Mapping boreal forest biomass with imagery from polarimetric and semi-polarimetric *SAR* sensors

Mapeamento da biomassa florestal boreal com imagens dos sensores *SAR* polarimétricos e semi-polarimétricos

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Abstract

Data from ALOS/Palsar and TerraSAR-X were used to estimate forest biomass in Boreal forest zone in Finland. In the study site in Heinavesi (forest biomass between 0 and 255 tons/ha), the HH-polarised component of dual-polarised ALOS/Palsar produced biomass estimation accuracies (RMSE) between 35 and 42 tons/ha. In the Kuortane site (biomass 0…188 tons/ha) the RMSE varied between 25 and 28 tons/ha. Since only two winter-time scenes from TerraSAR-X were available, TerraSAR-X results were very preliminary. The phase of the HH-VV cross-coherence produced the highest biomass-correlations among the TerraSAR-X derived features. This produced a biomass estimation accuracy (RMSE) of 49 tons/ha in the Heinavesi study site.

Key words: forest biomass; SAR; polarimetry.

Resumo

Dados do ALOS/Palsar e TerraSAR-X foram usados para estimar a biomassa florestal na região florestal boreal da Finlândia. Na área de estudos em Heinavesi (biomassa florestal entre 0 e 255 ton/hectares), a componente polarizada-HH de polarização dupla do ALOS/Palsar resultou a estimativa da precisão da biomassa (RMSE) entre 35 e 42 tons/hectares. Na área de Kuortane (biomassa florestal entre 0 e 188 ton/hectare) o RMSE variou entre 25 e 28 ton/hectare. Uma vez que apenas

duas cenas de inverno do TerraSAR-X estavam disponíveis, os resultados obtidos foram muito preliminares. A fase do HH-VV produziu as maiores correlações de biomassa entre os dados derivados da TerraSAR-X. Isto resultou em uma estimativa de precisão (RMSE) de 49 toneladas/hectare na área de estudo Heinavesi.

Palavras-chave: biomassa florestal; *SAR*; polarimetria.

Introduction

Forest biomass is a most important variable for climatic studies and for forest industries. Many studies have been conducted to estimate forest biomass using remote sensing techniques in the optical domain (e.g. HAME et al., 1997) and using radar (e.g. LE TOAN et al., 1992, DOBSON et al., 1992, RAUSTE, 2006 and many papers referred therein). Studies (e.g. RAUSTE et al., 1994) conducted using the Airsar sensor of JPL or other multi-frequency instruments suggest that the highest correlations with forest biomass are obtained using P band data (wavelength 63 cm). The current choice of frequencies from satellite sensors is limited to X (wavelength 3 cm), C (wavelength 6 cm), and L (wavelength 23 cm) bands.

Studies with polarimetric SAR, like the Airsar of JPL, also suggest that a fully polarimetric sensor enhances the potential to map forest biomass. The new polarimetric generation SAR satellites (ALOS/Palsar in 2006, TerraSAR-X in 2007, and Radarsat-2 in 2007) have created new opportunities to study and map forest biomass using space-borne sensors.

Measuring forest biomass on ground is a difficult and labour intensive task. Datasets of forest biomass for large area are difficult to find. In boreal forest, most of forest biomass is in tree stems. The total forest biomass is closely linked to forest stem volume. Based on regression analyses of biomass measurements and stem volume data (HAME et al., 1992), forest biomass can be estimated from boreal-forest stem volume data:

$$B = 0.6\ V \qquad\qquad (1)$$

where V is forest stem volume (m³/ha) and B is dry biomass (tons/ha).

