MAPPING AND MODELING OF BOREAL FOREST CHANGE IN TANDEM-X DATA WITH THE TWO-LEVEL MODEL

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Abstract – In this paper, three approaches to forest change modeling with the two-level model (TLM) are compared by fitting the TLM to 12 VV-polarized TanDEM-X acquisitions over a hemi-boreal test site in southern Sweden. It is observed that the best inversion results are obtained when rapid forest change (e.g., harvesting) is modeled as change in canopy density, while growth is modeled as change in forest height.

1. INTRODUCTION

Launched in July 2010, the TanDEM-X (TDM) [1] mission is the first synthetic-aperture radar (SAR) interferometer of its kind in space, consisting of two satellites in a tight tandem formation, thus allowing bistatic, single-pass interferometric SAR (InSAR) acquisitions. After more than 6 years of continuous operation, the system is still healthy and predicted to be operational until early 2020s.

A promising application of TanDEM-X is mapping and monitoring of forest change. Both anthropogenic forest change (e.g., deforestation and degradation), growth, and natural disasters (e.g., fires and storms) introduce fluxes in the terrestrial carbon stock. For more accurate climate modeling, these fluxes need to be accurately measured. Several studies have already shown the great potential of TanDEM-X for forest mapping and monitoring [2-4].

In particular, the two-level model (TLM) has proven itself useful for forest parameter estimation in boreal forests with known topography [5, 6]. The TLM models forests as two scattering levels, ground and vegetation, the latter with gaps. In [7], a multi-temporal TLM inversion scheme was proposed as a means for deforestation detection from canopy density change, with forest height assumed constant in time. It was also shown that the leaf-off effect can be observed for deciduous-dominated forest plots as a decrease in canopy density during the winter season.

In this paper, the concepts from [7] are further developed and evaluated. Three approaches to TLM inversion of multi-temporal TDM data are evaluated using 12 VV-polarized TDM acquisitions made during four consecutive summers between 2011 and 2014 over the managed, hemi-boreal test site Remningstorp, situated in southern Sweden. The three approaches represent three different ways to model forest change, and by studying inversion performance, conclusions about modeling accuracy can be drawn.

2. MODEL

The two-level model (TLM) models forest as two scattering levels, ground and vegetation, the latter with gaps in the horizontal direction. Volume decorrelation after topographic phase removal ($\tilde{\gamma}'$) is modeled using:

$$\tilde{\gamma}' = 1 - \eta' + \eta' \exp(i\kappa h) \quad (1)$$

where η' is the effective area-fill factor, h is the level distance, and κ is the vertical wavenumber, which describes the interferometric system setup [1]. The vertical wavenumber is related to the perhaps more intuitive height-of-ambiguity (HOA, height shift giving a 2π phase shift of the interferograms) through $\kappa = 2\pi/\mathrm{HOA}$.

The effective area-fill factor is related to the area-fill factor η (fraction of the total area covered by the vegetation level) and the backscattering coefficients for ground and vegetation (σ^0_{gr} and σ^0_{veg}, respectively) through:

$$\eta' = \frac{\eta\sigma^0_{veg}}{\eta\sigma^0_{veg} + (1-\eta)\sigma^0_{gr}}. \quad (2)$$

The effective area-fill factor is thus the fraction of total backscattering coefficient originating from the vegetation level.

In [5] it was shown that by fitting (1) to single-polarized, topographic phase-corrected TDM data, η' and h could be estimated without the need for any reference data other than a digital terrain model (DTM), and these two parameters were found correlated with similar metrics acquired with airborne lidar scanning (ALS).

The effective area-fill factor η' was found correlated with vegetation ratio (VR), which is the fraction of all lidar returns classified as canopy returns. η' can thus be treated as a metric of horizontal forest structure, assuming a constant ratio between ground and vegetation backscattering coefficients. The level distance h was found closely related to H50, which is the 50^{th} height percentile of all lidar returns classified as canopy returns. h can therefore be treated as a metric of vertical forest structure. Using a semi-empirical model and reference biomass data, above-ground forest biomass could further be estimated from h and η' with good accuracy [6].

In [7] it was shown that by simultaneous fitting of (1) to multiple single-polarized, topographic phase-corrected TDM acquisitions, forest change due to harvesting, as well as the leaf-off effect in deciduous-dominated plots, could be modeled as a change in η', when h was assumed constant over time. Moreover, high correlation between h and H50 was also observed.

In this paper, we propose to further develop this concept by modeling growth as constant annual increase in level distance (height):

$$h_i = \bar{h} + y_i d \quad (3)$$

where $\bar{h}$ is the level distance for the first year in the time series, y_i is the number of years after the first year in the time series, and d is the annual height gain.

In the following, three alternative ways to model forest change will be compared.

