FOREST HEIGHT ESTIMATION FROM INDREX-II L-BAND POLARIMETRIC INSAR DATA

Q. Zhang [a, *], J.B. Mercer [a], S.R. Cloude [b]

[a] Intermap Technologies Corp., #1200, 555 - 4th Avenue SW, Calgary, AB, Canada T2P 3E7 - (qzhang, bmercer)@intermap.com
[b] AEL Consultants, 26 Westfield Avenue, Cupar, Fife KY15 5AA, Scotland, UK - aelc@mac.com

Commission I, WG I/2

KEY WORDS: Forestry, SAR, Mapping, Vegetation, Estimation, DEM

ABSTRACT:

This paper presents some results of forest canopy height estimation from L-Band polarimetric InSAR data. Three approaches have been tested using a set of PolSARproSim simulated data as well as real data from the INDREX-II campaign. The approaches are: 1) DEM differencing, 2) 2-D search, and 3) Combined. The results show that the DEM differencing approach tends to underestimate the forest height by one third, while the other two approaches can achieve about 90% accuracy when there is sufficient ground return.

1. INTRODUCTION

Forest canopy height is one of the important parameters that can be utilized for purposes of indirect forest biomass estimation allometry [Mette, *et al*., 2004]. Recent advancement in Polarimetric SAR Interferometry (PolInSAR) [Cloude and Papathanassiou, 1998; Papathanassiou and Cloude, 2001; Cloude and Papathanassiou, 2003; Cloude, 2006] has made it possible to estimate the forest height through the use of the Random Volume over Ground (RVoG) model [Treuhaft and Siqueira, 2000; Papathanassiou and Cloude, 2001]. In this paper we will address the problem of tree height estimation using both simulated data [Williams, 2006] and real data from the INDREX-II campaign [Hjansek and Hoekman, 2006].

2. METHODOLOGIES

According to the RVoG scattering model, the complex interferometric coherence $\tilde{\gamma}$, can be written as [Papathanassiou and Cloude, 2001]:

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

where 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 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 and its thickness h_V as expressed in Equation (2).

$$\tilde{\gamma}_V = \frac{\int_0^{hv} \exp(ik_z z')\exp(\frac{2\sigma z'}{\cos\theta_0})dz'}{\int_0^{hv} \exp(\frac{2\sigma z'}{\cos\theta_0})dz'} \tag{2}$$

where K_z is the vertical wave number calculated from the incidence angle (θ) , the difference of two incidence angles from two antennas ($\Delta\theta$) and the wavelength (λ) of the radar system as in Equation (3).

$$K_Z = \frac{4\pi\Delta\theta}{\lambda\sin\theta} \quad \text{radians/meter} \tag{3}$$

The key point of interest for this application is the assumption that m is polarization dependent while $\tilde{\gamma}_V$ is not. Manipulating Equation (1), it can be seen that the complex coherence values will lie upon a straight line as a function of m within the unit circle on the complex plane [Cloude and Papathanassiou, 2003]. In particular, for large m, the straight line intersects the 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. A main objective of much of PolInSAR effort has been to develop robust methods to estimate h_V through an inversion process. In this work, we will be comparing three of these approaches.

In RVoG model inversion, the ground phase ϕ_0 is usually estimated first. This can be achieved by calculating the line-circle intersection on the complex plane [Cloude and Papathanassiou, 2003]. The straight line can be either fitted from a set of observed complex coherences (e.g., lexicographic coherences, Pauli decomposition coherences, and magnitude optimized coherences) or formed by the two ends of the estimated coherence region resulting from phase optimization

---

[*] Corresponding author.

processing [Tabb, *et al.*, 2002]. Forest height is then estimated from the complex coherence of a volume-dominated polarization by inverting Equation (1) with the assumption of *m*=0. This volume-dominated polarization can be the one corresponding to the high phase centre from phase optimization or alternatively, by using HV as an approximation.

We examine three approaches that have been proposed in the literature for forest height estimation: 1) DEM differencing, 2) 2-D search, and 3) Combined approach:

2.1 DEM Differencing

In the DEM differencing approach, the forest height h_v is estimated directly from the phase difference between the ground phase and the volume-dominated polarization phase [Cloude and Papathanassiou, 1998]. This approach enjoys the light computational load and simple implementation effort. However, as pointed out by Yamada *et al.* [2001], this approach tends to underestimate height because the phase centre of the selected volume-dominated polarization is seldom on the top of the canopy.

