C-BAND INTENSITY-BASED GROWING STOCK VOLUME ESTIMATES VERSUS THE MODIS VEGETATION CONTINUOUS FIELDS TREE CANOPY COVER: DOES C-BAND SEE MORE THAN CANOPY COVER?

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ABSTRACT

In [1] the validation of a novel algorithm for the retrieval of boreal forest growing stock volume, GSV, with multi-temporal stacks of ENVISAT ASAR C-band intensity data was presented. The high retrieval accuracies that were reported contradicted the widely accepted notion that C-band is not suited for GSV retrieval since the signal hardly penetrates into the canopies and rather reflects the horizontal structure of forests, e.g. the canopy cover, than their three-dimensional structural properties. In this paper we aim at providing evidence of the capability of C-band to sense the vertical structure by comparing the GSV maps that were produced for Central Siberia and Sweden with the MODIS Vegetation Continuous Field canopy cover product [2]. The comparison with reference GSV data showed that canopy cover is a major predictor for GSV up to the point of canopy closure, which was reached at the validation sites at ~200 m$^3$/ha. The GSV maps produced with ENVISAT ASAR data showed a clear sensitivity to GSV differences beyond canopy closure, suggesting that C-band senses more than just canopy cover but also the vertical forest structure.

1. INTRODUCTION

Forest biomass is a highly desired parameter concerning our understanding of the global terrestrial carbon balance because large amounts of carbon are stored in it. Synthetic Aperture Radar, SAR, can provide information about forest biomass or growing stock volume, GSV, which is a central parameter in forest inventories that can be used to infer on biomass. Since spaceborne SAR sensors acquire data independent of sun illumination or cloud cover, they enable wall-to-wall coverage in short time spans and their measurements could thus be used to obtain at a regular basis information about the forest resources and their changes, e.g. due to logging, forest fire, etc.

Repeated C-band (~5 cm wavelength) SAR backscatter intensity measurements have been available since the early 1990ies from a series of satellite missions (ERS-1, ERS-2, Radarsat-1, Radarsat-2, ENVISAT ASAR). However, such data are generally deemed as useless for the retrieval of forest biophysical parameters. C-band intensity was reported to suffer from 1) an early saturation with respect to increasing forest GSV or biomass and 2) a pronounced dependence upon the environmental conditions (e.g. freeze/thaw conditions, precipitation, soil moisture, snow properties). An improvement of performance with respect to single images was presented in [3,4]. For boreal forest sites in Sweden and Finland, the retrieval accuracy could be improved noticeably when having available a multi-temporal stack of ERS C-band images. These results and the meanwhile extensive multi-temporal C-band datasets acquired by ENVISAT ASAR in the medium to low resolution Wide Swath and Global Monitoring modes have motivated the development of a fully automated retrieval algorithm, the so-called BIOMASAR algorithm [1]. The BIOMASAR algorithm was first presented in [5] and has meanwhile been validated against reference measurements of GSV (in situ data as well as validated remote sensing products) for several boreal forest sites in Canada, Sweden and Siberia [1] with results beyond initial expectations.

C-band signals do not sense the stems. Either they penetrate the canopy through gaps and the measured backscatter comes from the forest floor or they are scattered back / attenuated in the uppermost layers of the canopy since in C-band the attenuation is supposed to be always strong. If this interpretation is correct, the measurements should not contain information about the three-dimensional structure of forests but rather about the horizontal discontinuities in form of the canopy cover, i.e. the percentage to which the canopy covers the forest floor. The correlation between C-band intensity and GSV would then be a result solely of the correlation between canopy cover and GSV and there would be no benefit from exploiting the existing C-band archives since maps that are operationally produced with optical remote sensing data like MODIS VCF provide a similar type of information. A simple conversion of the VCF canopy cover maps to GSV may produce similar results.
In order to evaluate if C-band SAR based GSV maps also contain information on the vertical structure, we investigate in this paper the relationship between VCF canopy cover and GSV and present a comparison of VCF-based GSV maps with those that were produced with the BIOMASAR algorithm and multi-temporal stacks of ENVISAT ASAR Global Monitoring data for Sweden and Central Siberia. Since VCF has been validated only partially yet, the paper includes a section dealing with the reliability of VCF in the areas considered for comparison with the ASAR products.

