Remote Sensing of Environment xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Decrease of L-band SAR backscatter with biomass of dense forests

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ARTICLE INFO

Article history:
Received 9 May 2014
Received in revised form 21 December 2014
Accepted 24 December 2014
Available online xxxx

Keywords:
Tropical forest
Carbon mapping
ALOS PALSAR

ABSTRACT

Synthetic aperture radar (SAR) is one of the most promising remote sensors to map forest carbon. The unique spaceborne and long-wavelength SAR data currently available are L-band data, but their relationship with forest biomass is still controversial, particularly for high biomass values. While many studies assume a complete loss of sensitivity above a saturation point, typically around 100 t.ha^{-1}, others assume a continuous positive correlation between SAR backscatter and biomass. The objective of this paper is to revisit the relationship between L-band SAR backscatter and dense tropical forest biomass for a large range of biomass values using both theoretical and experimental approaches. Both approaches revealed that after reaching a maximum value, SAR backscatter correlates negatively with forest biomass. This phenomenon is interpreted as a signal attenuation from the forest canopy as the canopy becomes denser with increasing biomass. This result has strong implications for L-band vegetation mapping because it can lead to a greater-than-expected under-estimation of biomass. The consequences for L-band biomass mapping are illustrated, and solutions are proposed.

1. Introduction

Forests act as both carbon sources and sinks through deforestation, degradation (Harris et al., 2012) and regrowth (Lewis et al., 2009). The monitoring of forest carbon stocks is a pressing concern to quantify the exchange of carbon between the surface and the atmosphere and therefore to reduce the uncertainty in the global carbon budget. Our knowledge of the distribution and amount of forest carbon is mostly based on ground measurements with relatively small field plots, which are not necessarily representative of their surrounding areas (Réjou-Méchain et al., 2014) and not uniformly distributed over forested areas and biomes (Gibbs, Brown, Niles, & Foley, 2007; Houghton, Hall, & Goetz, 2009). Thus, most estimates of emissions from deforestation are based on a handful of biome-average datasets where a single representative value of forest carbon per unit area is applied to broad forest categories or biomes (Achard, Eva, Mayaux, Stibig, & Belward, 2004; Achard et al., 2002; DeFries et al., 2002; Fearnside, 2000; Houghton, 1999; Ramankutty et al., 2007). Such approaches have led to strong inconsistencies between studies.

Remote sensing approaches offer considerable potential in support of forest monitoring as they provide long-term and repetitive observations over large areas. Standard optical data, such as provided by Landsat, are not sensitive to above ground biomass (AGB) beyond the canopy closure. However, using very high resolution optical data, the canopy texture can be characterised and then used to infer the AGB based on, for example, the Fourier-FOTO algorithm (Couteron, 2002; Couteron, Pelissier, Nicolini, & Paget, 2005). A few studies have successfully used such an approach to map AGB in high biomass areas, such as Proisy, Couteron, and Fromard (2007) in two mangroves areas in French Guiana, Ploton et al. (2012) in a wet evergreen forest in India and Bastin et al. (2014) in a moist forest area in the Democratic Republic of the Congo. These three studies showed that AGB can be retrieved with no signal saturation and with a relative error ranging from 15 to 17%. However, these studies are performed at local scale and are limited to the small imaging swaths (maximum of 15×5 km). The large scale application of the methods is limited by the data cost and the temporal consistency of data due to cloud cover.

At the landscape scale, airborne LiDAR data-based approaches have proven to be accurate enough to infer the canopy height and structure, and thus to map the forest AGB at a high spatial resolution. In a recent meta-analysis, Zolkos, Goetz, and Dubayah (2013) showed that the AGB can be retrieved with an error of 10% if the calibration is done using 1-ha plots. However, the cost of airborne LiDAR campaigns limits its use for large regions (however, see Mascaro, Asner, Davies, Dehgan, and Saatchi (2014)), and airborne campaigns are not feasible throughout the tropics for logistical and political reasons. Meanwhile, spaceborne LiDAR data are currently limited by discontinuous coverage

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http://dx.doi.org/10.1016/j.rse.2014.12.019
0034-4257/

and clouds (Baghdadi et al., 2013; Lefsky et al., 2005), and the derived large scale AGB products have low spatial resolution (1 km in Saatchi, Marlier, Chazdon, Clark, and Russell (2011) and 500 m in Baccini et al. (2012)). In a recent contribution, Mitchard et al. (2013) used a large network of field plots in Amazonia to show that the uncertainties of Saatchi and Baccini's maps were far larger than expected, with over- and under-estimations greater than 25%.

