ESTIMATION OF FOREST BIOMASS FROM AN AIRBORNE SINGLE-PASS L-BAND POL-INSAR SYSTEM

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Commission I, WG I/2

KEY WORDS: SAR, InSAR, IFSAR, Pol-InSAR, Forest, Biomass

ABSTRACT:

In this paper we describe forest height and biomass results obtained with an experimental airborne L-Band fully polarimetric, single-pass InSAR system over a test area in western Canada. The significance of the single-pass characteristic is that temporal decorrelation is avoided, allowing more robust Pol-InSAR forest parameter recovery. The derived tree height results were validated against those obtained from airborne lidar and were further supported by high resolution aerial photography. Canopy heights in coniferous stands with tree heights ranging from 15-30 meters were extracted using Pol-InSAR and relative to lidar-derived canopy heights, showed accuracies better than 10%. A forest biomass map was then created through height-biomass allometry. The goal is to demonstrate that above-ground biomass and hence carbon estimates can be provided at suitable accuracy and resolution levels using this technical approach. If successful, this would provide the potential to improve carbon baseline estimates in large forest areas, particularly in the tropics, where currently the estimated biomass uncertainty can be significant.

1. INTRODUCTION

According to UN estimates (UNDP, 2008), the destruction of forests on a global basis is responsible for almost 20% of annual CO_2 uptake into the atmosphere with well-known consequences for global warming forecasts. These estimates are at least partially based upon the monitoring, through remote sensing means, of the loss of forests combined with associated estimates of their pre-destruction biomass content. Forest biomass estimates however can have significant errors associated with the methods used in these estimates. Where it is feasible, biomass assessment may be performed by local small-area sampling techniques which themselves can have large associated estimation errors, especially in dense tropical areas. Much effort is being expended on various forms of satellite remote sensing to provide wide-area estimates of the biomass content of forests. In particular, there has been much research on the allometric relationships relating forest biomass to certain optical parameters (e.g. NDVI) (Roy and Ravan, 1996; Dong, *et al.*, 2003) as well as to radar backscatter (Imhoff, 1995; Leckie and Ranson, 1998). Unfortunately both NDVI and radar backscatter, saturates at the higher biomass levels. It has been demonstrated (Mette *et al*, 2003) that canopy height (as obtained by forest yield tables) has a very strong allometric relationship with a variety of European tree species in various conditions. It was further shown (Mette *et al*, 2004A; 2004B) using airborne systems, that through use of Polarimetric InSAR (Pol-InSAR) techniques at L- or P-Band, canopy heights can be recovered and show a similar strongly correlated allometric relationship with biomass even at the higher biomass levels of interest. This technology is behind at least two proposed satellite missions, *Tandem-L* (Moreira *et al*, 2009) and *BioSAR* (Boom and Snoeij, 2000).

However research using repeat-pass Pol-InSAR over forests, faces the problem of temporal de-correlation even over very short time periods (<30') (Lee *et al*, 2009) which can seriously degrade the results, particularly at L-Band. The solution is to use a single-pass system which eliminates the temporal de-correlation problem. This factor motivated the development, by Intermap, of an experimental single-pass airborne L-Band fully polarimetric InSAR system to assess performance in forest conditions in the absence of temporal de-correlation and residual motion issues. (removal of temporal de-correlation effects is similarly the driving factor behind the proposed Tandem-L satellite system which is effectively a single-pass design). Previous results (Mercer *et al.*, 2009A; 2009B) were presented that focussed initially on DTM extraction and then on forest height generation in an area that was largely populated by pine stands of heights ranging to 30 meters. Preliminary results suggested that tree height accuracies (relative to lidar-derived heights) in sampled subsets were better than 10% of tree height, while the DTM showed biases that were typically 2-3 meters above the true ground elevation.