2.2 2-D Search

Cloude and Papathanassiou (2003) introduced the 2-D search approach, in which, a look-up table (LUT) of complex interferometric coherences as calculated in Equation (1) is established, using a set of extinction coefficient values and forest height values. By finding the closest element in the LUT to the observed complex coherence, we can estimate extinction coefficient and forest height at the same time. Figure 1 illustrates the basic idea of this approach.

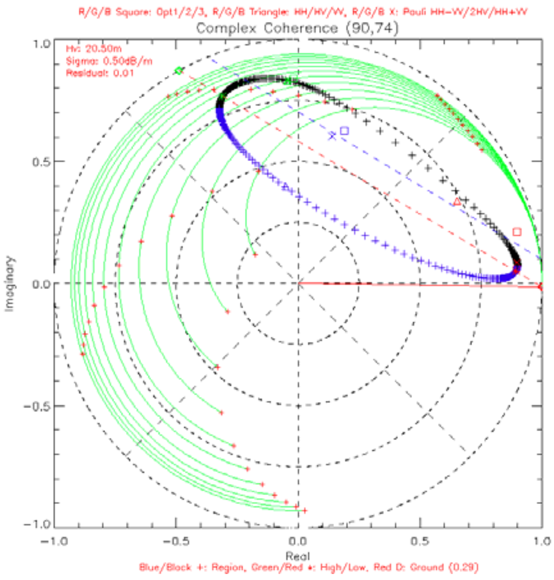

Figure 1. 2-D search approach for tree height estimation (see text).

In Figure 1, the green curves are estimated complex interferometric coherence according to Equation (1) assuming no ground return (m=0) with σ=0,0.1,…,1.0db/m from centre to outer and *hv*=0-40m with 0.5m as step. Red plus marks correspond to tree heights of: 10, 20, 30, and 40m. The black/blue pluses form the coherence region with the green star as the high phase end, which is used for tree height inversion. The closest point on the set of green curves is found by a 2-D array search and the corresponding tree height and the corresponding extinction rate are the inversion results.

One of the disadvantages of this approach is that it is very time consuming especially if a blind search is used and an accurate estimate is desired. A fine LUT (small step size for *hv* and σ) can increase the estimate accuracy but at the same time will significantly increase the computation time. To this end, some information can be used to guide the search and help reduce the searching time. For example, the knowledge of forest height range or the knowledge of extinction rate range, can narrow down the search space.

Another disadvantage of this approach is, if the selected coherence is not volume dominant (i.e. m = 0), then it will not be intersected by one of the LUT curves and the method will fail.

2.3 Combined Approach

An approach which combines elements of the previous approaches was proposed in [Cloude, 2006]. The estimated forest height consists of two terms. The first is from the DEM differencing approach, which tends to underestimate height. The second term provides an adjustment based on the forest height estimated from a zero extinction scenario, which can be directly achieved by inverting a *sinc* function (Equation (4)).

$$hv = \frac{\arg(\tilde{\gamma}_V) - \phi_0}{K_Z} + \varepsilon \frac{2\sin c^{-1}(|\tilde{\gamma}_V|)}{K_Z} \qquad (4)$$

In Equation (4), the first element is just the DEM differencing term, while the second term is an inversion using the coherence magnitude only for the zero extinction case. The second term is weighted by a factor ε which has a constrained range as argued in Cloude (2006).

3. RESULTS

In this research, the forest height estimation results from the three approaches are compared first on PolSARproSim [Williams, 2006] simulated L-Band data and then on repeat-pass L-Band PolInSAR data acquired by German Aerospace Center (DLR) E-SAR system in the European Space Agency (ESA)-sponsored INDREX-II campaign [Hjansek, *et al.*, 2005a]. The INDREX-II campaign was conducted in Novermber 2004 as an experimental airborne radar experiment campaign over Indonesian tropical forest. Some results of forest height estimation from this dataset have been reported in [Hjansek, *et al.*, 2005b; Kugler, *et al.*, 2006; Cloude, *et al.*, 2007]. DEM extraction beneath the forest canopy using this dataset has also been presented in [Mercer, *et al.*, 2007].