Synthetic aperture radar (SAR) is one of the most promising remote sensors to map the global forest AGB. Many studies have shown that long-wavelength radar data are sensitive to AGB. Research efforts based on airborne data and/or electromagnetic (EM) modelling have demonstrated that P-band data may be used for a larger range of AGB values than L-band data and thus should be privileged in forests with high biomass density (Le Toan, Beaudoin, Riom, & Guyon, 1992). The first P-band SAR satellite, BIOMASS, will be launched approximately 2020, having the objective to provide multi-temporal global forest AGB maps (ESA, 2012; Le Toan et al., 2011). Currently, the L-band ALOS PALSAR data acquired up to 2011 can be used to estimate the forest AGB, as well as its sequel, ALOS-2, launched in May 2014.

The L-band has been extensively used to estimate forest AGB (Carreiras, Melo, & Vasconcelos, 2013; Cartus, Santoro, & Kellndorfer, 2012; Saatchi et al., 2011; Santoro, 2003; Santos, Lacruz, Araujo, & Keil, 2002), based on a positive correlation between SAR backscatter and in situ AGB. However, contrasting results have been obtained concerning the range of biomass that can be retrieved. Literature results suggest that there is an AGB level above which there is a loss of sensitivity between the L-band backscatter and AGB (Imhoff, 1995), commonly called the saturation phenomenon. The saturation level using HV polarization has been found to range between 40 and 150 $t.ha^{-1}$ (Dobson et al., 1992; Le Toan et al., 2004; Saatchi, Halligan, Despain, & Crabtree, 2007; Sandberg, Ulander, Fransson, Holmgren, & Toan, 2011), reaching in some studies more than 250 $t.ha^{-1}$ (Hoekman & Quiriones, 2000; Lucas et al., 2010).

Questions can arise about the relationship between L-band backscatter and forest AGB beyond the saturation region. Many studies used a sigmoid function to describe the relationship between radar backscatter and AGB (Mermoz, Le Toan, Villard, Réjou-Méchain, & Seifert-Granzin, 2014; Mitchard et al., 2011) to represent the 'saturation' behaviour. Some studies suggested that the sensitivity to AGB can be observed up to 400 $t.ha^{-1}$ (Englhart, Keuck, & Siegert, 2011; Hamdan, Aziz, Rahman, 2011; Morel et al., 2011; Shugart, Saatchi, & Hall, 2010) and even 1000 $t.ha^{-1}$ (Mitchard, Saatchi, Gerard, Lewis, & Meir, 2009; Viergever, 2008). This finding is attributable to the use of a logarithmic (i.e., non-asymptotic) function to fit the experimental data, even though the positive correlation between SAR backscatter and AGB is usually not observed after 150–200 $t.ha^{-1}$. In addition to modelling results based on EM simulations of the Landes forest, France (Villard, 2009), one study reported a decreasing trend after 200 $t.ha^{-1}$ (Lucas et al., 2007) over dense mangrove forests in Australia, French Guyana and Malaysia, as well as another recent study over a forest–savanna mosaic in Cameroon (Mermoz, Le Toan, et al., 2014) and in Central African Republic (CAR) (Mermoz, Rejou-Mechain, et al., 2014). When retrieving AGB, the choice of the function describing the relationship between radar backscatter and AGB is crucial in the higher AGB range (i.e., >100–150 $t.ha^{-1}$) because it can lead to serious over- or under-estimation.

