not due to the different distance between the satellites.

For reciprocal media, the two bistatic pairs differ only in terms of noise representation. In this paper, reciprocity is assumed and thus only one bistatic pair from the alternating bistatic mode acquisitions is used. The TLM gives in that case a set of two complex equations:

$$\left\{ \begin{array}{lcl} \tilde{\gamma}_M & = & e^{2ik_z z_0}\left(1-\eta_0+\eta_0 e^{2ik_z\Delta h}\right) \\ \tilde{\gamma}_B & = & e^{ik_z z_0}\left(1-\eta_0+\eta_0 e^{ik_z\Delta h}\right) \end{array} \right. \tag{5}$$

where η_0 and Δh are assumed constant between the two acquisitions, the subscripts M and B refer to the monostatic and bistatic acquisition, respectively, and k_z is the vertical wavenumber of the bistatic acquisition.

In the case of unknown z_0, (7) is a system of four real-valued equations with three unknowns: z_0, η_0, and Δh, and it can be solved using numerical methods. However, z_0 is the topographic height and its estimation will be affected by 2π phase ambiguities. In order to simplify the inversion of z_0, $\tilde{\gamma}_M$ and $\tilde{\gamma}_B$ are first corrected for large topographic variations using a rough reference height model z_{ref}, and then the offset

$$\Delta z = z_{ref} - z_0 \tag{6}$$

is estimated during TLM inversion:

$$\left\{ \begin{array}{l} \tilde{\gamma}'_M = \tilde{\gamma}_B e^{-2ik_z z_{ref}} = e^{-2ik_z\Delta z}\left(1-\eta_0+\eta_0 e^{2ik_z\Delta h}\right) \\ \tilde{\gamma}'_B = \tilde{\gamma}_B e^{-ik_z z_{ref}} = e^{-ik_z\Delta z}\left(1-\eta_0+\eta_0 e^{ik_z\Delta h}\right) \end{array} \right. \tag{7}$$

An estimate of z_0 is then created subtracting Δz from z_{ref}. Possible choices for the reference height z_{ref} include a low-resolution DTM or an InSAR DEM.

In the case of the alternating bistatic mode data studied in this paper, a good choice of z_{ref} is the DEM obtained from the bistatic pair:

$$z_{ref} = z_B = \frac{\arg\tilde{\gamma}_B}{k_z}. \tag{8}$$

With this choice of z_{ref}, phase unwrapping is not necessary for the estimation of Δz. This can easily be verified by letting

$$z_{ref} = z_B + \frac{2\pi n}{k_z}$$

where n is an integer describing the ambiguities, and keeping in mind that the vertical wavenumber for the monostatic image is $2k_z$. The correction terms in (7) become:

$$\begin{array}{lcl} e^{-ik_z z_{ref}} & = & e^{-ik_z z_B} e^{-2i\pi n} = e^{-ik_z z_B} \\ e^{-2ik_z z_{ref}} & = & e^{-2ik_z z_B} e^{-4i\pi n} = e^{-2ik_z z_B} \end{array}$$

i.e., they are independent of n. On the contrary, if the monostatic DEM were used as the reference height:

$$z_{ref} = z_M + \frac{\pi n}{k_z}$$

then the respective correction terms would become:

$$\begin{array}{lcl} e^{-ik_z z_{ref}} & = & e^{-ik_z z_M} e^{-i\pi n} = (-1)^n e^{-ik_z z_B} \\ e^{-2ik_z z_{ref}} & = & e^{-2ik_z z_M} e^{-2i\pi n} = e^{-2ik_z z_B} \end{array}$$

which transfers the ambiguities in the reference height model into TLM inversion. Note that although unwrapping and absolute height calibration are not necessary for the estimation of Δz, they are necessary steps if an estimate of ground topography is to be created as $z_{ref} - \Delta z$.