The paper is structured as follows. In Section 2 the basics of the BIOMASAR algorithm are described and the datasets used are introduced. Chapter 3 starts with considerations about the reliability of VCF followed by a comparison of VCF with reference GSV maps for two of the BIOMASAR algorithm validation sites in Siberia and Sweden [6] in Section 3.2. In Section 3.3, the ASAR GSV maps for Sweden and Central Siberia are compared with the VCF based GSV estimates. The results are summarized in Section 4.

2. Methods and data

2.1 BIOMASAR algorithm

The BIOMASAR algorithm consists of the following steps:

- Calibration, terrain-corrected geocoding, speckle filtering and topographic normalization of the SAR data
- Training of a Water-Cloud-type of model that describes the intensity as function of GSV with the aid of the MODIS VCF product for each image in the multi-temporal stack at pixel level
- Inversion of the model for each of the backscatter measurements (i.e. pixels) to obtain GSV
- Weighted multi-temporal combination of the individual GSV estimates at a particular location to obtain improved estimates

In the BIOMASAR algorithm a simple Water Cloud-like model as those presented in [7,8] is used. The model relates the forest backscatter to the forest GSV. The two unknown model parameters are determined with the aid of the MODIS VCF product for each image in the multi-temporal stack at pixel level. After model training, the model is inverted to estimate GSV from a backscatter measurement. Having available a stack of backscatter measurements, it is possible to combine in a multi-temporal fashion the individual GSV estimates and retrieve a final GSV value. At C-band the retrieval has been shown to be extremely powerful when having a large multi-temporal stack of C-band intensity observations (at least 60). For a detailed description of the algorithm the reader is referred to [1,6].

The accuracy assessment of GSV retrieved with the BIOMASAR algorithm in the boreal forest at several study areas did not show saturation, i.e. the retrieval performed well up to 300 m³/ha. For the original resolution of the ENVISAT ASAR Wide Swath (100 m) and Global Monitoring (1 km) data, the GSV retrieval error was of the order of 50% but improved to about 20% when aggregating the retrieved GSV maps to a coarser pixel size with a factor of at least 10 by 10.

The key to the unprecedented results was the optimal exploitation of the SAR signal from many observations. Under frozen conditions, the SAR backscatter presents higher degree of penetration into the canopy and is not affected by soil moisture. These factors enhance the contrast between unvegetated and dense forest backscatter. By giving more weight to observations acquired under frozen conditions, it is possible to improve the accuracy of the GSV retrieval substantially.

With the BIOMASAR algorithm GSV maps have been produced for the entire area of Sweden and a 2.4 Mio km² large area in Siberia using GMM data that was acquired between December 2004 and April 2007 and between January 2005 and February 2006, respectively.

2.2. MODIS Vegetation Continuous Field

In its current version, VCF provides global estimates of canopy cover at 500 m pixel size for the years 2000 to 2005. The maps were created using a large number of multi-temporal metrics of the MODIS land reflectance bands [2]. These metrics were used as input to a regression tree classifier. For the production of the annual maps, the algorithm was kept constant, i.e. high inter-annual consistency of the MODIS measurements was presumed.

The VCF product has only partially been validated so far. Its accuracy was assessed in [2,9] by means of finer resolution optical remote sensing products for forest sites in Colorado and Zambia. The assessment showed that the accuracy of VCF increases when aggregating to coarser pixel sizes as for Colorado the coefficient of determination, $R^2$, improved from 0.81 at 500 m pixel size to 0.89 at 1 km pixel size and to 0.94 at 2 km pixel size. Similar results were obtained for the Zambian forest site. In a recent publication [10], the accuracy of the latest MOD44B Collection 4 VCF tree cover maps for the years 2000 to 2005 has been assessed by means of high-resolution Quickbird imagery for 396 sites distributed throughout the circumpolar taiga-tundra transition zone. The comparison resulted in a $R^2$ of 0.57 and an rms error of 13.4%. VCF tended to overestimate...
low canopy cover. It was assumed that VCF misclassified shrubs/woody vegetation as trees because of an insufficient spectral separability of these vegetation types.

2.3 Reference datasets

The following datasets were used as reference in this study:

1) For Central Siberia an extensive forest inventory database for the area of the forest enterprises Chunsky, Mansky, Bolshe Murtinsky and Irbeisky was used. For each stand the main forest parameters like GSV, diameter or height were given. The inventory data was last updated in 1998. For more details see [11].

