Tropical Forest Mapping using Multiband Polarimetric and Interferometric SAR Data

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Abstract

The potential of the combined use of multi-band polarimetric and interferometric airborne SAR for tropical forest mapping are discussed using the NASA/JPL AirSAR data from the PacRim-2 2000 campaign in Indonesia. Through orthorectification of the C-, L- and P-band fully polarimetric images, an accurate geometrically registration to the L-band VV-polarisation interferometric images was achieved. This fusion allows accounting for the disturbing effects of relief on the backscatter level in the fully polarimetric classification procedure applied. It will be shown that many forests types and the effects of forest fire thus can be accurately mapped, even in hilly terrain. This will be demonstrated by the analysis of large independently acquired ground truth data sets of land cover observations. In addition biomass and vegetation height data were collected for a large number of forest transects and several non-forest plots. Empirical relations with L- and P-band backscatter, and C- and L-band interferometric coherence and height, will be presented.

1. INTRODUCTION

There is a high level of interest in utilising Polarimetric Synthetic Aperture Radar (PolSAR) and Interferometric Synthetic Aperture Radar (InSAR) imaging for the inventory and monitoring of forest in Indonesia. It has historically been very difficult to obtain airborne aerial photographs or optical satellite imagery, which are currently applied on a routine basis, because of cloud, haze or smoke or hilly terrain [1]. Hence, PolSAR and InSAR data may be a viable alternative if the required information can be extracted from the data. At present there is little experience with the use of imaging PolSAR and InSAR radar data for this field of application.

Objective information derived from PolSAR and InSAR data could be potentially useful for numerous applications within the forest management community. Airborne PolSAR and InSAR are new techniques, which can be used to estimate forest parameters, such as: tree position, number of trees, crown dimension, land cover type, forest type, biomass level, vegetation height, etc. These parameters are of prime importance in forestry applications, environment and climate studies. When measured at a sufficiently high level of accuracy, these techniques are very attractive for operational implementation.

The main objective of this study is to evaluate tropical forest mapping and biomass estimation using new generation C-, L- and P-band fully polarimetric and C-, L-band Interferometric NASA/JPL AirSAR/TopSAR data. A model to compensate for the effect of relief on polarimetric signals of forest vegetation was applied. In general new models to improve land cover classification accuracy of the PolSAR data are needed and evaluated to understand the interaction of the radar waves and the vegetation giving the basis for accurate classification of PolSAR images. Polarimetric techniques developed for PolSAR mapping [2] using data collected in Colombia during the AirSAR 1993 deployment, will be tested on Indonesian PacRim-2 PolSAR data and integrated with InSAR data. It is assumed that the same method can be applied with some modification. A variety of polarization combinations will be investigated for application in forest cover type mapping and biomass classification. This work is a collaboration research of the Indonesian Ministry of Forestry and Estate Crops, the Tropenbos Foundation, Gibbon Foundation and Wageningen University, The Netherlands.

2. TEST SITE AND DATA SET DESCRIPTION

For this purpose a study area was chosen in an area of tropical rain forest, featuring a large variability of land cover and topographic conditions, in the surroundings of Balikpapan City, East-Kalimantan province, in Indonesia. Situated around central co-ordinates 0° 83’ latitude south and 116° 76’ longitude east, the study area is characterised by a complex mosaic of vegetation and land cover types, resulting from the natural conditions of the region, as well as from human activities that have changed the primary vegetation partially or totally. Consequently, it is possible to find areas with slopes
between 8% and 30% and elevation between 50 - 150 m above sea level, covered by variety of primary forests including Dipterocarp unburnt and burnt, secondary forest, areas of mangrove, etc.

The fieldwork data sets contain several selected areas. Global Positioning System (GPS) measurements and several photographs are also acquired to support analysis for accuracy assessment and validation of classification models. The intensive observations for the purpose of biomass measurement were made for 9 primary forests unburnt, 9 primary forests burnt and 7 secondary forests, each 4,000 m². An allometric equation calibrated for the East-Kalimantan province [3] was applied to estimate total above ground wet biomass using trunk diameter and height to the first living branch. Details on the PacRim-2 data base and ground data collection can be found in [4].