Study Sites and Data

Study sites were located in western and eastern Finland (Figure 1). The primary study site in Heinavesi (centre coordinates 62°17' north, 28° east) in eastern Finland consists of forest owned by UPM Ltd., who also supplied the forest inventory ground data. From a large number of forest stands, a subset of large stands (2 ha or larger) were selected for forest biomass studies. The main tree species are spruce (*Picea abies*), pine (*Pinus sylvestris*), and birch (*Betula pendula* and *Betula pubescens*). The average forest biomass was 66 tons/ha (variation from 0 to 255 tons/ha). The stem volume measurements are expected to be accurate (in terms of root mean square error) to about 20 percent. The derivation of forest biomass using equation (1) does not significantly reduce

Figure 1. Location of study sites in Finland (left) and a ground photo from a pine stand with a biomass of 93 tons/ha.
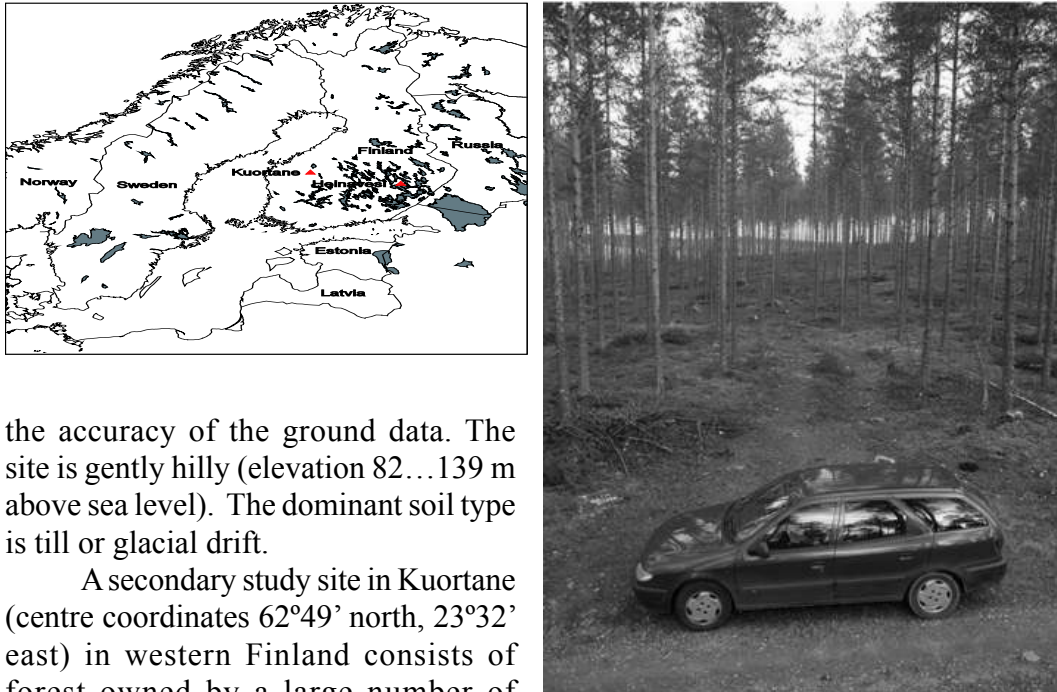
the accuracy of the ground data. The site is gently hilly (elevation 82…139 m above sea level). The dominant soil type is till or glacial drift.

A secondary study site in Kuortane (centre coordinates 62º49' north, 23º32' east) in western Finland consists of forest owned by a large number of private owners. The forest inventory ground data was supplied by the forest planning organisation "Etela-Pohjanmaan metsakeskus". The forest biomass varies between 0 and 188 tons/ha (average 57 tons/ha). The main tree species are the same as in the Heinavesi site. The soil is also here mostly till, but large areas of sandy soils also exist. The elevation varies between 80 and 130 m above sea level.

A digital elevation model (DEM) was purchased from Land Survey of Finland. The grid spacing of the DEM was 25 m, which was then interpolated (using cubic spline interpolation) to 12.5 m for ortho-rectification of ALOS/Palsar data and to 6.25 m for ortho-rectification of TerraSAR-X data.

Table 1 summarises the SAR data that were available in the Heinavesi study site. Meteorological data are from

Kuopio airport about 87 km from the study site. ALOS/Palsar data were in the so called level 1.1 format (single look complex). TerraSAR-X data were also SLC products.

The Kuortane site was used to verify results from the Heinavesi site. The ALOS/Palsar data available in the Kuortane site are listed in table 2. Meteorological data are from Kauhava airport about 42 km from the study site.