In this paper, we broaden the effort and show wider area DTM and tree height maps. We also show preliminary results for forest biomass estimation through height-biomass allometry. A height-based allometric relationship was used to convert the canopy height data to above-ground biomass. The project objective is to determine, using this experimental system, the accuracy and spatial resolution of above-ground biomass estimates, (and hence carbon estimates) that can be provided. If successful, this would provide the potential to improve carbon baseline estimates in large forest areas where currently the biomass uncertainty can be significant.

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An overview of the program is given in Section 2 followed by a brief description of the methods used in Section 3. Section 4 details our results and we summarize our findings in Section 5.

2. RADAR SYSTEM OVERVIEW

The radar system has been described in (Mercer *et al*, 2009A; 2009B) and we summarize its main features here. The design philosophy was driven by the desire to demonstrate, relatively quickly and inexpensively, the capabilities and issues associated with tree height and DTM generation using L-Band PolInSAR technology. Therefore the constraints regarding collection efficiency could be relaxed as a tradeoff for the cost and schedule gains. The principle impact was that flight altitude, and corresponding swath width, was not a major concern allowing the use of lower gain antennas and a shorter interferometric baseline. High S/N was achieved at lower altitude and a baseline was chosen that allowed for optimized $Kv = Kz*h/2$ (Cloude, 2006) for tree heights in the h = 20~30 meter range.

The platform was adapted from the TopoSAR quad-pol P-Band system flown on an AeroCommander. A rigid, horizontal, 3.5 meter long beam supported the two log-periodic, E- and H-plane antennas which were deployed at either end of the beam. The beam ran through the luggage compartment of the aircraft and due to its rigidity, a single INU/GPS unit was able to provide adequate attitude/position solutions. A single transmitter and receiver chain provided fully polarimetric data through a switching network that allowed pulses to be recorded in both ping-pong and non ping-pong modes. Therefore a total of 12 active channels were recorded on a pulse-sequential basis. At 1km design altitude, NESZ was better than 40db. Resolution was approximately 1.25 m. The major system design parameters can be found in (Mercer *et al*, 2009A).

3. METHODOLOGIES

3.1 Tree Height Estimation

We utilize the well-known Random Volume Over Ground (RVoG) Model (Treuhaft and Siqueira, 2000; Papathanassiou and Cloude, 2001) in which the projection of the observed complex coherences onto the unit circle represents the ground phase (Papathanassiou and Cloude, 2001). This is expressed in Eq. 1 as

$$\tilde{\gamma}(\vec{w}) = \exp(i\phi_0)\frac{\tilde{\gamma}_V + m(\vec{w})}{1 + m(\vec{w})} \qquad (1)$$

in which ϕ_0 is the phase related to the ground topography, m is the effective ground-to-volume amplitude ratio (accounting for the attenuation through the volume) and $\vec{w}$ represents the observed polarization state. $\tilde{\gamma}_V$ denotes the complex coherence for the volume alone (excluding the ground component), and is a function of the extinction coefficient σ for the random volume, its height h and the vertical wavenumber Kz The key point of interest for this application is the assumption that m is polarization dependent while $\tilde{\gamma}_V$ is not. In particular, for large m, the straight line intersects the complex unit circle and the associated phase at this point relates directly to the desired ground elevation. In the limit of no ground component (m=0), the observed coherence is given by the volume coherence, $\tilde{\gamma}_V$ rotated through ϕ_0. As discussed elsewhere (Mercer *et al*, 2009A; 2009B) we use a combination of an optimized phase approach (Tabb *et al*, 2002) in the high forest and an optimized coherence (Papathanassiou and Cloude, 2001) approach in low vegetation or bare areas to extract the ground phase. The tree height derivation is based upon an inversion technique described in (Cloude, 2006).

