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Inference of forest biomass using P-band circular-polarized radar signals

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Abstract

This paper examines the possibility of using P-band frequency, circular-polarized radar signals for mapping and monitoring of forest biomass from space while at the same time minimizing the limiting effect of Faraday rotation. Several examples from various types of forests (temperate, boreal, and tropical) are presented and analyzed. Predicted biomass levels from the radar are compared to estimates from forest inventories at both linear and circular polarizations. The results show that the two kinds of estimates are in good agreement, except when the phase difference between HH and VV-polarization is large in which case RR or LL-polarized radar signals overpredict forest biomass. This situation is encountered in the presence of flooded forest, or very wet trees. Also, in areas where the P-band radar response from the forest saturates (biomass greater than 200 tons/ha), it is shown that polarimetric information allows further analysis of the scattered signals to obtain additional information on the vegetation characteristics. One analysis technique uses a Cloude decomposition of polarimetric scattering. In the case of tropical rain forests, this analysis technique helps separate different vegetation communities and habitats which can subsequently be related to different biomass levels.

1. Introduction

Several studies have shown that radar backscatter at the longer wavelengths is strongly correlated with total aboveground biomass of forested areas up to a biomass level of about 200 tons/ha at P-band frequency ($\lambda = 68$ cm) [1-3]. The dynamic range in radar backscatter is highest at HV-polarization. However, linearly polarized signals are of limited use for spaceborne applications at the longer wavelengths due to the phenomena of Faraday rotation. In this study we investigate the possibility of using circularly polarized signals to retrieve forest biomass from SAR data gathered at P-band frequency. Polarimetric radar data collected by the same airborne system, the NASA/JPL airborne SAR (AIRSAR) instrument, over several test sites are used to synthesize the radar response from various types of forests at P-band circular-polarization. Using regression curves relating biomass to radar backscatter, radar predicted values of forest biomass are then compared to actual biomass values. Furthermore, in areas where radar backscatter saturates (biomass levels greater than 200 tons/ha) we examine whether polarimetric information would help further characterize the vegetation. One analysis technique uses a Cloude decomposition of polarimetric scattering [4]. We applied this technique on SAR data gathered from the tropical rain forest in Peru and discuss the results.

2. Airborne data and ground truth estimates

The examples considered in this study include a wide range of forested areas: maritime pine plantations in les Landes, France (44°31' North, 0° 55' East) [1]; lolloby pine plantations of Duke Forest, North-Carolina (35°59' North, 79°5' West) [2], boreal forests of the Bonanza Creek Experimental Forest, near Fairbanks, Alaska (64° 45' North, -148° West) [3], and tropical rain forests in the Manu National Park, Peru.

In the Landes Forest, forest stands are even-aged, well-managed, and mono-species. Total aboveground biomass varies from 11 tons/ha for the youngest forest stands which have been sampled, up to 150 tons/ha for 46 years old forest stands [1]. In the Duke Forest, forest stands are mostly stands of irregularly-spaced lolloby pine trees, but many stands are also a mixture distribution of decidous and coniferous species. Forest biomass ranges from 4 to 492 tons/ha [2], but here we limit the analysis to those stands where biomass is less than 230 tons/ha. The Bonanza Creek Experimental Forest, near Fairbanks, Alaska, in contrast to the other sites, is a natural forest which include many different tree species. Forest succession there is controlled by wildfire, slope, aspect, elevation and parent material. Total aboveground biomass ranges from 4 to 218 tons/ha [3]. Finally, the Manu National Park Forest, Peru, is tropical rain forest, including both floodplain successions and upland forests with total aboveground biomass as high as perhaps 600 tons/ha.

3. Predicted versus actual biomass

For each forest site, we extracted the radar response for polygonal areas corresponding to areas of similar biomass level for which ground truth information has been collected [1-3]. Radar backscatter was then plotted as a function of biomass and regression curves were derived to predict biomass from the radar. The regression curves are second (Landes site) or third (other sites) order polynomials in radar backscatter, σ^o, relating the logarithm of the biomass to either σ^o_{HV} in dB, or a combination of σ^o_{HV}, σ^o_{HH}, and σ^o_{VV}, all expressed in dB. Similarly, regression curves are derived relating biomass to σ^o_{RR}, or to a combination of σ^o_{RL} and σ^o_{RR}). Predicted biomass levels from the radar data are then compared to actual biomass levels. An error is computed as the average absolute difference between predicted and actual biomass divided by actual biomass and multiplied by 100, and is expressed in percent. The results are listed in Table 1.

For the Landes Forest, the error is 11% at linear polarization and relatively unchanged at circular polarization. L-band signals perform nearly as well as P-band signals, and combining together radar returns acquired at different polarizations does not improve the results obtained using only the cross-polarized radar returns.

For the Duke Forest, the error rates are higher than those obtained for the Landes Forest. This is expected because the stands are less homogeneous and not always dominated by the same species. P-band signals perform better than L-band signals because the biomass level of the forest stands is often greater than 100 tons/ha. Linear polarization and circular polarization yield comparable results except for P-band RR which overestimates the biomass level of two stands of low biomass. In those stands, the phase difference between HH and VV-polarization is 31° greater than that recorded in similar stands. This larger than expected phase difference between HH and VV yields a higher than expected value of σ^o_{RR}, and thereby an overestimated value of the stand biomass. When two channels are used in the regression, the results are significantly better, and the difference between linear and circular polarization is reduced.