Methodology

All SAR data were ortho-rectified using a DEM. Ground control points (GCPs) were used in ortho-rectification via a block adjustment process. The time-series of dual-polarised ALOS/Palsar scenes were also co-registered using

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Table 1. ALOS/Palsar and TerraSAR-X data in the Heinavesi study site

Sensor	Mode	Polarisations	Incidence angle (deg)	Date	Temp. (°C)	Rain
ALOS/Palsar	Dual	HH,HV	39	2007-06-12	14	R
ALOS/Palsar	Dual	HH,HV	39	2007-07-28	14	R
ALOS/Palsar	Dual	HH,HV	39	2007-09-12	10	R[1]
ALOS/Palsar	Polarimetric	HH,HV,VH,VV	24	2007-10-30	8	R
TerraSAR-X	SpotLight	HH,VV	54	2008-02-05	-6	S[2]
TerraSAR-X	StripMap	HH,HV	42	2008-03-30	-1	-

[1] *rain had stopped half an hour before acquisition*

[2] *light snowing had stopped 4 hours before acquisition*

Table 2. ALOS/Palsar data in the Kuortane study site

Mode	Polarisations	Incidence angle (deg)	Date	Temp. (°C)	Rain
Polarimetric	HH,HV,VH,VV	24	2006-11-11	0	R
Polarimetric	HH,HV,VH,VV	24	2007-03-29	6	-
Polarimetric	HH,HV,VH,VV	24	2007-05-14	11	R
Dual	HH,HV	39	2007-06-27	12	R
Dual	HH,HV	39	2008-08-12	19	R[3]
Dual	HH,HV	39	2008-09-27	4	-

[3] *rain had stopped one and half hours before acquisition*

tie-points (based on image correlation) in connection with the block adjustment. The ortho-rectification took as a starting point the geo-location data from image auxiliary files. These geo-location data were then revised by a 3-parameter geometric model (translations in northing and easting and rotation) in connection with block adjustment. The polarimetric ALOS/Palsar data were ortho-rectified in Stokes matrix format (RAUSTE et al., 2007). Before rectification, the SAR data were pre-averaged: dual-polarised ALOS/Palsar data over 5 lines by 1 columns, polarimetric ALOS/Palsar data over a 3-by-1 window, and TerraSAR-X data over a 5-by-5 window. Co-polarised cross-correlation was computed over the same averaging window:

$$\gamma = <S_{HH} S_{VV}{}^*>/sqrt(<S_{HH} S_{HH}{}^*><S_{VV} S_{VV}{}^*>)$$

(2)

*where S_{HH} = HH-polarised scattering matrix element and S_{VV} = VV-polarised scattering matrix element. Angle brackets <...> indicate averaging over the window, and * indicates complex conjugate.*

Linear regression models and correlation coefficient were used to evaluate performance in forest biomass mapping. Ro-ot mean square error (RMSE) was also used:

$$RMSE = sqrt(<(m_i - e_i)^2>)$$

(3)

where m_i is the measured biomass of forest stand i and e_i is the estimated biomass of stand i. Angle brackets <...> indicate averaging over all stands. The RMSE statistics were computed using the

"leave one out cross validation" method: when estimating the error of stand i, the regression model is computed using all other stands; the final RMSE figure is averaged over all stands.

Before regression analysis, radar data were averaged per forest stand. Averaging was done in power form. Square root was taken of the average to maintain the amplitude format of the data. Stand boundaries were taken from forest inventory GIS systems. A raster map of stands was generated using the stand boundaries. The stand mask was eroded by one pixel to reduce the influence of neighbouring stands on the stand-wise radar data.

Results

Forest biomass was estimated using equation (1) for all stands. To reduce the effects of variation due to soil type, all stands that had less than 1 ton/ha were left out from analysis. This left 104 stands in the Heinavesi Palsar dataset, 103 in the Heinavesi TerraSAR-X dataset, and 129 in the Kuortane Palsar dataset table 3 shows the correlation coefficient r and

residual mean square error (RMSE) for ALOS/Palsar data in the Heinavesi study site. Figure 2 shows the corresponding scatter diagrams between forest biomass and ALOS/Palsar amplitude data.