3.2 Biomass Calculation

Forest biomass may be estimated by direct or indirect methods. A 'standard' method for direct biomass estimation within forest stands is through the use of ground sampling sites within which, stem diameter at breast height (DBH = D), tree height (h) and stem density (N) can be measured directly. Then by treating a tree as a tapered cylinder with taper factor $0< f <1$, the stem volume can be calculated and with further knowledge of the wood density (ρ) the stem biomass/unit area (B) can be determined as an average over the sample area and standardised in terms of Mgm or tonnes per hectare (ton/ha) as shown in Eq. 2 (Mette *et al*, 2004A). Additional biomass from branches and leaves may be sampled locally and applied as a fraction of the stem biomass.

$$B = \rho \cdot (\frac{\pi}{4} \cdot D^2) \cdot f \cdot h \cdot N \qquad (2)$$

Species-dependent allometric relationships developed as functions of D^2 or D^2h may be used as simplifications of this expression with parametric coefficients determined heuristically. However it may be expensive or impractical to make these direct measurements in remote areas. Therefore indirect remote sensing methods, based upon allometric relationships with various parameters, including optical radiance and radar backscatter are widely researched. As noted in the introduction, however, estimates saturate at higher levels of biomass for both optical (based on NDVI) and radar (based on backscatter). In this work we follow that of Mette, *et al.* (2003; 2004A; 2004B) in utilising biomass-height allometry.

Referencing timber yield curves for Germany, Mette *et al.*, (2004B) showed that a simple tree-height power-law relationship (Eq. 3) provides a strong allometric relationship for biomass across several species and stand conditions (at least in closed forest conditions) and importantly, does not appear to saturate at the higher biomass levels. Moreover, the biomass relationship appears more robust than those with other parameters such as stand age, D^2 or basal area.

$$B = a\, h^b \qquad (3)$$

In the context of direct measurements from the ground, this is not too helpful since tree heights are often difficult to measure in dense forests. However there are several approaches for measuring canopy height remotely including the use of airborne lidar and InSAR. In the following (and as first demonstrated by Mette *et al*., 2004B) we will describe the extraction of height using Polarimetric InSAR through inversion of the RVoG model.

The intention in this project was to acquire directly-measured biomass data in the test area and to perform a regression analysis using an expression of the form of Eq. 3, from which the coefficients a, b would be obtained. At the time of this writing we do not yet have the desired biomass data. Hence we will apply the same coefficients (Eq. 4) as those determined for the European forests described in (Mette *et al.*, 2004B) and determine whether the results are plausible relative to generalized values determined by ground measurements for the same species in proximate areas.

$$B = 0.8\, h^{1.75} \qquad (4)$$

where B is in (tonnes/ha) and tree height h is in meters.

4. RESULTS

4.1 The Test Areas

The majority of the work reported here has been done in a forested area near the town of Edson in central Alberta, Canada. The area is well suited for these tests because it consists of a pattern of alternating forest and clear-cut patches. The forest in this area is mainly composed of lodgepole pine trees with heights ranging from 10-30m and with relatively homogeneous growth in the forested patches. Fig. 1 shows a ground photo looking towards the forest. Canopy height in this sub-area is about 20 meters with typical tree spacing about 3-5 meters. The alternating patches often exhibit patterns of regrowth subsequent to re-planting. Ancillary data for the area includes lidar: both bare earth and 'feature' data are used in the analysis. The canopy height used as relative 'truth' is derived from the envelope of the feature data. Specifically the highest point within a 5 meter search window represents the canopy at that point. This is similar to the h_{100} metric sometimes used (Kugler, *et al.*, 2006) and we will refer to it by the same name. Additionally, high resolution colour air-photo was available. The L-Band data were acquired in two periods: November 2007 and June 2008. The ancillary data were 1-2 years older than the L-Band data so that some changes will have occurred in the interim.

