Remote Sensing of Environment 139 (2013) 60–67

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

# Monitoring spruce volume and biomass with InSAR data from TanDEM-X

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ARTICLE INFO

*Article history:*
Received 10 October 2012
Received in revised form 23 July 2013
Accepted 29 July 2013
Available online 27 August 2013

*Keywords:*
InSAR
Forest inventory
Volume
Biomass
Nonlinear mixed models

ABSTRACT

There is a need for monitoring methods for forest volume, biomass and carbon based on satellite remote sensing. In the present study we tested interferometric X-band SAR (InSAR) from the Tandem-X mission. The aim of the study was to describe how accurate volume and biomass could be estimated from InSAR height and test whether the relationships were curvilinear or not. The study area was a spruce dominated forest in southeast Norway. We selected 28 stands in which we established 192 circular sample plots of 250 $m^2$, accurately positioned by a Differential Global Positioning System (dGPS). Plot level data on stem volume and aboveground biomass were derived from field inventory. Stem volume ranged from zero to 596 $m^3$/ha, and aboveground biomass up to 338 t/ha. We generated 2 Digital Surface Models (DSMs) from InSAR processing of two co-registered, HH-polarized TanDEM-X image pairs – one ascending and one descending pair. We used a Digital Terrain Model (DTM) from airborne laser scanning (ALS) as a reference and derived a 10 m × 10 m Canopy Height Model (CHM), or InSAR height model. We assigned each plot to the nearest 10 m × 10 m InSAR height pixel. We applied a nonlinear, mixed model for the volume and biomass modeling, and from a full model we removed effects with a backward stepwise approach. InSAR height was proportional to volume and aboveground biomass, where a 1 m increase in InSAR height corresponded to a volume increase of 23 $m^3$/ha and a biomass increase of 14 t/ha. Root Mean Square Error (RMSE) values were 43–44% at the plot level and 19–20% at the stand level.


## 1. Introduction

During the last two decades there has been a considerable increase in the use of remote sensing for mapping of forest biomass and volume. Monitoring of biomass, and carbon, is receiving increased attention because of the needs for reporting to international initiatives and conventions such as the REDD (Reduced Emissions from Deforestation and forest Degradation in Developing Countries) and the UN-FCCC (United Nations Framework Convention on Climate Change). Satellite remote sensing is likely to be a major data provider in the future (Lynch, Maslin, Balzter, & Sweeting, 2013; Patenaude, Milne, & Dawson, 2005). Airborne Laser Scanning (ALS) enables wall-to-wall mapping with high accuracy (Hyyppä et al., 2008; Næsset, 2004a,b), and is increasingly used in forest management planning. Currently, photogrammetry based on aerial imagery is also receiving increased attention, due to commercial software that automatically generates 3D point clouds, which have similar properties as ALS echoes (Bohlin, Wallerman, & Fransson, 2012; Breidenbach & Astrup, 2012; St-Onge, Vega, Fournier, & Hua, 2008). However, data from airborne sensors may have too low aerial capacity and a lack of temporal consistency. Satellite data have been tested with variable results, both optical (Fransson, Smith, Askne, & Olsson, 2001; Magnusson & Fransson, 2004; Mäkelä & Pekkarinen, 2004; Tomppo, Haakana, Katila, & Peräsaari, 2008) and SAR data. The SAR methods include backscatter intensity (Holopainen et al., 2010; Imhoff, 1995), polarimetry (Goncalves, Santos, & Treuhaft, 2007; Santos et al., 2003), InSAR coherence (Eriksson, Magnusson, Fransson, Sandberg, & Ulander, 2007; Hyyppä et al., 2008), InSAR height (Gama, dos Santos, & Mura, 2010; Neeff, Dutra, Santos, Freitas, & Araújo, 2005; Solberg, Astrup, Gobakken, Næsset, & Weydahl, 2010), PolinSAR (Le Toan et al., 2011) and radargrammetry (Karjalainen, Kankare, Vastaranta, Holopainen, & Hyyppä, 2012). Various limitations exist for satellite remote sensing methods, i.e. saturation, low accuracy and effects of weather conditions and clouds. There is a need for satellite remote sensing methods that can overcome these limitations. BIOMASS is a P-band SAR satellite mission dedicated to forest biomass monitoring (Le Toan et al., 2011). It will provide biomass estimation based on a combination of backscatter, coherence and PolInSAR (Polartimetric SAR Interferometry) techniques. With its long wavelength (~69 cm) the microwaves will interact mainly with coarser structures in the canopy, i.e. stems and coarse branches which contain the majority of the biomass. However, it is planned for launch in 2020.

In the present study we are testing 3D SAR with a short wavelength as an alternative that would be available already today, and which enjoys the advantages of high areal capacity from a satellite platform; cloud-free imagery from the SAR sensor; and the correlation between height and forest volume and biomass. There are four different 3D SAR methods, which can be used alone or in combination (Toutin & Gray, 2000). Relative or absolute elevations can be derived from phase-

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http://dx.doi.org/10.1016/j.rse.2013.07.036

differences in an image pair (interferometry), from parallaxes in an image pair (radargrammetry), from shadow lengths and pixel brightness (clinometry), or from the shift of the co-polarized polarimetric signature maximum (polarimetry). We are here employing interferometric X-band SAR from the Tandem-X mission. This is a bistatic acquisition with two satellites going in formation, where microwave pulses are sent from one satellite at a time and the echo is received by both. The travel length of the echo differs between the two SAR sensors, and this generates phase differences varying over the area. These phase differences can be processed into a DSM. The X-band has a short wavelength (3.1 cm) with a limited penetration in vegetation. The DSM is located close to the top of the vegetation canopy, and contains both terrain topography and vegetation heights.