3.1 Results from Simulated Data

The PolSARproSim simulator developed by Dr. Mark Williams (Williams, 2006) is used to generate L-Band polarimetric SAR data over a forested area. PolSARproSim is a fully polarimetric-interferometric coherent SAR scattering and imaging simulator. It is distributed as part of ESA's PolSARpro, a polarimetric SAR data processing and educational toolbox. Detailed design document and algorithm specifications can be found in (Williams, 2006). PolSARproSim is capable of generating PolInSAR images with different wavelengths, imaging geometries, ground surface properties, forest types, etc. It is well suited for performing sensitivity analyses with respect to various parameters although it should be noted that is has yet to be validated over a large range of conditions. We have used the simulator to create a number of datasets with different input parameters. For illustration purpose, the cases of 20m Pine tree and 10m deciduous trees over a ground surface with three different smoothness levels are selected as our simulated datasets. Table 1 summarizes the simulation configurations. Note the surface property value is only a scalar number with "0" as smoothest and "10" as roughest. Similarly the ground moisture content value uses "0" for driest case and "10" for wettest case. The outputs of the simulator consist of co-registered SLCs at different polarizations, a flat-earth phase file, and a vertical wave number (*Kz*) file. The *Kz* value for this simulated data is 0.13 Rad/m.

Platform Altitude (m)	3000
Incidence Angle (°)	45
Baseline H / V (m)	10 / 0
Ground Surface Properties	0, 5, 10
Ground Moisture Content	4
Trees Species	Pine 1/ Deciduous
Mean Tree Height (m)	20/10
Forest Stand Density (Stems/Ha)	300/150
Forest Stand Area (Ha)	1

Table 1. PolSARproSim simulation configuration

The results of tree height estimation are shown in Figure 2 for 20m pine tree and Figure 3 for 10m deciduous trees. In both cases, we have three outputs for the three types of ground surface. In Figure 2 and 3, the green and blue solid lines are the phase centers corresponding to the two ends of the coherence region; the red solid line is the estimated ground phase center, and the green and blue dashed lines are the height from: Ground plus Estimated h_V using approach two and three respectively. These profiles are in the range direction with illumination from the left. There appears to be an edge effect – probably from layover – that causes the anomaly at the leading edge of the profiles. We ignore it in this work.

The results show that when the ground surface is smooth, permitting strong dihedral return, (or in another words, when the ground contribution is large enough), the phase optimization algorithm works well in estimating the ground elevation for both types of trees. Subsequently, three tree height estimation algorithms gave a quite encouraging result. The DEM differencing approach estimated about 70% of the designed h_V, while the other two estimated about 90% with very similar performance (See Table 2).

When the ground contribution becomes less, the estimation of ground elevation becomes worse, as expected. This in turn reduces the tree height estimation accuracy. In case (c) where there is almost no ground return, the topographic phase estimate is biased and noisy. Without 'a priori' ground information in this case, the derived canopy height will be severely underestimated and noisy.