As can be seen in figure 2, the relation between L-band amplitude and forest biomass saturates around 90 tons/ha. Of the two polarisations of the Palsar dual-polarised mode, the HH polarisation is slightly more robust against the saturation, which is shown as a slightly higher correlation coefficient and smaller biomass estimation error than in HV polarisation. If restricted to the range below saturation point (0…90 tons/ha), HV polarisation would give more accurate biomass estimates. The HH polarisation from the only polarimetric scene of the Heinavesi site performs worse than the HH polarisation from the dual-polarised scenes. This is most likely due to steeper incidence angle in polarimetric mode (24 degrees) compared to the dual-polarised mode (39 degrees).

The biomass estimation results of the Heinavesi study site were verified with data from the Kuortane site (Table 4). As the biomass level in Kuortane was lower the saturation had less influence

Table 3. Correlation coefficient (r) and residual mean square error (RMSE) between ALOS/Palsar amplitude data and forest biomass in the Heinavesi study site. Polarimetric scenes are marked with "/Pol"

Scene	Polarisation	r	RMSE (tons/ha)
2007-06-12	HH	0.66	42.4
2007-06-12	HV	0.59	45.6
2007-07-28	HH	0.71	39.6
2007-07-28	HV	0.60	44.9
2007-09-12	HH	0.78	35.0
2007-09-12	HV	0.67	41.5
2007-10-30/Pol	HH	0.47	49.9
2007-10-30/Pol	HV	0.64	43.1
All of above	All	0.84	33.0

Figure 2. Stand-wise Palsar amplitude data in Heinavesi study site: left HV, right HH
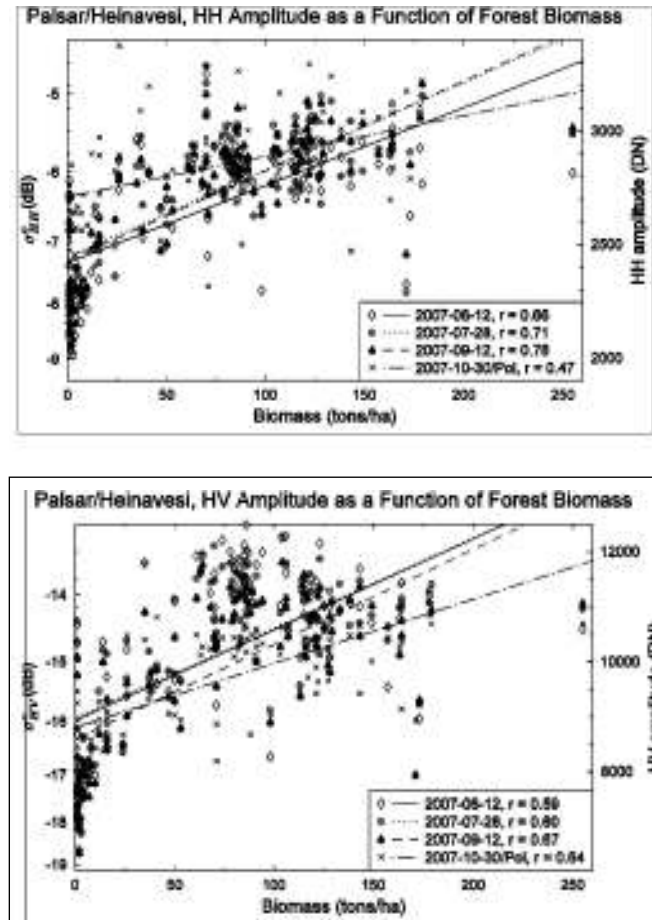
on the biomass estimation results. As in the Heinavesi site, co-polarised (HH and VV) data from polarimetric scenes (incidence angle 24 degrees) produced low correlations. Cross-polarised data (both in the polarimetric scenes and in the dual-polarized scenes 2007-06-27, 2008-08-12, and 2008-09-27) produced high correlations and low RMSE values. As suggested by a study using polarisation synthesis (RAUSTE et al., 2008), circular co-polarisation performed approximately as well as the cross-polarised data.