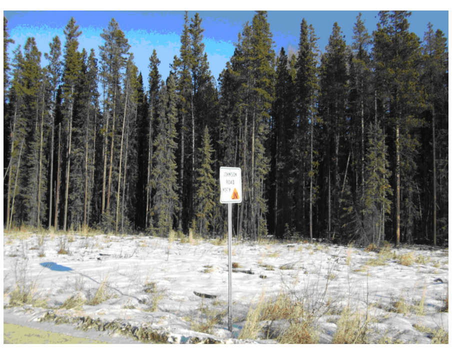

Figure 1. Ground photo during L-Band data acquisition

4.2 Tree Height Results

The coherence (magnitude) optimization and coherence region algorithms have been applied to the dataset. The estimated canopy height is shown in Fig. 2 (e). Qualitatively, the Pol-InSAR-estimated tree height map is quite consistent with the lidar-derived tree height map, which is shown in Fig. 2(d). The exception to this is among the shorter (~10 meter) canopy samples which appear to be overestimated by Pol-InSAR. This may be due to the fact that the system parameters are optimized for 20-30 meter heights as noted in section 2.1.

In Fig. 3, we show one profile with L-Band tree height on the top of Lidar DTM. The location of this profile line is identified as 1 in Fig. 2(a), and the profiles are plotted from left to right. It is clear that the L-Band tree height is in agreement with lidar tree height inside a forest with average tree height around 25m on different terrain slopes. Statistics calculated for the large tree patch in the middle (Fig. 2 (a)) shows the canopy height was underestimated by about 0.7m with ±1.3m standard deviation (~5%) for this dataset.

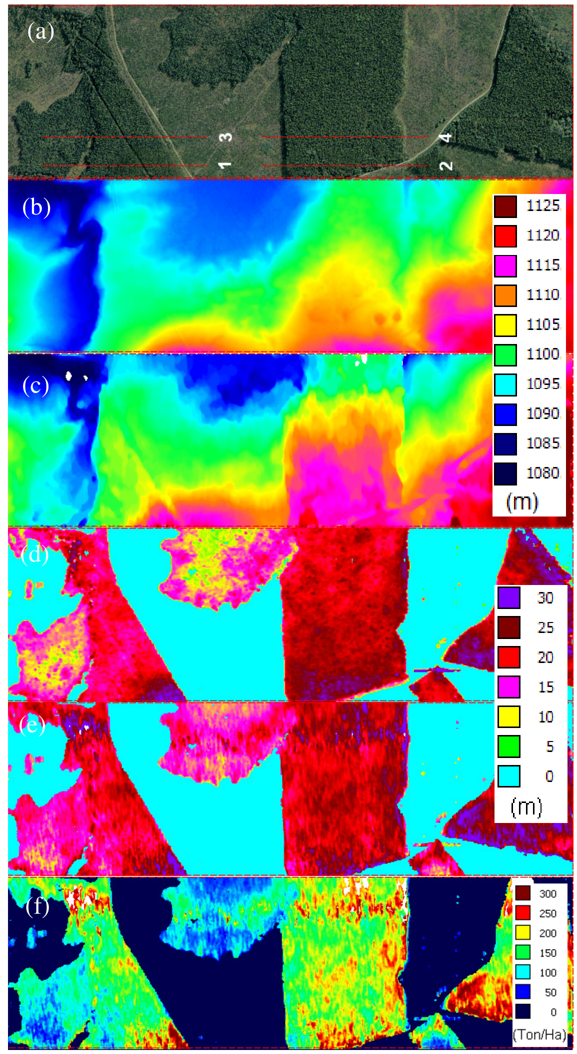

Figure 2. (a) Profiles on the air photo, (b) Lidar bald-earth DTM, (c) L-Band DTM, (d) Lidar tree height map, (e) L-Band estimated tree height map (f) Biomass estimated from (e)

The ground elevation derived from the optimized coherence magnitude follows the terrain quite well on the bare/new growth areas, but inside the forest canopy appears to be similar to the X-Band DSM height. The elevation derived from the phase optimization process within the forest patches however, reflects the ground elevation over most of the test area. A merging routine was designed to combine these two results to generate an L-Band derived DTM to preserve elevation continuity across the forest boundary. The resulting L-Band DTM is shown in Fig. 2(c). This is also illustrated in the profile of Fig. 3, where the blue lines represent the L-Band DTM elevation.