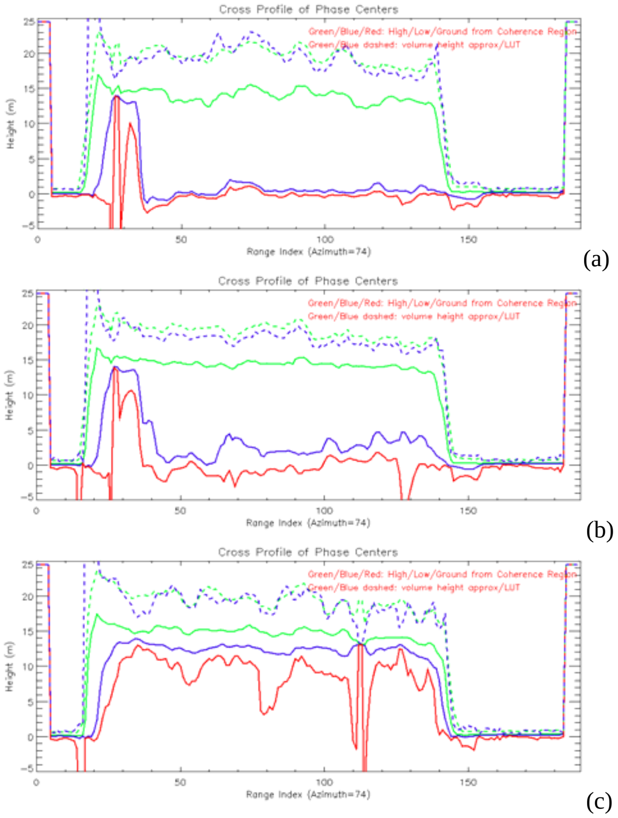

Figure 2. Volume height estimation results from PolSARproSim simulated dataset for 20m pine tree: a) top - smooth ground surface; b) middle - medium rough ground surface; c) bottom - rough ground surface (See text).

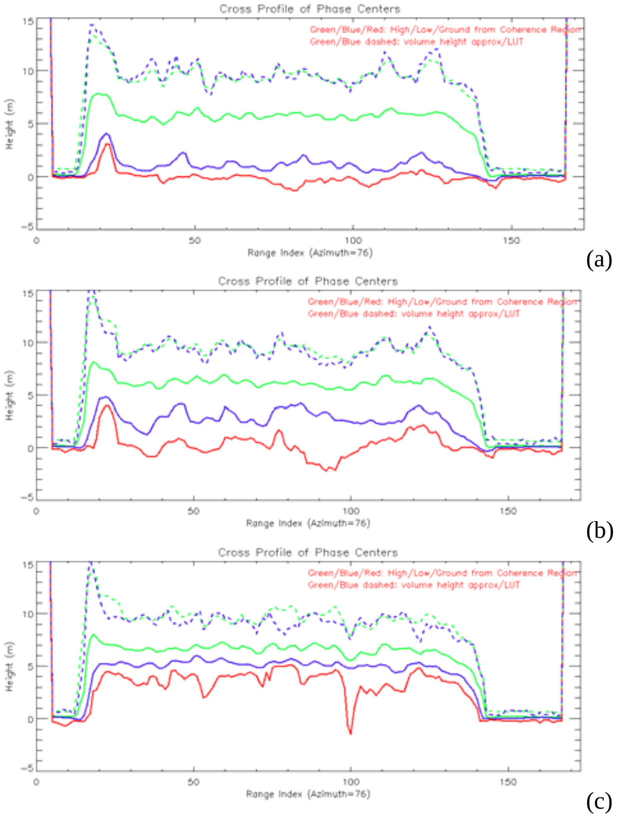

Figure 3. Volume height estimation results from PolSARproSim simulated dataset for 10m deciduous tree: a) top - smooth

ground surface; b) middle - medium rough ground surface; c) bottom - rough ground surface (see text).

Dataset	Ground Roughness	Appr. Two	Appr. Three
20m Pine	Smooth	19.7±2.2m	19.4±2.4m
	Median rough	17.8±1.9m	18.8±2.0m
	Rough	9.9±2.3m	10.0±2.0m
10m Deciduous	Smooth	9.6±0.9m	9.6±0.8m
	Median rough	9.0±0.9m	9.1±1.0m
	Rough	5.6±1.2m	5.9±0.8m

Table 2. Estimated tree height from PolSARproSim simulated datasets

3.2 Results from INDREX-II Data

In November 2004, DLR conducted an ESA-sponsored airborne radar campaign over Indonesian tropical forest, called INDREX-II (Hjansek, *et. al.*, 2005a). Data from that campaign has subsequently been made available by ESA. We selected one of the test sites called Mawas-E as our study area because of its flat topography and the availability of measured tree height samples. The area is a tropical peat swamp forest located in Kalimantan, Indonesia. The L-/P-Band InSAR data were acquired by DLR's E-SAR system in a quad-pol, repeat-pass mode along with single-pass X-Band data.

Figure 4 shows a subset of the X-Band amplitude image acquired in the same campaign over the Mawas-E test site. The area is flat and there is a clear transition from bare area to forest area moving from west to east (from left to right in Figure 4). The left part of the image is a bare or low vegetated area, where we can expect the X-Band DSM (Digital Surface Model) is close to the ground thus we can use this area to normalize or validate the DEMs derived from L- or P-Band data.

