Forest Height Estimation in Tropical Rain Forest using Pol-InSAR Techniques

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Abstract— **Tropical rain forest environments are highly complex and heterogeneous in terms of species composition and structure and is often difficult to access. Radar remote sensing is for large tropical regions the only available information source for monitoring. Pol-InSAR is a novel developed radar remote sensing technique sensible to the vertical structure of forest that allows the estimation and mapping of forest height. In this paper we demonstrate forest height inversion at two frequencies - L Band and P Band – by means of Pol-InSAR using INDREX-II data and addresses the problem of temporal decorrelation**

Keywords-component: Polarimetric SAR Interferometry, (Pol-InSAR), Forest height estimation, Temporal decorrelation, Tropical forests, INDREX-II

I. INTRODUCTION

In the frame of the ESA sponsored INDREX II campaign [3], [7] a wide range of SAR data over tropical forest conditions were acquired in Indonesia. The selected test sites include typical forest formations of South East Asia like peat swamp forests and lowland dipterocarp forests which are the most important regional forest types. Forest was mapped in a multi-frequency (X- C- L- and P-band) interferometric (X-band) or fully polarimetric interferometric (L- and P-band) mode. The latter allows forest height estimation by means of POl-InSAR techniques [1] [2].

Indeed, forest height estimation form polarimetric single- and/or multi-baseline data has been demonstrated in a series of airborne experiments over a variety of natural and commercial; temperate and boreal test sites by different stand and terrain conditions [4]. However the performance over tropical forest conditions could not been validated due to the lack of suitable data.

In order to close this gap, one of the main scientific questions faced in INDREX-II was to determine if L Band radar signal penetrates the dense tropical forest down to the ground and if Pol-InSAR techniques can be used for the mapping of tropical forest heights. In [5] and [6] and the applicability of INDREX II data for forest height estimation in tropical forest was proofed and preliminary results were presented.

In the following inversion results of P and L Band will be compared. In a second step, a dual frequency approach (using X Band) for the detection of temporal decorrelation will be introduced.

II. TEST SITES

The first test site estimated is the Sungai Wain forest located close to the city of Balikpapan in East Kalimantan, Indonesia. It is typical lowland Dipterocarp forest with biomass levels up to 400t/ha and tree heights up to 60m. Sungai Wain is situated in a hilly terrain with steep slopes. Big areas burnt during the El Nino events 1982 and 1998 are now covered with Macaranga forest, a secondary forest type.

The second test Site is Mawas, in central Kalimantan. This region includes several large (ombrogenous) peat domes covered by tropical peat swamp forest types. Typically these vary gradually from a relatively tall (30 m) and dense forest at the edges towards small (15 m or lower) and open forest types at the centre of a dome with biomass levels from 20 to 250 t/ha. The terrain is quite flat.

III. POL INSAR HEIGHT INVERSION

It is known that the (complex) volume decorrelation contribution $\tilde{\gamma}_V$ of the interferometric coherence is directly linked to the vertical distribution of scatterers F(z) through a (normalized) Fourier transformation relationship [8].

$$\tilde{\gamma}_V = exp(i\kappa_z z_0)\frac{\int_0^{h_V} F(z')exp(i\kappa_z z')dz'}{\int_0^{h_V} F(z')dz'} \qquad (1)$$

where κ_z is the effective vertical (interferometric) wavenumber that depends on the imaging geometry and the radar wavelength λ

$$\kappa_z = \frac{\kappa\Delta\theta}{sin(\theta_0)} \qquad \text{and} \qquad \kappa = \frac{4\pi}{\lambda} \qquad \text{-2)}$$

and $\Delta\theta$ is the incidence angle difference between the two interferometric images induced by the baseline. z_0 is a reference height.