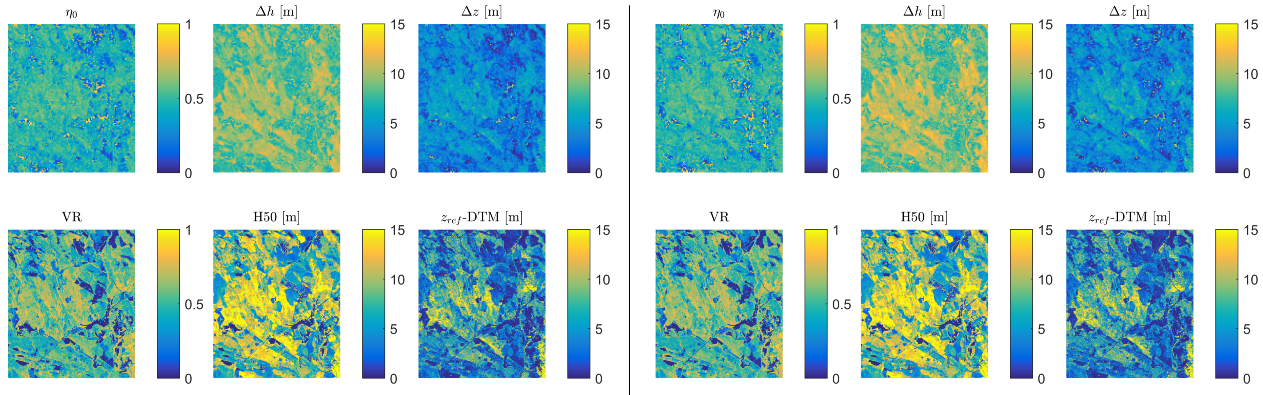
3 Experimental Data

This study focusses on Krycklan, a boreal test site in Northern Sweden. Krycklan features a mixed coniferous forest consisting primarily of Norway spruce and Scots pine, and it is situated in relatively hilly terrain, approximately 50 km north-west of the city of Umeå.

Two TanDEM-X acquisitions made in the alternating bistatic mode are studied here. The acquisitions were made on the 8th and 19th of September 2011, at VV- and HH-polarizations, respectively, both at a nominal incidence angle of 33 degrees. The respective HOAs for the bistatic pairs were 47 m and 50 m. TanDEM-X data were geocoded and interferometrically processed using the same processing chain as in [8,9], but the topographic phase was not corrected for.

As reference, lidar data acquired during the BioSAR 2008 campaign are used. The data were collected using the helicopter-borne TopEye system. The raw point cloud was processed to a digital canopy model (DCM), and then 10 m×10 m maps with different forest metrics were derived. Two forest metrics are of interest for this study:

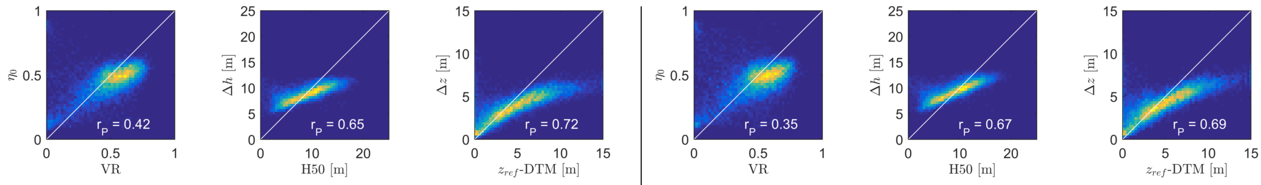
- forest height H50, which is the median of all lidar returns above 1 m,
- vegetation ratio (VR), which is the fraction of all returns that originate above 1 m.