For investigation of the C-, L- and P-band polarimetric (HH, HV, VH and VV polarisation combinations) and interferometric C- and L-band data the AirSAR/TopSAR acquisition of September 14, 2000 will be used. The radar data used in this study are from the second generation AirSAR system [5]. It is an experimental airborne SAR, using three frequency bands and is fully polarimetric. The training set samples consist of 34 delineated areas of at least 70 pixels in a 29°-61° range of incidence angles. The field averaged Stokes scattering element data of the database is used to calculate field averaged values for backscatter, phase difference and correlation.

3. APPROACH

The usefulness of Digital Elevation Model (DEM) derived from InSAR and certain combination of frequency bands, polarization, polarimetry and the effect of speckle have to be evaluated for tropical forest mapping application. This was done in several steps, which will be described briefly.

3.1 The Effect of Relief Canopy Surface Geometry

It is well known that airborne Synthetic Aperture Radar (SAR) images are based on the principle of range differences between the objects and sensor for a certain scanline. Because of the imaging mechanism of radar signals small relief differences can be perceived well, notably at small grazing angles. For an opaque isotropic volume scatterer, $\gamma$ (gamma) does not depend on grazing angle, but will depend on the slope of the vegetation surface (Fig 1.i). Processing algorithms to compute $\gamma$ start from the assumption that the terrain is flat, and hence assume the intercepted power is proportional to $1/2 \cdot c \cdot \tan(\theta)$. In fact, it is proportional to $1/2 \cdot c \cdot \tan(\theta + \alpha)$ (Fig 1.ii), where $\alpha$ is the angle of slope in range direction [6] which can be derived from InSAR data. The value of $\gamma$ in the processed image is therefore related to the value of $\gamma_f$ for an identical object with the upper surface oriented parallel to the horizontal plane, as

$$\gamma = \gamma_f \cdot \frac{\tan(\theta + \alpha)}{\tan(\theta)}$$  \hspace{1cm} \text{Eq. 1}$$

It can be shown that when undulations have been averaged out, for this model the linear average of $\gamma$ is independent of the degree and location of slopes.

3.2 Forest Cover Type Classification

To evaluate the classification capacities of the attributes estimated from the AirSAR image, a data base was created for C-, L- and P-band polarimetric data and slope correction image based on L-band interferometry. The polarimetric classification technique introduced in [2] is exploited to assess AirSAR’s potential for forest cover type mapping and biomass classification. The classification results can be simulated as a function of the number of independent looks, a fully polarimetric multi-band approach to classification and introduces probability density functions (pdf) for multi-look samples of a certain class, for intensity, phase difference as well as coherence magnitude. The effect of speckle is introduced in the simulated classification by using the field average values and random derived samples from the theoretical distributions, increasing the number of samples to be classified and resulting in wider distributions. The Kolmogorov-Smirnov tests of fit can be used to test the deviations from the model of the distributions after adding speckle. The maximum likelihood (ML) classification of an observation to be classified as a certain class is the product of the joint Gaussian distributions of the
backscatter multiplied by the likelihood of the phase difference values and the likelihood of the correlation values. The confusion matrix, the overall classification accuracy and the confusion between pairs of classes can be calculated for each simulated classification. The evaluation of the classification capacities was done through the analysis of the classification result, specifically the contingence tables and Kappa statistics for simulations performed for a single channel, combination of two and three channels and full polarimetric information. It is important to notice that a contingence table gives a measure of the overall classification accuracy and presents errors of commission and omission while the Kappa statistic is used to compare between classification results.

Fig 1. i) For an opaque isotropic volume scatterer, $\gamma$ is independent of grazing angle $\theta$ (case a and b) and dependent on slope $\alpha$ (case c). ii) Measurement geometry for a flat surface (of the canopy) and a tilted surface in range direction.