The estimation of vertical forest structure parameters from interferometric measurements can be addressed as a two step process: In the first step (*modelling*) *F(z)* is parameterized in terms of a more or less limited set of physical forest parameters that are related through Eq. 1 to the interferometric coherence. In the second step (*inversion*), the volume contribution of the measured interferometric coherence is then used to estimate *F(z)* and to derive the corresponding parameters. A widely and successfully used model for *F(z)* is the so called Random Volume over Ground (RvoG), a two layer model consisting of a volume and a ground layer [9][1]

$$F(z)=\tilde{m}_V \exp\left(\frac{2\sigma}{\sin(\theta_0)}z\right)+m_G\delta(z-z_0) \qquad \text{-3)}$$

where m_V and m_G are the ground and volume scattering amplitudes and σ a mean extinction coefficient. Eq. 7 leads to

$$\tilde{\gamma}_V=\exp(i\kappa_z z_0)\frac{\tilde{\gamma}_{V0}+m}{1+m} \qquad \text{-4)}$$

where $\varphi_0=\kappa_z z_0$ is the phase related to the ground topography z_0 and m the effective ground-to-volume amplitude ratio accounting for the attenuation through the volume

$$m=\frac{m_G}{m_V I_0} \qquad \text{-5)}$$

$\tilde{\gamma}_{V0}$ is the volume decorrelation caused in the absence of the ground layer (i.e. $m_G=0$)

$$\tilde{\gamma}_{V0}=\exp(i\kappa_z z_0)\frac{\int_0^{h_V}\exp(i\kappa_z z')\exp\left(\frac{2\sigma z'}{\cos\theta_0}\right)dz'}{\int_0^{h_V}\exp\left(\frac{2\sigma z'}{\cos\theta_0}\right)dz'} \qquad \text{-6)}$$

Neglecting temporal decorrelation and assuming a sufficient calibration/compensation of system (e.g. SNR) and geometry (range/azimuth spectral shift) induced decorrelation contributions Eq. 4 can be inverted in terms of a quad-pol single baseline acquisition [1], [2]. In this case the (regularised) inversion problem is balanced with five unknowns $(h_V,\sigma,m_{1-2},\phi_0)$ and three measured complex coherences $[\tilde{\gamma}(\vec{w}_1)\ \ \tilde{\gamma}(\vec{w}_2)\ \ \tilde{\gamma}(\vec{w}_3)]$ each for any independent polarization channel providing estimates for forest height [2].

$$\min_{h_V,\sigma,m_i,\phi_0}\left\|\left[\tilde{\gamma}(\vec{w}_1)\ \ \tilde{\gamma}(\vec{w}_2)\ \ \tilde{\gamma}(\vec{w}_3)\right]^T-\left[\tilde{\gamma}_V(h_V,\sigma,m_1)\ \ \tilde{\gamma}_V(h_V,\sigma,m_2)\ \ \tilde{\gamma}_{Vo}\exp(i\phi_0)\right]^T\right\| \qquad \text{-7)}$$

Eq. 7 is used to invert INDREX-II data sets at L- and P-band presented and discussed in the following.

IV. INVERSION RESULTS IN L AND P BAND

The inversion has been applied on the Pol-InSAR data sets acquired over the Sungai Wain site for each frequency individually: at L-band using the 10m spatial baseline and at P-band using the (equivalent in terms of wavelength scaling) 30m spatial baseline. The impact of frequency on the inversion of Eq. 7 is discussed in [11]. From the inversion process areas affected by geometrical and coherence constrains have been excluded as described in [5] and [6]. A detail of the obtained forest heights is shown in Figure 1. scaled from 0 to 60m masked areas are black. Comparing the results at both frequencies, no significant differences appear. Both images cover the same height range and reflect a similar forest height structure. As the mask applies in both images at different pixels a direct comparison between L and P Band can only be performed at points where both inversions deliver reliable results which are the condition for the following analysis.