2) A Landsat data based kNN forest growing stock volume map of Sweden was available for the year 2000. For the analysis presented in this paper, the map in the area of the counties Västra Gotaland in southern Sweden and Västerbotten in northern Sweden was considered. The error of the Landsat data based GSV map was reported to be 33 % at stand level for a forest site in Southern Sweden [12]; the error reduced to < 20 % when aggregating the map over > 100 ha large areas.

3. Results & Discussion

3.1 VCF accuracy

An accuracy assessment of VCF for the BIOMASAR validation sites would have required a large amount of reference data, either high resolution optical imagery or in situ measurements. Since such data was not available for this study, we focused on the interannual consistency of the maps as indicator for the reliability of the canopy cover estimates.

The interannual consistency of the VCF maps for the years 2000 to 2005 was first assessed by plotting the VCF canopy cover values from one year versus those from another year. Figure 1 illustrates this for the area of the Bolshe-Murtinsky forest enterprise in Central Siberia. The figure shows an overall high consistency of the maps with an \( R^2 \) in the range of 86 to 89 % when relating the 2000 map to the maps of the consecutive years from 2001 to 2005. At the Swedish validation sites, the consistency was somewhat lower with an \( R^2 \) in the range of 65 to 75 %.

When analyzing the variations of canopy cover at a particular pixel location in the 2000 to 2005 maps, different types of trends could be observed. Figure 2 shows the canopy cover estimates in the 2000 to 2005 VCF maps for 8 pixel locations as well as linear trend lines that were fitted to the data. Figure 2 (a) shows the most frequent case where the canopy cover estimates hardly changed from year to year whereas Figure 2 (b) shows cases with significant decreases in canopy cover (F statistics, \( p<0.05 \)); note that in the areas considered there were as many pixel locations with significant increases as with decreases in canopy cover. Figure 2 (c) shows pronounced variations in the canopy cover estimates from year to year.

The high stability of the canopy cover estimates in Figure 2 (a) indicated the reliability of the canopy cover retrieval at this particular location whereas the large and inconsistent variations in Figure 2 (c) clearly indicated problems in the estimation. Figure 2 (b) also shows variations in canopy cover between 2000 and 2005 but the high statistical significance of the trend (F statistics, \( p<0.05 \)) suggested that these changes were related to real forest cover changes on the ground, e.g. because of logging, forest fires, etc. Due to the lack of in situ data reporting forest cover changes between 2000 and 2005 we could, however, not verify this assumption. A comparison of the trends in the 2000 to 2005 VCF maps with a map reporting forest fires that occurred between 1992 and 2003 in Central Siberia [13] indicated, however, the suitability of VCF for change detection since many of the areas that were affected by fire revealed a significant decreasing trend in the 2000 to 2005 VCF maps [6].

Regarding the noise in the canopy cover estimates (in form of the sum of squared residuals with respect to the five year trend at a particular pixel location) differences depending on the canopy cover level were observed (see Figure 3). The strongest noise, i.e. the largest residuals, occurred for the lower to intermediate canopy cover ranges. As could have been expected, the noise decreased at all canopy cover levels when aggregating the maps to coarser pixel sizes. The reason for the increased noise level in the lower to intermediate canopy cover ranges became evident when relating the residuals in the VCF maps with respect to the five year trend to the land cover class, which was inferred from the Globcover map [14]. The residuals were clearly higher in case of the land cover types related to woody vegetation / shrubland (almost by factor two compared to the other classes) with the most likely explanation for this being an insufficient spectral separability of low woody vegetation and trees. These observations were well in line with the results in [10] where VCF was observed to overestimate low canopy cover in the taiga-tundra transition zone because it tended to misclassify low woody vegetation as trees.
3.2. VCF canopy cover vs. GSV

In order to characterize the relationship between canopy cover and GSV, a simple regression model was used, based on the relationship presented in Santoro, 2002 between the forest GSV and the so-called area-fill factor, i.e. a measure of canopy closure of the forest. In this context it was assumed that the area-fill factor and VCF canopy cover denote the same type of information, so that the relationship between VCF tree cover percentage and GSV could be written as follows:

\[ VCF = 100(1 - e^{b\cdot GSV}) \]  

(6)

In (1), the coefficient \( b \) represent a factor that in theory is related to forest structural properties. The VCF and reference maps have been compared at different pixel sizes and the model in (1) has been fitted to the data. Since the inventory data for Siberia was last updated in 1998 and the kNN maps for Sweden were produced with Landsat data from 2000, we used the VCF map for the year 2000 for the comparison. The comparison of VCF with the reference GSV maps revealed a clear nonlinear relationship between both parameters. At the full resolution of VCF, the relationship was quite noisy but improved clearly at all test sites when further aggregating the maps to coarser pixel sizes. At 1 km pixel size the \( R^2 \) for canopy cover was between 0.7 (Siberia) and 0.9 (Västra Götaland, Sweden) and exceeded 0.9 at all sites when aggregating the maps to at least 10 km pixel size.