4. RESULTS AND DISCUSSION

4.1 Backscatter Analysis

Using 10 samples in Primary forest unburnt and burnt, 7 secondary forest and 9 mangrove forest, an analysis of the averaged backscatter value obtained for each forest cover type before and after slope correction is shown in Fig 2. In general C-band has higher $\gamma$ values. C-band reflection is high when a layer of green leaves is present. L- and P-band radiation penetrates deeper and reflection is high when living trunks are present.

For L-band there is a clear distinction between each cover type especially for primary forest unburnt and burnt parts. In C-band there is no contrast at all. Although most areas are located in undulating terrain, the effect of slope correction has very little difference. That can be explained by the fact that sample areas are in the $29^\circ$-61$^\circ$ incidence angle range. There is no difference of slope effect in Mangrove area for all band and polarisation because the area is flat. Secondary forest has variation because of mixed vegetation as remnants of fire events and some isolated high trees that survived.

Fig. 2 Averaged backscatter in C-, L- and P-band for mangrove, primary forest (unburnt), primary forest burnt and secondary forest.
4.2 Forest Cover Type Classification

The simulated classification results before and after slope correction for the four forest cover types (primary forest unburnt, primary forest burnt, secondary forest and mangrove) using a single and multi channel combination at 0.5 dB speckle level and 95% level of confidence are shown in the Table 1.

Classification using only the information provided by a measurement of $g$ for a single channel shows very low overall classification accuracy, ranging from 38.40% for C-HH to 68.57% to L-HH. In general the single channel C-band classifications have the lowest accuracies although tend to increase after slope correction. That does not significantly increase the accuracy and thus seems not suitable for forest cover type classification. The result obtained using $g$ values for two or three channels and fully polarimetric information (phase difference and polarimetric correlation) shows an increase in the overall classification accuracy. The values range from 85.91% for C-int + L-int (‘int’ means intensity in HH+VV+HV) to 90.71% for C-pol + L-int + P-int and also tend to improve after slope correction.

Table 1. Overall Maximum Likelihood (ML) classification accuracy (in %) at the 95% confidence level for a selection of combination at 0.5 dB speckle level, the statistic Kappa and large sample variance of Kappa.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Before</th>
<th>After</th>
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<tbody>
<tr>
<td></td>
<td>$\widehat{K}$</td>
<td>$\widehat{\sigma}^2$</td>
</tr>
<tr>
<td>C-int, P-pol</td>
<td>88.23</td>
<td>0.84580</td>
</tr>
<tr>
<td>C-int, L-pol</td>
<td>87.77</td>
<td>0.84026</td>
</tr>
<tr>
<td>C-pol</td>
<td>63.17</td>
<td>0.51821</td>
</tr>
<tr>
<td>C-int</td>
<td>60.46</td>
<td>0.48310</td>
</tr>
<tr>
<td>L-HH</td>
<td>68.57</td>
<td>0.57739</td>
</tr>
<tr>
<td>C-int, L-int</td>
<td>85.91</td>
<td>0.81770</td>
</tr>
<tr>
<td>C-int, P-int</td>
<td>87.46</td>
<td>0.83610</td>
</tr>
<tr>
<td>C-polL-intP-int</td>
<td>90.71</td>
<td>0.87927</td>
</tr>
<tr>
<td>C-VV, C-HH</td>
<td>56.40</td>
<td>0.42650</td>
</tr>
<tr>
<td>C-VV</td>
<td>45.71</td>
<td>0.27698</td>
</tr>
<tr>
<td>C-HH</td>
<td>38.40</td>
<td>0.18218</td>
</tr>
</tbody>
</table>

Comparing this result with [2] at the same level of confidence and speckle, it is convincing that less accurate classification results are obtained for East-Kalimantan area test site for every channel combination. This can be explained by the fact that this test site is more complex (i.e. disturbed) with a diverse mosaic of tropical forest vegetation.