We see two possible applications of an X-band InSAR DSM. First, if available, an external DTM can be subtracted from the DSM providing InSAR heights, from which volume or biomass can be derived by model inversion. Secondly, if a DTM is not available, temporal changes in volume and biomass may still be monitored if the relationship between volume (biomass) and InSAR height is straight linear and constant over time. In this case temporal changes in volume (biomass) could be derived directly from the temporal changes in the DSM. There would be a fixed change in volume and biomass per meter change in the InSAR DSM.

The aim of this study was to test whether bistatic X-band InSAR data from the TanDEM-X mission can be used to monitor stem volume and aboveground forest biomass. The objectives were:

1. To describe how accurate volume and biomass can be estimated, and
2. To test whether the relationship is straight linear, whereby temporal changes in biomass and volume could be monitored without having a DTM as input.

## 2. Materials and methods

### 2.1. Study area

The study was carried out in the Lardal municipality in southeast Norway, and was centered at 59.4° north and 9.9° east. The study area contains a forest, with some intermixed peat lands and lakes, as well as a valley with agricultural lands. The forest is managed for timber production, and is divided in stands of various age and development stages. For this study, the digitized stand map with stem volume data was made available, as was a DTM with 10 m × 10 m resolution generated from an ALS data set with 10 pulses per $m^2$.

### 2.2. Field data

Based on the stand map we initially selected 40 stands for field sampling. First, we selected all compact stands with an area between one and three hectares. Compact stands were selected to avoid problems with defining stand borders in the field, and were defined as

$$\sqrt{A}/P > 0.2 \quad (1)$$

where A is the stand area and P is the perimeter. Secondly, in order to ensure a wide range of volume and biomass we stratified the stands in two groups, i.e. with high (>150 $m^3$/ha) and low volume (<150 $m^3$/ha) estimates in the forest management plan. Within each of the volume strata, we randomly selected 20 stands for field sampling. In each stand, we made a 20 m × 20 m grid and randomly selected seven of the grid nodes as plot locations. At each location we established a 250 $m^2$, circular sample plot in which we carried out field inventory. Three plot locations were discarded, because they were located in a part of the stand that had been clear-cut recently. For this study we selected the spruce-dominated stands, by excluding 12 stands which had less than 50% spruce volume. With these selections, the field data set comprised 28 stands containing 192 sample plots. The size of these stands varied from 1.0 to 2.9 ha, with a mean value of 1.9 and a standard deviation of 0.5. Measurements according to the Norwegian National Forest Inventory protocol were carried out on the sample plots (Anon, 2008). The location of the plot centers were accurately recorded with differential GPS measurements. Species and DBH were recorded for each tree >5 cm DBH. Tree height was measured for a subset of 10 trees per plot. The heights of the remaining trees were estimated based on height–diameter models for each plot. The volume including bark of the trees was calculated from standard Norwegian models (Vestjordet, 1967), and this was aggregated per plot as per-hectare volume. Aboveground biomass of the trees was derived from the models of Marklund (1988) with height and diameter as predictor variables. It included stem wood, stem bark, stump, and live and dead branches, and was aggregated to per-hectare biomass for each plot (Table 1).

### 2.3. TanDEM-X data

We used two TanDEM-X strip map image pairs from the summer and autumn of 2011. One ascending acquisition was taken in the afternoon (16:54) on 23 July 2011. The weather in the study area was rainy (30–50 mm rain during 24 h) and the mean temperature was around 15 degrees. A descending acquisition was taken in the early morning (05:40) on 1 September 2011. It was minor precipitation during the 24 h before the acquisition (<10 mm) and a mean temperature of 5–10 degrees. The polarization was horizontal (H) both on send and receive, and the incidence angles were 36° and 42°, respectively. The data were received as co-registered Single Look Complex (SLC) data in CoSSC format. Each pair was processed to an InSAR DSM using the Sarscape 5.0 module of the ENVI 5.0 software. An interferogram was generated from each image pair, and this was further processed into a differential interferogram by removing the range dependent, and the terrain topography dependent parts of the phase differences. The ALS DTM was used as input in this step. These differential interferograms represented the phase differences caused by vegetation height, in addition to phase noise, as well as possible inaccuracies in the orbit data and in the atmospheric corrections. The phase noise in the TanDEM-X data could result from volume decorrelation and system noise. The differential interferograms were filtered with the Boxcar adaptive filter, which reduces phase noise and enables an accurate phase unwrapping later. We removed phase offset and phase ramp errors originating from possible orbit and atmospheric inaccuracies by fitting the following model to 30 Ground Control Points (GCPs):

$$\Delta\varphi = k_0 + k_1\mathrm{RG} + k_2\mathrm{AZ}, \quad (2)$$

where $\Delta\varphi$ was the phase difference at each GCP, $k_0$, $k_1$ and $k_2$ were correction factors, and RG and AZ were the range and azimuth coordinates (Table 2). The GCPs were subjectively laid out at locations without trees, i.e. where the InSAR DSM should have the same elevation as the DTM. These locations were selected as having high coherence and relatively flat terrain with low fringe density, i.e. in clear-cuts and agricultural fields. Hence, in these GCPs the final phase differences should be minor.

**Table 1**
Statistics for the 192 field plots.

| Variable | Unit | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| Volume, total | $m^3$/ha | 216 | 132 | 0 | 596 |
| Volume, spruce | $m^3$/ha | 188 | 125 | 0 | 596 |
| Volume, pine | $m^3$/ha | 10 | 38 | 0 | 267 |
| Volume, broadleaves | $m^3$/ha | 19 | 33 | 0 | 199 |
| Above ground biomass | t/ha | 134 | 79 | 0 | 338 |