Since TerraSAR-X data distribution in the TerraSAR-X AO projects started in January 2008, TerraSAR-X data were available only from winter period. Based on previous studies (e.g. RAUSTE, 2006), summer data are expected to perform better than winter data in forest biomass estimation. Table 5 shows the correlation coefficient and RMSE data for the two TerraSAR-X scenes of the Heinavesi study site. Figure 3 shows a scatter diagram for amplitude data. Unlike in ALOS/Palsar data (Table 3) the correlation between

Table 4. Correlation coefficient (r) and residual mean square error (RMSE) between ALOS/Palsar amplitude data and forest biomass in the Kuortane study site. Polarimetric scenes are marked with "/Pol"

| Scene	Polarisation	r	RMSE (tons/ha)
2006-11-11/Pol	HH	0.23	41.5
2006-11-11/Pol	HV	0.70	30.3
2006-11-11/Pol	VV	0.09	42.4
2006-11-11/Pol	Circular co-pol	0.71	29.7
2007-03-29/Pol	HH	0.03	42.6
2007-03-29/Pol	HV	0.70	30.4
2007-03-29/Pol	VV	0.37	39.5
2007-03-29/Pol	Circular co-pol	0.68	31.2
2007-05-14/Pol	HH	0.27	40.9
2007-05-14/Pol	HV	0.76	27.1
2007-05-14/Pol	VV	0.09	42.5
2007-05-14/Pol	Circular co-pol	0.72	29.2
2007-06-27	HH	0.74	28.3
2007-06-27	HV	0.80	25.0
2008-08-12	HH	0.78	26.2
2008-08-12	HV	0.78	26.4
2008-09-27	HH	0.80	25.3
2008-09-27	HV	0.79	25.6
All of above	All	0.89	21.9

Table 5. Correlation coefficient (r) and residual mean square error (RMSE) between TerraSAR-X data and forest biomass in the Heinavesi study site

| Scene	Polarisation	r	RMSE (tons/ha)
2008-02-05	HH	-0.59	50.8
2008-02-05	VV	-0.51	54.2
2008-02-05	Coherence magnitude	0.15	62.3
2008-02-05	Coherence phase	0.61	49.4
2008-03-30	HH	-0.49	54.8
2008-03-30	HV	-0.35	59.2
All of above	All	0.71	46.3

forest biomass and SAR amplitude is negative in TerraSAR-X amplitude data (Table 5). The negative correlation can be connected with soil and canopy moisture content in these winter-time scenes with high incidence angle (54 and 42 degrees). The magnitude of correlation coefficient is also lower than in ALOS/Palsar data, which is most likely due to the shorter wavelength of TerraSAR-X.

The level of HH backscatter in the 2008-02-05 scene is almost 2 dB lower than in the 2008-03-30 scene (Figure 3). This difference is most likely due to the low temperature (-6 ºC) during the February acquisition – the forest canopy components and ground were firmly frozen during the acquisition. On 2008-03-30, the temperature fluctuated around 0 ºC, and there was more liquid water in

