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Performance of GNSS-R GLORI data for biomass estimation over the Landes forest

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ABSTRACT

The Above-Ground Biomass (AGB) is a key parameter used for the modeling of the carbon cycle. The aim of this study is to make an experimental assessment of the sensitivity of Global Navigation Satellite System (GNSS) reflected signals to forest AGB. This is based on the analysis of the data recorded during several GLORI airborne campaigns in June and July 2015, over the Landes Forest (France). Ground truth measurements of tree height, density and diameter at breast height (DBH), as well as AGB, were carried out for 100 maritime pine forest plots of various ages. The GNSS-R data were used to obtain the right-left (Γ_{RL}) and right-right (Γ_{RR}) reflectivity observables, which are geo-referenced in accordance with the known positions of relevant GPS satellites and the airborne receiver. The correlations between forest AGB and the GNSS-R observables yield the highest sensitivity at high elevation angles (70°-90°). In this case, for (Γ_{RL}) and the reflectivity polarization ratio (PR = Γ_{RL}/Γ_{RR}) estimated with a coherent integration time Tc = 20 ms, the coefficients of determination R^2 are equal to 0.67 and 0.51, with a sensitivity of −0.051 dB/[10^6g (Mg) ha^{-1}], and −0.053 dB/[Mg ha^{-1}], respectively. The relationships between AGB and the observables are confirmed through the use of a 5-fold cross validation approach, with several different coherent integration times.

1. Introduction

The accurate estimation of forest characteristics, in particular their biomass, is essential to an improved understanding of the carbon cycle, and more specifically greenhouse gas emissions. In this context, low-frequency remote sensing based on the use of monostatic radars, and Synthetic Aperture Radars (SAR) in particular, has shown considerable potential for the estimation of this parameter (Mermoz et al., 2014; Baghdadi et al., 2015; Baghdadi and Zribi, 2016). Mermoz et al. (2014) demonstrated the strong potential of space-borne missions in the L-band (wavelength of about 25 cm) for the mapping of forest biomass, including dense tropical forests, with radar signal saturation occurring at approximately 150 Mg ha^{-1}. ESA's BIOMASS mission, which has a launch date planned for 2022 and will make use of a P-band radar (wavelength close to 70 cm), has been designed to map forest AGB on a global scale (Le Toan et al., 2011). Passive microwave sensors such as SMAP and SMOS have also shown considerable potential for the global retrieval of Vegetation Optical Depth and biomass (Konings et al., 2016; Brandt et al., 2018).

In this context, the use of a Global Navigation Satellite System (GNSS) as a source of opportunistic signals for bistatic radar observations, also known as GNSS reflectometry (GNSS-R), has now become a relatively mature remote-sensing technique for the monitoring of the Earth's surface (Martin-Neira, 1993; Zavorotny et al., 2014; Darrozes et al., 2016; Jin et al., 2014; Emery and Camps, 2017).

While most early GNSS-R studies focused on oceanographic applications, an increasing interest has been shown for land surface applications in the last 15 years (Zavorotny et al., 2003; Masters et al., 2004; Rodriguez-Alvarez et al., 2009, 2011; Larson et al., 2009, 2010; Egido et al., 2012; Egido, 2013; Egido et al., 2014; Motte et al., 2016a; Wu and Jin, 2014). Initial demonstrations were made from towers, followed by aircraft (Egido et al., 2012; Egido, 2013; Egido et al., 2014),

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stratospheric balloons (Carreno-Luengo et al., 2015, 2016) and more recently from low Earth orbit (Carreno-Luengo et al., 2017; Camps et al., 2016; Chew et al., 2016; Unwin et al., 2011; Ruf et al., 2012). These were designed to evaluate the sensitivity of GNSS-R measurements to geophysical parameters of interest, such as soil moisture and above-ground vegetation biomass.

Several current space-borne missions can measure GNSS-R signals reflected by the Earth's surface. These include the Techdemosat-1 demonstrator (Camps et al., 2016; Chew et al., 2016), the recently launched, dedicated CYGNSS constellation (Ruf et al., 2012), and the candidate European receiver GEROS (Wickert et al., 2016). As these missions are now opening up new opportunities for systematic global observations of the Earth's surface, it is essential for the interaction between GNSS signals and land surfaces to be well understood.

In the case of forest biomass estimations, only a small number of experimental and theoretical studies have assessed the potential of GNSS-R techniques (Egido et al., 2014; Wu and Jin, 2014; Carreno-Luengo et al., 2015, 2016). Following the GRASS airborne campaigns in Italy, Egido et al. (2014) revealed the strong potential of Γ_{RL} righ-left reflectivity measurements for the retrieval of biomass. In this study it was found that the GNSS-R signal remained unsaturated up to a (relatively high) biomass level of more than 300 Mg ha^{-1}, with an estimated sensitivity of 1.5 dB/(100 Mg ha^{-1}). However, the number of reference fields was limited to just five, and the retrieved empirical relationships were not validated. Using data from the BEXUS campaigns derived from observations of boreal forests taken from a stratospheric balloon, Carreno-Luengo et al. (2015, 2016, 2017) revealed strong dynamic variations in their coherent reflectivity. However, these results did not lead to the development of quantitative relationships between reflectivity and biomass. Using the GNSS-R signals provided by the SMAP mission, Carreno-Luengo et al. (2016) also demonstrated the sensitivity of various GNSS-R observables to variations in AGB, even at levels as high as 350 Mg ha^{-1}, corresponding to tropical forests. Theoretical studies of bistatic modeling have also revealed the potential of GNSS-R signals for the retrieval of forest biomass (Carreno-Luengo et al., 2016; Ferrazzoli et al., 2010; Gueeriero et al., 2013; Pierdicca et al., 2014, 2012).