Figure 4 shows that the model in (1) represented a reasonable description of the relationship between canopy cover and GSV. Interestingly, the unknown parameter \( b \) in (1) was almost constant at \( ~ -0.005 \) to \( -0.007 \) ha/m\(^3\) at all test sites which suggested a straightforward conversion of canopy cover to GSV. GSV could be estimated from VCF when inverting (1) for GSV:

\[ GSV = \frac{1}{b} \ln\left(1 - \frac{VCF}{100}\right) \]  

(2)
and considering the unknown $b$ a constant (0.006 ha/m$^3$).

3.3. SAR versus VCF based GSV retrieval

With (2) we have produced GSV maps from VCF for the entire area of Sweden as well as the part of Siberia for which the BIOMASAR GSV maps were produced. The GSV retrieval accuracy with VCF was assessed for the BIOMASAR validation sites to obtain a direct comparison of the retrieval performance.

Table 1 summarizes the retrieval accuracies achieved with the ASAR data and VCF for different pixel sizes. To take into account growth between the year of compilation of the reference datasets and the year of acquisition of the ASAR data (between 5 and 7 years), the reference GSV values were updated using area-specific growth factors reported in literature. For details see [6].

Compared to the GSV retrieval with the radar data, the VCF based retrieval was characterized by:

1) a 5 to 10 % worse accuracy in terms of the relative RMSE
2) a larger always positive bias, i.e. the VCF based GSV estimates were on average too low

Figure 5 shows a pixelwise comparison of the ASAR and VCF GSV maps for Västra Götaland in southern Sweden at 10 km pixel size. At this pixel size the noise and uncertainty components in the reference and the retrieved GSV are small [1]. The figure clearly shows why the ASAR data based retrieval performed better than that with VCF. Unlike the ASAR map, the VCF GSV map saturated at about 200 m$^3$/ha, which is the approximate GSV for which VCF reports maximum canopy closure. The radar map, instead, reported GSVs up to ~270 m$^3$/ha. In other words, C-band SAR is sensitive to GSV differences beyond canopy closure and, at least for the images acquired under frozen conditions, senses the vertical structure of forests.

When visually comparing the GSV maps for Siberia, similar observations as in Figure 5 could be made. Figure 6 shows the maps that were produced for Central Siberia. In the southern densely forested part, the VCF GSV map clearly reports lower GSVs. In addition, the VCF GSV map tended towards higher canopy cover values in the taiga-tundra transition zone north of the densely forested area. This was most likely due to the spectral confusion between trees and low woody vegetation; note that the bias because of the overestimation of the lower GSV ranges did not compensate for the bias due to the underestimation of the highest GSVs.

5. CONCLUSIONS

In this paper we aimed at providing evidence for the benefit of exploiting the large existing archives of SAR data that have been collected in the frame of several spaceborne missions, i.e. ERS-1, ERS-2, Radarsat-1/2 and ENVISAT ASAR, for the mapping of forest resources.

The comparison of GSV maps that were produced with ENVISAT ASAR ScanSAR data for Sweden and Central Siberia with the MODIS VCF canopy cover product clearly indicated that C-band data does not only see the horizontal structure of forests, i.e. the canopy cover, but also their vertical structure since GSV differences beyond the point of canopy closure were identified.

An exploitation of the existing C-band archives at continental scale would thus provide invaluable information about the existing forest resources. In ESAs archives there are enough ENVISAT ASAR ScanSAR data to produce circumboreal GSV maps.
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REFERENCES


Figure 1. VCF canopy cover estimates for the year 2000 versus those for the years 2001 to 2005 for a forest site in Central Siberia.

Figure 6. GSV maps for a 2.4 Mio. km² large area in Central Siberia. The left plot shows the map produced with ENVISAT ASAR Global Monitoring data with 1 km pixel size. The right plot shows the GSV map that was obtained by converting VCF to GSV using Eq. (7).