Approach 1 (A1): both the effective area-fill factor and level distance are allowed to change between acquisitions. This results in the following formulation for acquisition i:

$$\tilde{\gamma}'_i = 1 - \eta'_i + \eta'_i \exp(i\kappa_i h_i). \quad (4)$$

Note that the multi-baseline aspect of multi-temporal acquisitions is taken into account by allowing individual κ-values for each acquisition. This approach is the same as the original TLM inversion method proposed in [5].

Approach 2 (A2): the effective area-fill factor changes between acquisitions, while height remains constant in time:

$$\tilde{\gamma}'_i = 1 - \eta'_i + \eta'_i \exp(i\kappa_i \bar{h}) \quad (5)$$

where $\bar{h}$ is a level distance representative for the entire study period. Note that this approach effectively assumes that the vertical structure does not change in time. This approach was introduced in [7].

Approach 3 (A3): the effective area-fill factor changes between acquisitions, while growth is modeled as a constant annual increase in height using (3):

$$\tilde{\gamma}'_i = 1 - \eta'_i + \eta'_i \exp\left(i\kappa_i\left(\bar{h} + y_i d\right)\right). \quad (6)$$

This approach effectively separates the rapid forest change primarily affecting the horizontal structure (e.g., harvesting) from the slower forest change primarily affecting the vertical forest structure (growth).

For visualization purposes, the estimated values for η' are converted to area-fill factor estimates η using the equation obtained by solving (2) for η and using $\sigma^0_{gr}/\sigma^0_{veg} = 0.25$, which gives good results in comparison with VR.

3. EXPERIMENTAL DATA

Twelve TDM acquisitions made over the hemi-boreal test site Remningstorp, situated in southern Sweden, are used in this study. The test site is a managed hemi-boreal forest, dominated by spruce and pine, but also with some deciduous tree species, mainly birch, and it is located in flat terrain. All TDM acquisitions are VV-polarized, with a nominal incidence angle of 41 degrees, and with HOA values between 31 m and 63 m. The acquisitions were made between June and August of four consecutive summers (two in 2012, three in 2011 and 2013, four in 2014).

Pre-processing done at DLR included co-registration, common-band filtering, and wavenumber shift filtering. Interferometric processing was done using software provided by GAMMA Remote Sensing AG. A sliding 5×5 window was used for generating interferograms, and topographic and "flat Earth" phase components were modeled from the DTM and subtracted from complex interferogram. Absolute phase and coherence calibration were also done.

As reference, ALS data acquired in August of 2010 and 2014 are used. Both datasets have been processed to the same point density of