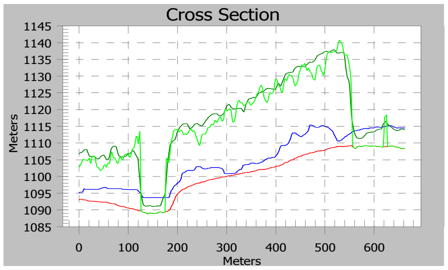

Figure 3. Elevation profile of Line 1 in Fig. 2(a): red – Lidar DTM, dark green – Lidar h_{100}, light green – L-Band tree height, blue – L-Band ground. Note that the tree height profiles are with reference to the underlying DTM.

4.3 Biomass Results

The biomass calculated from the estimated tree height using Eq. 4 is shown in Fig. 2(f). The map shows a general biomass decreasing trend from south (right-hand-side in the map) to north with some variations inside each tree patch. Table 1 gives the mean and standard deviations of five selected areas of interest (AOIs) depicted in Fig. 4. The overall mean and standard deviation for these five AOIs is: 171±29 ton/ha.

Figure 4. AOIs for biomass statistics

AOI Index	Biomass (ton/ha)	
	Mean	**Stdev**
1	105	20
2	154	35
3	93	29
4	181	27
5	232	35
Mean	171	29

Table 1. Biomass Statistics

The uncertainties in these biomass estimates arise from two sources: 1) The validity of the allometric relationship (i.e., the form and the coefficients); and 2) The tree height measurements. We have validated our tree height estimation using the lidar-derived tree height but we have not validated the allometry equation and its coefficients for the lodgepole pine species. We should note that the standard deviations of the estimated biomasses in Table 1 correspond to the relative height extraction uncertainties and do not address errors in the allometric equation itself.

At the time of writing this paper, we have not obtained biomass 'truth' for our test sites. However Monserud *et al* (2006) created a forest biomass map for lodgepole pines in Alberta based on measured diameter at breast height and tree height for a large number of permanent sample plots (PSP) from both public and private sources. According to their biomass map, our test site has a total biomass value ranging from 100 to 300 tonnes/ha. The estimates provided in Table 1 above, appear to be well within the expected range as deduced from the Monserud map. However it should be noted that the Monserud map is very broad-brush insofar as it represents a biomass surface, interpolated from the coarsely-spaced PSP data. Therefore there is no direct correspondence with the finely-grained biomass estimates depicted in Fig. 2(f) and Table 1.

5. DISCUSSION AND CONCLUSIONS

Destruction of forest biomass, particularly in the tropics, is well known as source of CO_2 emissions. It is highly desirable that coverage, resolution and accuracy of global forest biomass baseline information be improved. Height-biomass allometry offers the potential to obtain saturation-free forest biomass at higher biomass levels than currently available. Long-wavelength Pol-InSAR, through inversion of a physical model, appears to provide an effective means of obtaining canopy heights.

In this work we have presented results from an airborne, single-pass, fully polarimetric InSAR at L-Band. Canopy heights (15-30m) of lodgepole pine at a test site in Alberta, were obtained and validated against lidar. Spatial resolution is less than 30 meters. Biomass was determined using an allometric equation obtained by others for different species in Europe. The biomass values have not yet been validated against local ground truth, but are consistent with large area samples measured directly. Efforts are underway to obtain the desired data for validation purposes. We hope to replace the demonstration system described with an operational system which should be more appropriate for large area biomass extraction.

ACKNOWLEDGEMENTS

The authors would like to acknowledge their many colleagues at Intermap who have made the L-Band program a reality. We also thank Terrapoint Canada Inc. for providing the Lidar ground truth data. The air photos were acquired under license from Valtus Imagery Services.

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