Figure 3. Stand-wise TerraSAR-X amplitude data as a function of forest biomass in Heinavesi study site: left SpotLight scene of 2008-02-05, right StripMap scene of 2008-03-30
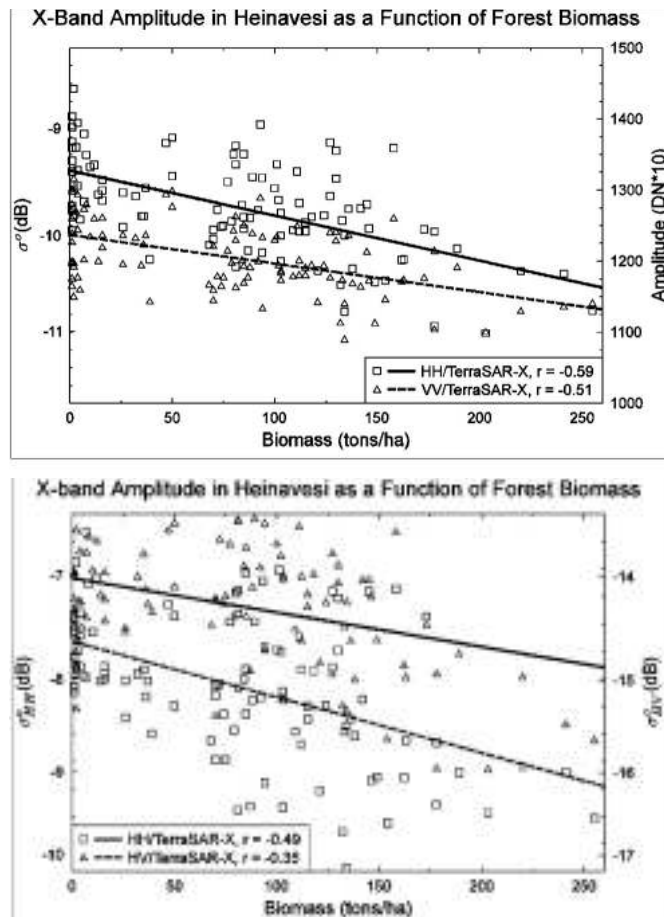
Figure 4. HH-VV coherence magnitude and phase in TerraSAR-X data in the Heinavesi study site as a function of forest biomass
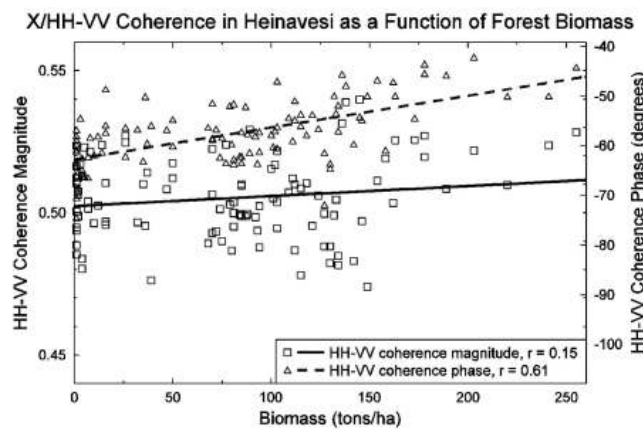
the components of forest canopy and in the soil.

Figure 4 shows a scatter diagram between forest biomass and the HH-VV cross-coherence data of scene 2008-02-05. The correlation between coherence magnitude and biomass is low and positive. This is unlike in repeat-pass interferometry, where small wind-induced changes in the positions of twigs and branches between image acquisitions produce negative correlation between coherence magnitude and biomass. In the case of (single-scene) cross-coherence between HH and VV polarisations, there are no such positional changes.

The phase of the HH-VV cross-coherence is more correlated with forest biomass. One reason for this correlation can be the changing proportion of the so called double-bounce component (reflected from ground to tree stems or *vice versa*) in HH polarisation. As the double-bounce component travels a longer distance than a single-bounce scattering from twigs and branches, the phase of HH polarisation (and the phase difference between HH and VV polarisations) changes as the proportion of double-bounce component decreases with increasing biomass (and increasing attenuation by the forest canopy). The phase of HH-VV cross-coherence essentially measures the HH-VV difference of the backscattered signal. The fairly high correlation between the phase of HH-VV cross-coherence and forest biomass was only observed in TerraSAR-X data. In the polarimetric ALOS/Palsar scene of 2008-10-30, the phase of HH-VV cross-coherence was uncorrelated with forest biomass.

The correlation of TerraSAR-X amplitude data and forest biomass seems to be fairly low in winter-time scenes. Despite this, clear-cut areas can be detected in visual analysis because boundaries between open areas and high forest can be seen due to the cast shadows produced by the forest edge. The high spatial resolution of TerraSAR-X facilitates this type of visual interpretation.

Discussion

ALOS/Palsar data can be used for mapping boreal forest biomass for wide areas if the accuracy requirements are not very high and if high-biomass forests do not occupy large areas in the area to be mapped. This latter condition is true in the northern part of the boreal forest zone close to the arctic bush land and tundra zones. Both dual-polarised and fully polarimetric scenes can be used, but polarimetric data may cause difficulties due to the narrower image swath and holes in image coverage.

TerraSAR-X results are very preliminary because only two winter-time scenes were used in the study. Despite the high frequency of X-band data, TerraSAR-X data with high incidence angles of over 40 degrees were correlated to forest biomass. The highest correlations were found between the phase of co-polarised cross-coherence and forest biomass. TerraSAR-X data with a high spatial resolution seem well suited for mapping of clear-cut areas using visual interpretation.

Acknowledgements

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