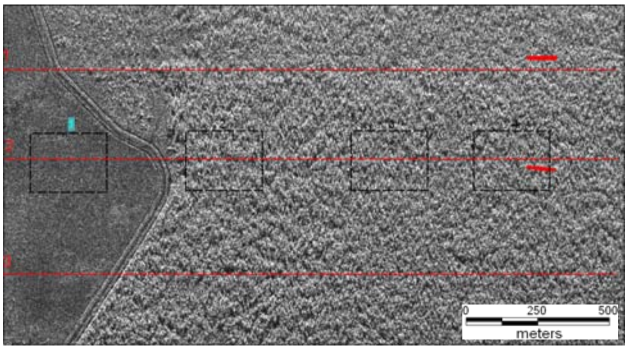

Figure 4 Selected ROI on X-Band image: The two red short lines on the right hand side of the image are two tree transects. The tree height measurements were carried out concurrently with the data acquisition campaign (see Figure 4, the two red short lines in the right hand side of the image). According to the ground measurement, there are more than half of the measured trees that are short, thin and branchless, which form a very dense understory with a height ranging from 2m to 8m and a spacing around 1m. Trees with branches are about 17m high on average. Figure 5 also shows two of the ground photos taken in the forest near the tree transect. The photos show that the taller trees have branches and large canopy crowns while the understory consists of branchless, thin, and relatively shorter trees.

To quantify the average forest height, the two tree measurement sites, each 100 meters long by 10 meters wide, are divided into non-overlapping 10mx10m subplots, resulting in 10 subplots for north site and 10 for south site. The highest measured tree height in each subplot is defined as h_{100} (Mette, *et. al.*, 2004). In addition, as a second check in the case of h_{100} not being representative of the canopy, the second highest measured tree height in each subplots is also determined and called h'_{100}. The forest in the test site can be described as "undisturbed peat swap forest" and is relatively dense, high, and uniform (Hajnsek and Hoekman, 2006). Therefore, the canopy height seen by a radar system over each subplot can be represented by either h_{100} or h'_{100}. Figure 6 gives h_{100} and h'_{100} as measured from tree transects. The average h_{100} value is about 23m, while the average h'_{100} value is about 20m. The latter values show a smaller spread in heights.

Figure 5 Ground photos of the forest

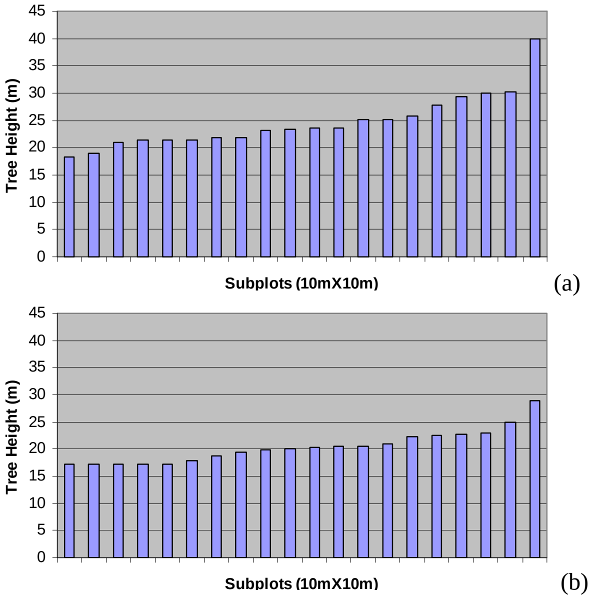

Figure 6 h_{100} height (a) and h'_{100} height (b) as measured from tree transects (see text).

The phase optimization and three tree height estimation approaches were applied to L-Band 10m baseline dataset. Figure 7 shows the outputs from the three approaches. The statistics of the estimated tree height around the tree transect area is given in Table 3.

