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Forest classification and impact of BIOMASS resolution on forest area and aboveground biomass estimation

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A B S T R A C T

The European Space Agency (ESA) is currently implementing the BIOMASS mission as 7th Earth Explorer satellite. BIOMASS will provide for the first time global forest aboveground biomass estimates based on P-band synthetic aperture radar (SAR) imagery. This paper addresses an often overlooked element of the data processing chain required to ensure reliable and accurate forest biomass estimates: accurate identification of forest areas ahead of the inversion of radar data into forest biomass estimates.

The use of the P-band data from BIOMASS itself for the classification into forest and non-forest land cover types is assessed in this paper. For airborne data in tropical, hemi-boreal and boreal forests we demonstrate that classification accuracies from 90 up to 97% can be achieved using radar backscatter and phase information. However, spaceborne data will have a lower resolution and higher noise level compared to airborne data and a higher probability of mixed pixels containing multiple land cover types. Therefore, airborne data was reduced to 50 m, 100 m and 200 m resolution. The analysis revealed that about 50–60% of the area within the resolution level must be covered by forest to classify a pixel with higher probability as forest compared to non-forest. This results in forest omission and commission leading to similar forest area estimation over all resolutions. However, the forest omission resulted in a biased underestimated biomass, which was not equaled by the forest commission. The results underline the necessity of a highly accurate pre-classification of SAR data for an accurate unbiased aboveground biomass estimation.

1. Introduction

Forests play an important role in the global carbon cycle and support climate change mitigation by acting as natural carbon sink (Gibbs et al., 2007; van der Werf et al., 2009). The BIOMASS mission was selected as European Space Agency's (ESA) 7th Earth Explorer Mission in 2014. The objectives of the mission are to provide repeated systematic and spatially-explicit estimates of aboveground forest biomass of forests at global scale. These estimates will be used to quantify carbon emissions and sinks from forests reducing terrestrial carbon flux uncertainties in the global carbon cycle (ESA, 2012; Le Toan et al., 2011).

Both the sensitivity of P-band synthetic aperture radar (SAR) data to forest biomass and the methods that process radar data into forest biomass have been extensively investigated in the past with the help of airborne campaign datasets (Le Toan et al., 2011; Villard and Le Toan, 2015; Sandberg et al., 2011; Soja et al., 2013; Santos et al., 2003; Hoekman and Quinones, 2000). In most if not all of these studies the forested areas were identified visually or using *a priori* field information focusing the studies on the evaluation of the biomass retrieval algorithm. Similarly, high accuracies in land cover and forest/non-forest classifications have been reported in previous investigations in temperate and tropical forests with long wavelength SAR like L- and P-band (Santos et al., 2003; Hoekman and Quinones, 2000, 2002; Lee et al., 2001; Freitas et al., 2008; Lardeux et al., 2009, 2011; van der Sanden and Hoekman, 1999). In general, P-band SAR performed superior to other wavelengths in forest classifications (Lee et al., 2001; van der Sanden and Hoekman, 1999; Santos et al., 2003). The intensity of P-band in HV polarization was considered to have high potential since it is most sensitive to stems and branches allowing to uniquely separate forests from low vegetation types (Le Toan et al., 1992, 2011; Lee et al., 2001). These historical results underline the potential of the BIOMASS mission to provide accurate forest/non-forest classification, which could then be used to identify candidate areas for forest biomass inversion.

However, it is important to note that much of the work discussed above focuses on airborne SAR data and the specific context for the BIOMASS mission has not been specifically investigated in terms of forest/non-forest classification. This is important as the future BIOMASS SAR images are characterized by a much

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lower resolution (e.g. a single look resolution of roughly 600 m^2 compared to 2–16 m^2 which is typical for airborne sensors) as well as lower signal-to-noise ratios. The frequency of mixed pixels increases with lower resolution by integrating different land cover types in a single resolution cell (Fisher, 1997; Simard et al., 2000; Lu, 2006; Lu et al., 2016). Mixed pixels are identified as an important uncertainty in aboveground biomass estimation with remote sensing (Lu, 2006; Lu et al., 2016). Mixed pixels occur mostly at edges, transition zones and for objects smaller than the resolution (Fisher, 1997; Simard et al., 2000). For the specific case of forest/non-forest classification with coarse resolution data, this could result in a different forest extent compared to high resolution as well as the potential omission of forest fragments (Magdon and Kleinn, 2012). Somewhat counter-intuitively often a minimal decrease of classification accuracies was frequently observed using coarser resolution (Hsieh et al., 2001; Chen et al., 2004; Enwright et al., 2014; Roth et al., 2015).