(a) 20110908, VV

(b) 20110919, HH

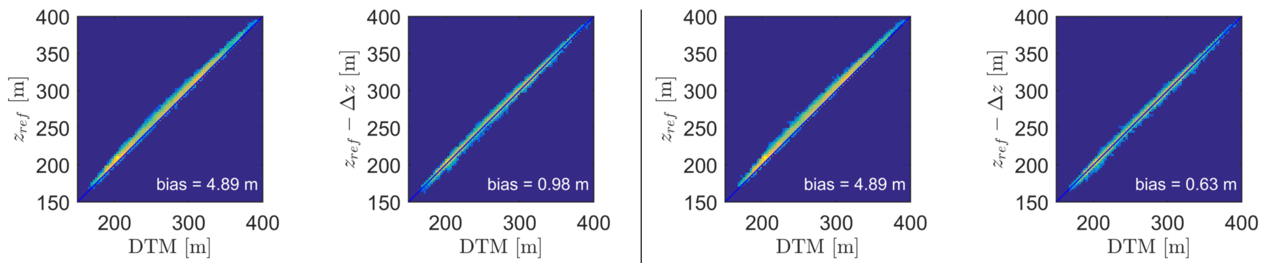
Figure 2: Maps showing TLM inversion products (top row) in comparison with similar lidar metrics (bottom rows). As reference height z_{ref}, DEM obtained from the bistatic pair was used.



(a) 20110908, VV

(b) 20110919, HH

Figure 3: Scatter plots showing the correlation between TLM inversion products and similar lidar metrics. As reference height z_{ref}, DEM obtained from the bistatic pair was used. The Pearson correlation coefficient r_P is shown.



(a) 20110908, VV

(b) 20110919, HH

Figure 4: Scatter plots showing the improvement of ground topography mapping after correction of z_{ref} with Δz estimated from TLM inversion. As reference height z_{ref}, DEM obtained from the bistatic pair was used. Measured bias is shown, computed as the average difference between estimate and reference.

The reference DTM used in this study has been provided by Swedish National Land Survey (Lantmäteriet), it has a resolution of $2\,\mathrm{m}\times 2\,\mathrm{m}$, and it has been acquired during a national lidar scanning campaign.

4 Results and Discussion

Inversion results are shown in Fig. 2(a) for the VV-polarized acquisition from the 8th of September and in Fig. 2(b) for the HH-polarized acquisition from the 19th of September. The corresponding scatter plots are shown in Fig. 3(a) and Fig. 3(b). In comparison with reference lidar metrics, a good correlation is observed, but also a bias can be seen. Lidar DTM is used as reference for z_0. It can be observed that in a dense forest, Δz is underestimated due to insufficiently strong ground contribution. Similarly, Δh and η_0 are underestimated, probably because the two most significant levels are not ground and vegetation, but two levels within the canopies. However, as it can be observed in the scatter plots in Fig. 3, the correlation is good in spite of the observed bias, and an empirical correction function may improve estimation.

In Fig. 4, scatter plots comparing two ground topography estimates with a lidar DTM are shown. It can clearly be observed that z_{ref} (which here is the bistatic DEM) overestimates ground topography, as expected from an X-band DEM. However, after correction with Δz, most of the bias is reduced.

The observed good correlation between TLM parameters and reference metrics from lidar shows that the proposed approach gives meaningful results. However, the presence of a clear bias hints that the estimated quantities are do not necessarily measure the same properties. In previous studies on TLM [8–10], where the bottom level was forced to be the ground level, good correlation between Δh and H50 was observed. In this study, however, the bottom level not always coincides with the ground level, and biases are thus observed. Further studies are needed to better understand the cause of the observed biases.

It is possible that the proposed approach may be used on dual- or multi-baseline TanDEM-X data acquired on different occasions. This may require letting η_0 to be acquisition-dependent, in a similar manner as it was done in [10].

5 Conclusion

In this study, a dual-baseline two-level model inversion approach is presented. Three parameters are estimated in the inversion: one related to canopy density, one related to forest height, and one being a correction factor for ground topography mapping. A comparison with similar lidar-based metrics shows a good correlation, but also significant biases. Further studies are needed for better understanding of the origin of the observed biases.

Acknowledgements

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