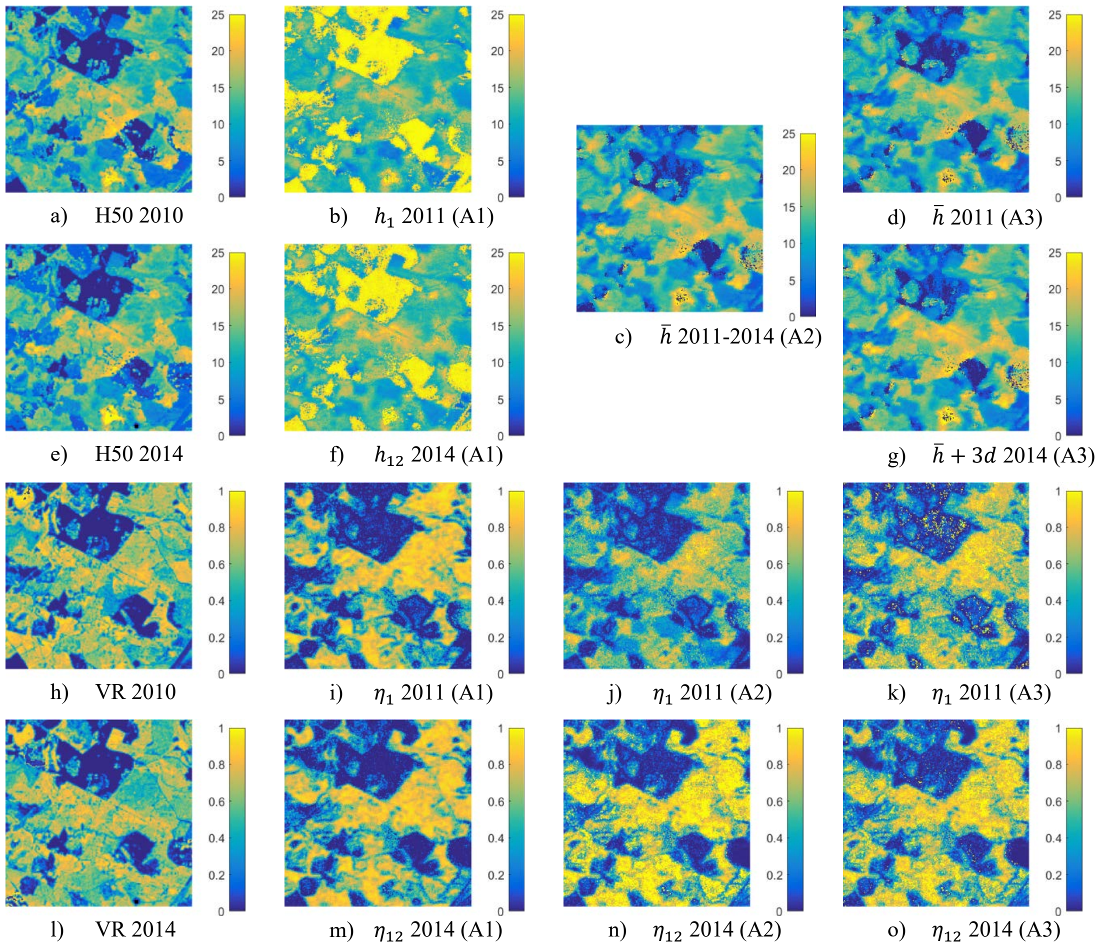

Figure 1: Results from TLM inversion of 12 TanDEM-X acquisitions for a 2.25 km × 2.25 km patch in the central part of Remningstorp. In the first column from the left, reference data from ALS are shown. Inversion results for A1, i.e., where both level distance and area-fill factor change over time, are shown in the second column from the left. The third column shows inversion results for A2, i.e., when only area-fill factor varies over time. The fourth column shows inversion results for A3, i.e., when area-fill factor varies over time and has a constant annual gain.

approximately 10 points per square meter. In this study, we use two ALS-based forest metrics derived within resolution cells of 15 m x 15 m: vegetation ratio (VR, fraction of all laser returns classified as canopy returns) and H50 (50th percentile of all laser returns classified as canopy returns). Note that the ALS data from 2010 were acquired one year prior to the first

TDM acquisition, and some changes during the time until the first TDM acquisitions have occurred.

The DTM used in this study was provided by Swedish Land Survey as part of the new national DTM available for entire Sweden with a 2-m posting and with a vertical height accuracy better than 0.5 m.

TLM inversion was carried out separately for each of the three approaches. For A1, the inversion was carried out using the equations presented in [5] and 12 estimates of η' and h were obtained, one pair for each acquisition. For A2 and A3, the inversion was carried out by solving a set of 12 complex equations using a non-linear least squares-based equation solver. For both A2 and A3, one estimate of $\bar{h}$ was obtained together with 12 estimates of η'. For A3, one estimate of d was also obtained.

4. RESULTS AND DISCUSSION

Sample results are shown in Fig. 1. In the first column of figures, ALS-derived forest height and canopy density metrics H50 and VR are shown for 2010 and 2014. In the remaining three columns, corresponding metrics obtained with A1, A2, and A3, respectively, are shown. First and third rows of images show forest height and canopy density metrics for the years 2010 (for ALS data) and 2011 (for TDM data), whereas second and fourth rows of images show forest height and canopy density metrics for 2014.

A comparison of forest height estimates can be seen in Fig. 1a-g). A2 and A3, with constraints on height, have the advantage that they are less susceptible to height estimation ambiguities (due to the multi-baseline nature of multi-temporal TDM data), and they provide very good estimates of forest height for the entire area. At the same time, A1 fails in the case of open areas, where the estimated height is clearly too high. Note that for A2, only one estimate of forest height is obtained, and it should be treated as a representative height for the entire period 2011-2014. The assumption of forest height being constant between 2011 and 2014 is to some degree supported by the fact that H50 does not change significantly between 2010 and 2014, see Figs. 1a) and 1e). A3, with growth modeling, predicts a small increase of forest height (up to around 0.8 m/year).

A comparison of canopy density estimates shows that for A1 and A3, canopy density estimates for 2011 and 2014 are similar (compare Fig. 1i) with Fig. 1m) and Fig. 1k) with Fig. 1o)), whereas for A2, canopy density increases significantly from 2011 and 2014 (compare Fig. 1j) with Fig. 1n)). This indicates that in case of lacking growth modeling and height constrained to be constant for all years, the change in forest caused by growth is instead modeled as an increase in canopy density. Such large increase in canopy density is not observed in ALS data, and it is therefore considered to be unrealistic. Therefore, a conclusion can be made that A3 provides the same good forest height estimation as A2, but thanks to growth modelling, canopy density estimation has better performance than for A2.

Note that harvesting in the bottom-right part of the shown area in Remningstorp is correctly detected as a decrease in canopy density. Note also that the clear-cut in the bottom-left part of the shown area occurred between the first ALS and TDM acquisitions and is already visible on the first TDM acquisition. Note also that in the case of A2 and A3, forest height in areas which were clear-cut during the study period is the pre-harvesting forest height, as harvesting is modeled by the TLM in A2 and A3 as a decrease in canopy density, with forest height kept constant. For the ALS-metric H50, post-harvesting height is close to zero.

5. CONCLUSION

It is concluded that the best inversion results are obtained if rapid forest change (e.g., harvesting) is modeled as change in canopy density (i.e., horizontal structure), whereas slow forest change (due to growth) is modeled as change in forest height (i.e., vertical structure).

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