Responding to the context above, the main objective of this study is to quantify the performance of forest area estimation with space borne P-band SAR data and identify potential biases in aboveground biomass estimation due to lower resolution. One might argue that forest omission and commission are equal thus resulting in similar forest area and biomass estimation. The study makes extensive use of recent airborne data collected through ESA-sponsored campaigns across three different forest biomes, which are described in Section 2. The forests covered by airborne data had a long history of forest inventories and were considered as typical for northern latitude forests in flat and relief terrain (Ulander et al., 2011; Hajnsek et al., 2008, 2009) as well as tropical lowland forest (Dubois-Fernandez et al., 2011, 2012). High-resolution airborne data is used to verify and confirm previous results from other studies (Santos et al., 2003; Hoekman and Quinones, 2000, 2002; Lee et al., 2001; Freitas et al., 2008; Lardeux et al., 2009, 2011; van der Sanden and Hoekman, 1999). However, the aforementioned studies were mainly based on single-date acquisitions, whereas the used campaigns and also BIOMASS mission enable multi-temporal analysis. This could be used on the one hand in multi-temporal speckle filtering in order to decrease speckle noise with minimal loss of spatial resolution (Quegan and Yu, 2001; Quegan et al., 2000). On the other hand, multi-temporal phase information like the interferometric coherence was frequently used to improve land cover classifications significantly with shorter wavelengths like P-band (Wegmuller and Werner, 1995, 1997; Bruzzone et al., 2004; Schlund et al., 2014), whereas using polarimetric phase information resulted in low improvement for forest classifications (Lee et al., 2001; Lardeux et al., 2009).

Space borne data will be simulated by decreasing the resolution to 50, 100 and 200 m fully accounting speckle characteristics of the BIOMASS mission. The 50 m resolution is compliant to the forest disturbance product of the BIOMASS mission, whereas 200 m corresponds to the forest biomass product (ESA, 2012). Therefore, these resolutions were assessed in addition to 100 m resolution as middle resolution between 50 m and 200 m. Subsequently, the forest area estimation of airborne data will be compared to the space borne data and the potential bias in biomass estimation will be assessed. The methods are described in Section 3. Results are presented in Section 4 and discussed in Section 5. Section 6 concludes the study.

2. Data

2.1. Tropical forest

Airborne SAR experiments were conducted during the TropiSAR campaign, which was acquired with the SETHI system from ONERA (Dubois-Fernandez et al., 2012, 2011). During this campaign airborne SAR data was collected over the Paracou test site with dense tropical forest in French Guiana in August and September 2009 in order to assess the potential of P-band SAR for tropical forest biomass and height estimation (Dubois-Fernandez et al., 2011). Fully polarimetric P-band SAR data were acquired with a center frequency f_c of 397.5 MHz (Dubois-Fernandez et al., 2012), corresponding to a wavelength λ of about 75 cm. The SAR data had a resolution of approximately 1.5 m in azimuth and 1 m in range direction. The altitude of the airplane was about 4000 m and the incidence angle ranged between 24° to 62°. Data with zero spatial baseline but temporal baselines of 2–22 days were used (Table 1).

Data of permanent forest plots were also available, whereas 15 plots had a size of 6.25 ha and one plot 25 ha. Nine of these plots had a disturbance history, whereby seven were mature rain forest (Dubois-Fernandez et al., 2011). The aboveground biomass of the reference plots ranged from 258 to 432 t/ha. In addition, plots within plantations with a size of 0.5 ha were provided. Therefore, heterogeneity within training areas was ensured in order to cover a broad range of forest biomass values. In addition, airborne light detection and ranging (LiDAR) data was available acquired with a Riegl laser rangefinder. The pulse density was 8 pulses per m^2. The final digital elevation model (DEM) and canopy height model (CHM) were sampled to 1 m pixel size. Optical Landsat 8 and high resolution Sentinel-2 data were used as additional reference.

2.2. Hemi-Boreal forest

P-band SAR data for the hemi-boreal forest biome was collected with the E-SAR system from the German Aerospace Center (DLR) during the BioSAR-1 campaign in Remningstorp, Sweden in March 2007 (Hajnsek et al., 2008). The data was acquired in full polarimetric mode with f_c of 350 MHz (λ = 85.7 cm). The SAR data had a resolution of approximately 1.6 m in azimuth and 2.1 m in range direction. Four datasets with a temporal baseline less than one hour were used. The spatial baseline ranged from 0 to 80 m (Table 1). Aboveground biomass estimates from forest stands and forest plots were available. The 68 stands and plots had an average size of 0.5 ha with a biomass range from 11 to 287 t/ha (Ulander et al., 2011; Hajnsek et al., 2008). Airborne LiDAR was acquired with a TopEye system over the study area in August 2010, with a pulse density of 10–30 pulses per m^2. A DEM and CHM were provided with a pixel size of 0.5 m. High resolution optical Sentinel-2 data supported the interpretation of forest and non-forest areas.

2.3. Boreal forest

P-band SAR data for the boreal forest biome was collected with the E-SAR system from the German Aerospace Center (DLR) during the BioSAR-2 campaign in Krycklan, Sweden in October 2008 (Hajnsek et al., 2009). Similar to the BioSAR-1 campaign, the data was acquired in full polarimetric mode with f_c of 350 MHz (λ = 85.7 cm). The SAR data had a resolution of approximately 1.6 m in azimuth and 2.1 m in range direction. The altitude of the airplane was about 3900 m and the incidence angle ranged between 25° to 55° (Hajnsek et al., 2009). Different datasets were acquired within less than a hour difference, but with different spatial baselines (Table 1).

In total, 31 forest stands with forest inventories and aboveground biomass estimates were available, where 27 of them were fully covered by the radar acquisitions and used for this study. Norway spruce and Scots pine are the dominating tree species. The forest stands had a size of about 3–28 ha with an average size of about 10 ha. The biomass of the stands ranged from 27 to 153 t/ha (Hajnsek et al., 2009; Neumann et al., 2012). Airborne LiDAR data was acquired in August 2008 with the TopEye system using an average point density of approximately 5 pulses/m^2. A DEM and CHM