Appr. One	Appr. Two	Appr. Three
8.5±4.2m	18.7±6.1m	17.5±4.2m

Table 3. Estimated tree height from INDREX-II Data

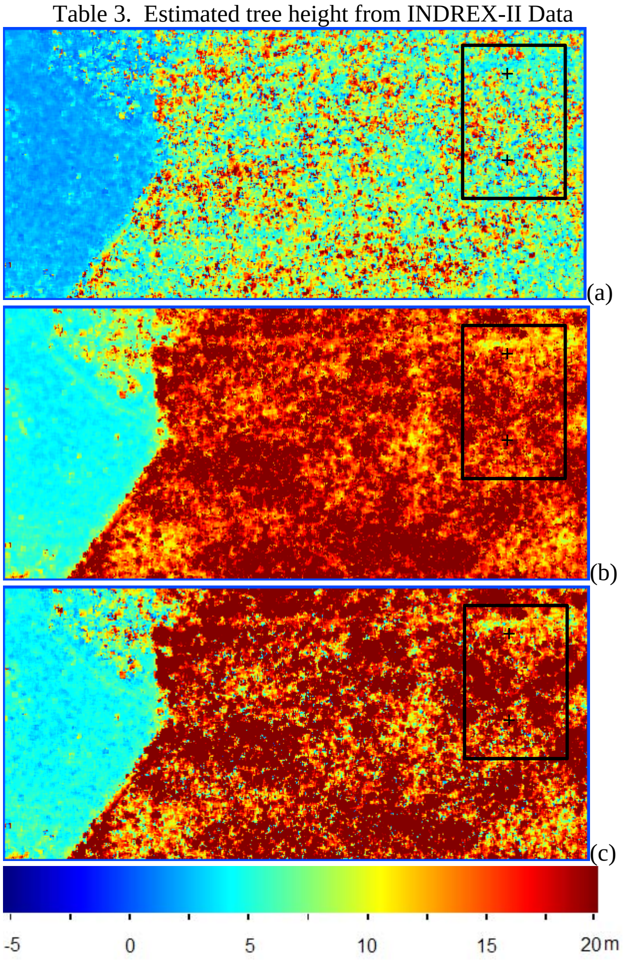

Figure 7 Estimated forest height from INDREX-II data using three approaches: (a) DEM differencing; (b) 2-D search; (c) Combined. The region inside the black box is used for statistics. The two "+" signs are the locations of two tree transects.

From Figure 7 and Table 3, it is observed that, assuming the average tree height in the region is 20m (i.e., $< h'_{100}>$), the DEM differencing approach is estimating about 42% of $<h'_{100}>$. The 2-D search approach gives the best result, 95% and the combined approach 88%. This is at a similar level to the results from the simulated dataset. If the results, on the other hand, are referenced to $<h_{100}>$ rather than $<h'_{100}>$ an additional 3 meter underestimate is observed. At this point there is no strong argument to prefer the one metric over the other as the more representative canopy height.

However, the estimated tree height from INDREX-II L-Band dataset is much noisier than those from simulated dataset mainly due to the noisier estimation of ground elevation. Although space precludes showing them here, the elliptical regions estimated from this dataset are typically much smaller, with lower coherence, rounder appearance and show an apparent lack of dihedral bounce. Two major contributors to this are likely: (1) temporal decorrelation, (2) the dense understory of the forest, which may act to attenuate the dihedral response of the larger trees. Consequently the phase separation was reduced resulting in poorly shaped coherence regions and inaccurate estimation of ground phase. This has been observed in results from other PolSARproSim simulated datasets, where the ground roughness was increased such that dihedral return was severely limited. In these instances, the calculated coherence region becomes more circular and the resulting ground phase projections become noisier. This in turn affects the forest height estimation.

4. CONCLUSIONS

Three different approaches to forest height estimation have been tested on both simulated and real L-Band PolInSAR data. The results from the simulated data are quite encouraging. The forest height estimated by the DEM differencing is normally underestimated at a level of about 2/3 of the true forest height. The results from the other two approaches are very similar to each other and are within about 10% of the simulated canopy height provided that ground return (dihedral bounce) is adequate. It should be noted that with the simulated data set, there are no negative effects caused by temporal decorrelation or other factors associated with real data.

The results from real data are compared against ground measurements. It is concluded that the estimated forest height from 2-D search approach is quite close to the average h'_{100}, roughly within 10% error. The combined approach is slightly worse than the 2-D search approach, getting about 15% but with a significant reduction in the computational load. On the other hand, the height estimates from real dataset are considerably noisier and less robust than for the simulated data. It is suggested that the comparative noisiness and additional biases are due to some temporal decorrelation of the repeat pass data, and to additional attenuation of the signal in the lower part of the canopy due to a dense understory that is not incorporated into the RVOG model.