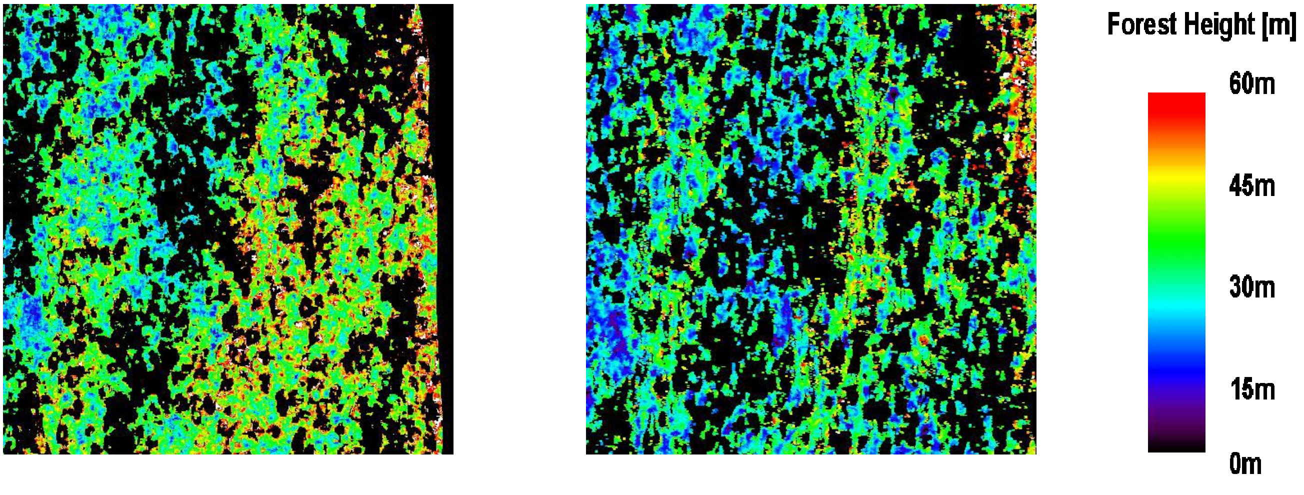

Figure 1. Detail of height map for the Sungai Wain forest: left: L-band 10m baseline, right: P-band 30m baseline; maseked areas are black;.

Figure 2. presents a pixel based comparison between L and P Band heights. Both measurements are obviously well correlated. The correlation is about 0.84 (i.e. P Height = 0.84 L Height). This means that the height estimates in P Band are about 16% lower than at L Band. The corresponding histograms are shown in Figure 3. for both frequencies: They follow almost a Gaussian distribution with mean value at L Band of about 34m and at P Band about 29m.

Thera are two possible reasons for this behaviour: The first one is the reduced sensitivity of P band to (volume) height variations caused by the low extinction values. This can lead to an underestimation of forest height at P-band in less dense forest environments. The second one is the impact of temporal (or other) decorrelation at the L-band that can lead to an overestimation of forest height.

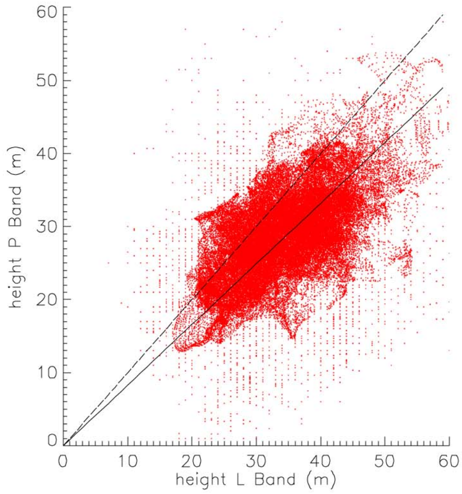

Figure 2. L Band vs. P Band height estimates (low pass filtered)

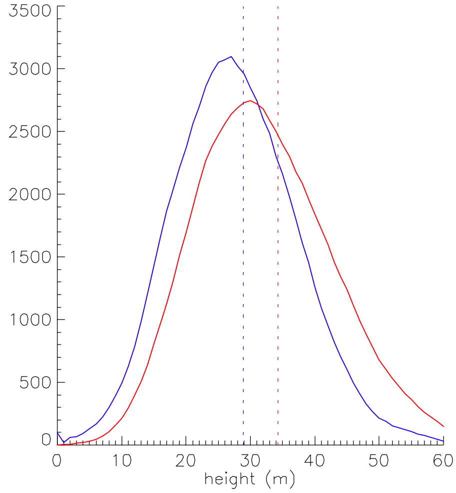

Figure 3. Height histograms at L Band (red) and P Band (blue); Mean: L Band=34m, P Band=29m; Maximum: LBand=30m, PBand=27m

V. TEMPORAL DECORRELATION

As INDREX-II was performed at the beginning of the rainy season some of the data acquisition flights had to be performed under windy conditions. In consequence, some of the repeat-pass acquisitions (at L and P Band) especially in the Mawas test site are affected by wind induced temporal decorrelation. Assuming a scalar temporal decorrelation that affects only the volume (canopy) part and the measured interferometric coherence becomes according to [10]

$$\tilde{\gamma}(\vec{w}) = exp(i\kappa_z z_0)\frac{\gamma_{Temp}\tilde{\gamma}_{V0} + m(\vec{w})}{1+m(\vec{w})} \qquad \text{-8)}$$

An inversion by means of Eq. 6 without accounting for γ_{Temp} leads to a critical overestimation of forest height [10].