For the Bonanza Creek Experimental Forest, error rates are higher than for the Landes Forest. Again, it was expected that in natural forests the retrieval of forest biomass would be more difficult because of a significant spatial variability in tree height, age, density, diameter, and species within each stand, combined with the complex interactions of the radar signals with a spatially varying three dimensional structure of the canopy. The results are only slightly better at P-band than at L-band, and using linear polarization rather than circular polarization. Using several polarizations together instead of separately improves the results significantly. Looking at those stands for which the errors are large at circular polarization we found the following. The biomass level of alder stands is always overestimated, even using linear polarization, but these trees were not in normal conditions in 1993. All alder stands had been severely damaged in 1992, leaving all trees broken, flattened to the ground, and permanently damaged. Second, two mixted stands of white spruce and balsam poplar trees yield higher than expected predicted biomass levels at circular polarization. These two stands are characterized by a phase difference between HH and VV of about 70 to 94° at P-band and 58 to 70° at L-band, significantly larger from that observed in other forest stands of similar biomass. We visited one of these stands in 1991 and found that balsam poplar trees in that stand were rotten, with very wet tree-trunks. Strong double-bounce interactions between the wet tree-trunks and the ground layers probably could explain the unusual radar response of these stands at circular polarization.

Radar predictions on May 1991 for BCEF (not shown in Table 1) are comparable to those obtained in July 1993, except at circular polarization. In one stand of black spruce, P-band RR largely overestimates biomass. Photos taken at the time of the overflight reveal that this stand included large patches of water consecutive to a major flooding event of the forest 2 days earlier. It is therefore not surprising that the phase difference between HH and VV polarization in that stand is much larger than in other black spruce stands, thereby yielding an enhanced radar response at circular polarization and an overestimated biomass level from the radar.

In summary, the results suggest that using circular polarization is a viable approach for mapping forest biomass from a spaceborne radar, provided that the forest does not exhibit particular conditions such as a flooded forest floor or very wet/damaged trees. In that case, combining RR and RL radar signals helps improve the biomass estimates obtained using RR alone, but large errors can still be made. Perhaps some of these uncertainties could be removed by considering time series of images from the same area, for instance estimating forest biomass at the peak of the dry season.

4. Analysis of polarimetric scattering

The application of Cloude's decomposition to imaging radar polarimetry has been described previously [4]. The purpose of this decomposition is to decompose the average covariance matrix of each pixel into a unique sum of covariance matrices representing single scatterers. The first and second eigenvectors of the decomposition represent scattering matrices that can be interpreted directly in terms of odd and even numbers of reflections; while the third eigenvector corresponds to diffuse scattering from randomly oriented scatterers. This decomposition has been implemented on a pixel per pixel basis to help analyze polarimetric radar images. In many instances, it is observed that even in areas where radar backscatter is expected to saturate, because the average biomass level is greater than 200 tons/ha, the radar is able to separate different types of vegetation communities through differences in scattering behavior.

Here we consider the example of tropical rain forest from the Manu National Park, Peru (12°5' South, 71°8.5' West). A biomass map was generated for this area using P-band HV-polarization. Except for the few stand bars at the edges of the Rio Manu river, forest biomass in that area is typically between 200 and 600 tons/ha, i.e. beyond the saturation level of the radar. Yet, many areas have predicted biomass levels below the saturation point. Some of these estimates probably are correct. For instance near the banks of the river, biomass is expected to be lower than 200 tons/ha. In some other areas, the radar estimates are clearly in error, either because of topographic effects (upland forests on slopes facing away from the radar), calibration uncertainties, or perhaps because radar backscatter may actually decrease at the higher biomass levels. We are currently investigating the source of these errors.

The Cloude decomposition of the radar image is shown in Fig. 1a c at P-, L-, and C-band frequency. At C-band, scattering is dominated by scattering from randomly oriented cylinders thin compared to the wavelength. At L- and especially P-band, we notice an increased number of even number of reflections, probably the result of a deeper penetration of the radar signals through the coniferous canopy resulting in trunk-ground double reflection scattering. Although the scattering from the forest is still dominated by scattering from randomly oriented thin cylinders, double reflection scattering dominates in a few areas. Areas colored in red are aguajales or palm trees, areas colored yellow (mixture of double bounces and diffuse scattering) are swamp forests, green areas are mature forests, and dark green areas near the river are successional cecropia forest. Each one of these vegetation communities has a different biomass level.

References

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Site	Frequency/Polarization.	Error (L)	Error (C)	Frequency/Polarization
		%	%	
Landes	L-band HH, HV, VV	21	22	L-band RR and RL
08-16-89	L-band HV	13	12	L-band RR
	P-band HH, HV, VV	12	11	P-band RL and RR
	P-band HV	11	12	P-band RR
Duke	L-band HH, HV, VV	29	43	L-band RR and RL
09-02-89	L-band HV	45	43	L-band RR
	P-band HH, HV, VV	28	30	P-band RL and RR
	P-band HV	31	46	P-band RR
BCEF	L-band HH, HV, VV	20	26	L-band RR and RL
07-21-93	L-band HV	27	32	L-band RR
	P-band HH, HV, VV	19	26	P-band RL and RR
	P-band HV	31	38	P-band RR

Table 1 Error rates of biomass retrieval from the radar at different frequencies and polarizations for three different forest sites.