ACKNOWLEDGMENT

We thank European Space Agency for providing the data, Alberta Ingenuity Fund for partial financial support, and Dr. Mark Williams for valuable comments regarding PolSARproSim.

REFERENCE

Cloude, S.R., Papathanassiou, K.P., 1998. Polarimetric SAR Interferometry, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 36, No.5, pp.1551-1565.

Cloude, S.R., Papathanassiou, K.P., 2003. Three-stage inversion process for polarimetric SAR interferometry, *IEE Proceedings - Radar Sonar Navigation*, Vol. 150, No. 3, pp.125-134.

Cloude, S.R., 2006. Polarization coherence tomography, *Radio Science*, Vol. 41, RS4017, 2006.

Cloude, S.R., Zhang, Q., Mercer, B., 2007. Tropical Forest Structure Estimation using L-Band Polarization Coherence Tomography (PCT). *Proceedings of 5th International Symposium on Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications.* September 25-28, 2007, Bari, Italy.

Hjansek, I., Kugler, F., Papathanassiou, R., Scheiber, K., Horn, R., Moreira, A., Hoekman, D., Davidson, M., Attema, E., 2005a. INDREX II – Indonesian Airborne Radar Experiment

Campaign Over Tropical Forest in L- and P-Band, *Proceedings of PolInSAR 2005*, January 17-21, 2005, Frascati, Italy.

Hjansek, I., Kugler, F., Papathanassiou, K., Horn, R., Scheiber, R., Moreira, A., Hoekman, D., Davidson, M., 2005b. INDREX II – Indonesian Airborne Radar Experiment Campaign Over Tropical Forest in L- and P-Band: First Results, *Proceedings of IGARSS 2005*, V6, pp.4335-4338, July 25-29, 2005, Seoul, Korea.

Hajnsek, I., Hoekman, D., 2006. INDREX-II – Indonesian Radar Experiment Campaign over Tropical Forest in L- and P-band, *ESA Final Report*, 142 pages.

Kugler, F., Papathanassiou, K., Hajnsek, I., Hoekman, D., 2006. INDREX-II – Tropical Forest Height Estimation with L and P Band Polarimetric Interferometric SAR, *Proceedings of EUSAR 2006*, May 16-18, 2006, Dresden, Germany.

Mercer, B., Zhang, Q., Lumsdon, P., 2007. L- And P-Band Polarimetric InSAR for DEM Extraction Beneath Tropical Canopy Using INDREX-II Data Sets. *Proceedings of Advanced SAR Workshop 2007*, September 11-13, 2007, Vancouver, Canada.

Mette, T., Papathanassiou, K., and Hajnsek, I., 2004. Biomass estimation from polarimetric SAR Interferometry over heterogeneous forest terrain, *Proceedings of IGARSS 2004*, pp. 511-514, Anchorage, Alaska, USA. September 20-24, 2004

Papathanassiou, K.P. and Cloude, S.R., 2001. Single-Baseline Polarimetric SAR Interferometry, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 39, No.11, pp.2352-2363.

Tabb, M., Orrey, J., Flynn, T., Carande, R., 2002. Phase Diversity: A Decomposition for Vegetation Parameter estimation using Polarimetric SAR Interferometry, *Proceedings of EUSAR 2002*, pp. 721-724.

Treuhaft, R.N., and Siqueira, P.R., 2000. The vertical structure of vegetated land surfaces from interferometric and polarimetric radar. *Radio Science*, Vol. 35, No. 1, pp. 141-177.

Williams, M., 2006. PolSARproSim Design Document and Algorithm Specification. *http://envisat.esa.int/polsarpro/Manuals/PolSARproSim_Design.pdf*, last accessed on September 10, 2007.

Yamada, H., Yamaguchi, Y., Rodriguez, E., Kim, Y., and Noerner, W.M., 2001. Polarimetric SAR interferometry for forest canopy analysis by using the super-resolution method. *IEICE Trans. Fundam. Electron. Commun. Computer. Sci.*, 84(12), pp. 1917-1924.