One way to evaluate γ_{Temp} is to make use of the available single-pol (VV) single-pass X-band acquisition as it is unaffected by temporal decorrelation. The high extinction values at X-band allows a simplification *F(z)* by ignoring completely the ground scattering component (assuming *m=0)* and fixing the extinction to a given (non-zero) value. This leads to a determined inversion problem [11]

$$\min_{h_V,\phi_0} \left\| \tilde{\gamma}^X(\vec{w}) - \tilde{\gamma}_V^X(h_V,\phi_0 \,|\, \sigma=\sigma_0) \right\| \qquad \text{-9)}$$

Eq. 9 can be further reduced to a single parameter problem by neglecting the ground phase

$$\min_{h_V} \left\| \; |\tilde{\gamma}^X(\vec{w})| - |\tilde{\gamma}_V^X(h_V,\phi_0 \,|\, \sigma=\sigma_0)| \; \right\| \text{-10)}$$

Eq. 10 can be inverted by a single interferometric channel providing forest height estimates. Of course a generalisation of Eq. 10 is critical: The maximum volume height that can be estimated is limited by the penetration depth that decreases with increasing extinction. With further increasing height the interferometer do not "see" anymore the whole volume and the height estimation "saturates". However, the Mawas test site is characterised by very low and less dense forest conditions leading to moderate extinction values for X-band.

The obtained forest height estimates are now used to approximate the volume decorrelation contribution at L- (and P-) band for the HV channel. Assuming a zero extinction (i.e. $\sigma_L = 0$) and a zero ground scattering (i.e., $m(HV)=0$) the volume decorrelation is given by

$$|\tilde{\gamma}_V^L(HV)| = |\tilde{\gamma}_{V0}^L(HV)| = sinc(\frac{\kappa_z^L h_V}{2}) \qquad \text{-11)}$$

where *sinc(x)=sin(x)/x.* Having an estimate of the (absolute) volume decorrelartion contribution at *HV* permits now to estimate the temporal decorrelation contribution at L- (and P-) band.

$$\gamma_{Temp} = |\tilde{\gamma}(HV)| / |\tilde{\gamma}_{V0}^L(HV)| \qquad \text{-12)}$$

Figure 4. *Estimated temporal decorrelation of* L Band (left) and P band (middle) for the Mawas test site: scaled from black: γ_{Temp}=0 to white: γ_{Temp}=1; Histogram of estimated γ_{Temp} (from 0.6 to 1): L Band=red, P band=blue.

The obtained γ_{Temp} maps with the corresponding histograms are shown in Figure 4. At L-band γ_{Temp} is about 0.90 while at P-band it is 0.95 – as expected – lower at about 0.05. The temporal baseline was about 20 minutes for both frequencies.

Note that a potential underestimation of the forest height used in Eq. 11 (because of saturation for example) will bias the volume decorrelation estimation and leads to an underestimation of the temporal decorrelation. In contrary, an overestimation of the forest height (due to an underestimated extinction) will lead to an overestimation of the temporal decorrelation or even to ratios larger than one.

The localised high decorralation "points " visible at L-band and even more at P-band are due to single large trees that are underestimated when inverting the X-band coherence leading therefore to high temporal decorrelation retions.

VI. CONCLUSIONS

In this study forest heights at L Band and P Band were shown. Comparing both results L Band estimations where in average approximately 5m higher than P Band results. This effect could be caused by an insensitivity of P Band to small twigs and branches (sees in general not the complete forest height) and by a higher sensitivity of L Band to decorrelation effects which generates a bias resulting in overestimated heights.

In the second part a dual frequency (X Band in combination with L or P Band) approach for the detection of temporal decorrelation was introduced. Whereas this method is only applicable if the X Band signal contains a ground contribution

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