The objective of this paper is to revisit the relationship between L-band SAR backscatter and forest biomass for a large range of AGB values using both theoretical and experimental approaches. The focus is put on the high biomass range, for which the predicted AGB values may vary substantially between studies. The emphasis is on the tropical forests for which the carbon stocks and spatial distribution of carbon are poorly known despite containing 59 and 27% of the land terrestrial vegetation and soil carbon stocks (Dixon et al., 1994). Note that this approach targets the tropical forests but could be valid for various forest types with dense canopy and for various radar frequencies, though some specific parameterizations would be required.

The following section introduces the theoretical approach. Section 3 provides information on the study site and the field and SAR data. Section 4 describes the experimental approach, and Section 5 discusses the results.

2. Theoretical approach

2.1. Electromagnetic modelling to simulate forest backscatter at L-band

We aimed to model the backscatter at L-band from dense canopy forests as a function of AGB to investigate and physically explain their relationship. In this work, it is not intended that the dense canopy simulated by the model represents in detail the forest observed experimentally. Simulations were achieved from a discrete description of the forest canopy, using canonical shapes such as cylinders for the scatterers (Fig. 1).

Simulations were run through the MIPERS (Multistatic Interferometric Polarimetric ElectroMagnetic) model (Villard, 2009). The vegetation scatterers are modelled by four classes of dielectric cylinders (one class for the trunk and three classes for the branches) with varying height (h_t is the trunk height and $(h_i)_{1\leq i\leq 3}$ is the branches height) and radius (r_t is the trunk radius and $(r_i)_{1\leq i\leq 3}$ is the branches radius) and gathered into horizontal layers according to the spatial statistical distribution of their classes. The MIPERS model needs as inputs dielectric cylinder heights and radii, together with the number of trees N_t, the ratio h_t/h with h the total tree height, and the radar characteristics (frequency, incidence angle, polarization). Each of the four classes of cylinders are defined by the Gaussian distributions of their height and radius and by specific distributions for the Euler angles driving their 3D orientations. Following a Monte-Carlo process, these geometrical parameters are drawn for each cylinder to compute their scattering contribution. On the contrary, the mean extinction coefficient associated with each layer is an averaged (integral) expression according to the Foldy–Lax formulation (Ishimaru, 1978). Following the Distorted Born Wave Approximation (Tsang, Kong, & Ding, 2000), the total backscatter is deduced from the coherent sum (preserving the geometric and proper phase) of each scatterer contribution. The most important scattering mechanisms at L-band arise from direct contributions from scatterers belonging to the vegetation layers and the ground and from their coupling through the so-called double bounce scattering mechanism.

The geometrical parameters describing the forest are required by the EM simulations. Since in situ measurements are difficult to perform, a forest growth model has been developed to deduce all the geometrical parameters for a chosen AGB, ranging from 50 to 450 $t.ha^{-1}$ with 50 $t.ha^{-1}$ steps. Based on the allometric relationships, the main steps of the forest growth model have been synthesized in Fig. 2 and detailed in Appendix A. Because our field dataset (see Section 3.2) lacked tree height measurements, allometric relationships were selected from the literature. We chose the allometric relationships given in Asner et al.

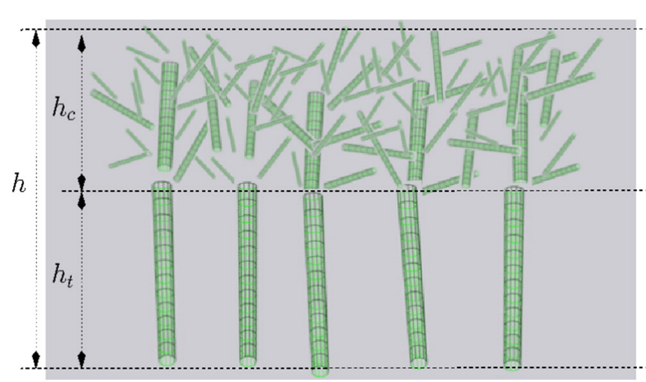

Fig. 1. Illustration of the two-layered forest model. Vegetation scatterers are modelled by dielectric cylinders with various height and radius and are gathered into two horizontal layers. h is the total tree height, h_t is the trunk height and h_c is the crown height.