In this context, the present study focuses on the analysis of the potential of airborne GNSS-R data for the retrieval of forest AGB. The analysis is based on a specific experiment which included five flights with the GLORI instrument, over a site covered by ~20,000 ha of maritime pine in the Landes forest. The experiment was carried out between June and July 2015, and the data was recorded under a wide range of forest conditions, using GNSS-R measurements. Our results are based on the analysis of a large ground forest database, which was produced soon after the GLORI campaigns. This paper is structured as follows: Section 2 describes the airborne campaigns, study site and ground-truth collection protocols. In Section 3, the sensitivity of GNSS-R observables to forest AGB is analyzed, and in Section 4 the results are discussed and validated. Our conclusions are presented in section 5.

2. Materials and methods

2.1. Study site

The study site is located in South West France, near to Bordeaux and the Atlantic coast (Fig. 1). It includes two zones known as "Nezer" (~6 × 10 km; 44.57 °N, 1.03 °W) and "Tagon-Marcheprime" (~17 × 10 km; 44.71 °N, 0.93 °W), which are approximately 10 km apart. Its forest cover is dominated by maritime pine (*Pinus pinaster* Ait) plantations and has a total surface area of ~20 000 ha.

The site lies within the perimeter of the Landes de Gascogne forest, Europe's largest maritime pine forest (~1 million hectares), but outside the coastal dunes. With the exception of these dunes, the topography is nearly flat, with a mean altitude of several tens of meters. The soils are comprised mainly of sandy podzols (Augusto et al., 2010).

In the Landes forest the maritime pine stands are intensively managed and even-aged. At the present time, these stands are generally clear-cut when they reach ~50 years of age, and reforestation is achieved by replanting, which in most cases is carried out 2–3 years later. The stands are periodically thinned, in general every five years, once the plantation has reached ~10-15 years of age. The spatial structure of the pine trees is thus rather homogeneous throughout any given stand, as shown by the small difference between the mean and maximum tree heights. The mean tree height ranges between 0 and approximately 25 m. The understory vegetation (various species of woody shrub such as heather, and perennial herbaceous plants such as fern or graminaceous plants) is periodically cleared during the first years following reforestation, and prior to each thinning operation. The cover fraction of the understory vegetation is thus highly variable from one stand to another.

The Tagon-Marcheprime zone is more varied in forest structure than the Nezer zone. Its stands are smaller (7 ha on average compared to 12 ha). The Tagon-Marcheprime zone is managed by many different forest owners, whereas the second zone is managed by two forestry companies. In addition, in the Nezer zone the Storm Klaus severely damaged a large portion of the oldest stands in 2009 (Chehata et al., 2014), and therefore, age was generally less than 25 years in 2015. In the Tagon-Marcheprime zone, very few of the stands were more than 50 years old in 2015.

Both of these zones were chosen in an effort to cover all the range of forest structure variables (age, DBH, height, tree density) and AGB, which is specific to maritime pine stands in the Landes forest. The study site selection was thus based on a good *a priori* knowledge of this region, assisted by the use of the most recently available geographic information (land-use and forest maps, aerial photographs, forest management databases), combined with experience gained from previous remote sensing-based studies. In particular, over the last two decades several studies have been carried out over these two zones, using radar and optical data to estimate the AGB and other key forest structure variables (Le Toan et al., 1992; Garestier et al., 2009; Beguet et al., 2014).

2.2. GNSS-R airborne data

The airborne GNSS-R data presented below was collected with the GLORI Instrument (Motte et al., 2016b). This is a polarimetric GNSS-R instrument designed for aircraft operations. Two antennas are connected to the receiver: the first of these is an up-looking Right Hand Circular Polarization (RHCP) antenna used to monitor the direct signals transmitted by GNSS satellites, and the second one is a down-looking dual-polarization antenna (RHCP and Left Hand Circular Polarization (LHCP)) used to collect the signals reflected from the Earth's surface. Both polarizations are cross-calibrated by means of a transfer switch. The nadir antenna is qualified in terms of isolation between the two polarizations (LHCP and RHCP). The instrument's cross-polarization isolation is better than 15 dB at angles up to 45° from boresight (45° elevation), for both LHCP and RHCP ports. At cross-polarizations below 15 dB, the system's performance was considered inadequate for polarimetric measurements (Motte et al., 2016b). The antenna patterns were measured in an anechoic chamber, and had a half-power beam width of approximately 40°. In the present study, we analyzed signals recorded at elevations ranging between 50° and 90° only, in order to avoid the potential influence of strong noise resulting from inaccuracies in the antenna diagram corrections, cross-polarization isolation degradation at lower elevation angles (below 50°), as well as multi-scattering effects between direct and reflected signals (as described by Motte and Zribi (2017)).

Five scientific flights were carried out with a French research ATR-42 aircraft, over the southwest of France, for a period of two-weeks during the GLORI campaigns, in June-July 2015 (Fig. 1). This allowed several agricultural areas of interest (Zribi et al., 2018), as well as the