4.3 Biomass Empirical Relationship

An allometric equation calibrated for the East-Kalimantan province [3] was applied to estimate (total above ground wet) biomass of the plots of primary forest unburnt, primary forest burnt and secondary forest, using trunk diameter and height to the first living branch. The potential for biomass class mapping was studied by evaluating the backscatter for all 9 transects of primary forest unburnt, primary forest burnt and 7 transects of secondary forest for which biomass indirectly was estimated. For these fields, the above ground wet biomass was found to vary over the range of 112-199 ton/ha (1 ton = 1,000 Kg; 1 Ha = 10,000 m²) for primary forest unburnt, 31-115 ton/ha for primary forest burnt and 25-153 ton/ha for secondary forest). Gamma values (in dB) were fitted to the biomass using linear relationships.

The main results are summarised in Table 2. In general the correlation coefficients are lower and only have small differences between before and after slope correction. The maximum value of $r$ is only 0.48 and is found for L-HV. All other value are lower than 0.38. In addition the range/SEE ratio values are lower. Apparently this direct approach, i.e. using backscatter-biomass relationships, leads to poor results for this site. Scatter plots showing the relation between biomass and radar signal for several bands and polarisation and forest cover types reveal the underlying causes for these poor results.
Table 2. Relationship between backscatter, expressed as $\gamma$ [dB] and biomass in ton/ha for several frequency and polarisation combinations. The correlation coefficient $r$, standard error of estimate (SEE), the total range of $\gamma$ of the experimental data and the ratio of range and SEE before and after slope correction.

<table>
<thead>
<tr>
<th>Before</th>
<th>After</th>
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<tbody>
<tr>
<td>C-HH</td>
<td>0.139</td>
</tr>
<tr>
<td>C-HV</td>
<td>0.120</td>
</tr>
<tr>
<td>C-VV</td>
<td>0.094</td>
</tr>
<tr>
<td>L-HH</td>
<td>0.349</td>
</tr>
<tr>
<td>L-HV</td>
<td>0.483</td>
</tr>
<tr>
<td>L-VV</td>
<td>0.386</td>
</tr>
<tr>
<td>P-HH</td>
<td>0.140</td>
</tr>
<tr>
<td>P-HV</td>
<td>0.214</td>
</tr>
<tr>
<td>P-HH</td>
<td>0.235</td>
</tr>
</tbody>
</table>

Fig. 3.a-b shows results for L-HV and P-HV respectively. A distinction is made between three forest types (primary forest burnt, primary forest unburnt and secondary forest) for before and after slope correction. For L-HV the correlation and the range/SEE ratio are higher compared with other band and polarization. In this case there is a slight relation between biomass and also a clear dispersion between samples of different forest type (primary forest unburnt and burnt). For P-HH any clear relationship cannot be observed, the correlation and the range/SEE ratio are very low.

In the case of applying simple relationships the confusion between forest types with very low biomass and high biomass due to the early saturation of the backscatter intensity level will certainly have large effects on the accuracy of the biomass map estimation. For that reason the possibility of using the structural forest type map classification [7] to create a biomass map indirectly is considered as a possible solution.

Fig 3. Scatter plots between the estimated above ground wet biomass in plots of different forest cover types before and after slope correction and corresponding intensity value expressed in Gamma [dB], (a) for L-HV and (b) for P-HV.

The variation of the InSAR correlation (coherence) parameter as a function of the total biomass is illustrated in Fig 4. For C-VV the correlation with biomass is very low. The fluctuation of the coherence value in primary forest with different height seems to be substantial. The same situation occurs in the secondary forest, which often comprises remnants of the former primary forest. For L-VV the correlation between coherence and biomass is also low. Also between InSAR height and biomass, the correlation is low while the interferometric coherence value is very high. It is difficult to explain this result. It might be that InSAR data have some multi-path error [8].

Fig 4. Scatter plots between the estimated o fresh weight above ground biomass in plots of different forest type and corresponding interferometric correlation (coherence), (a). C-VV, (b). L-VV and (c) L-VV InSAR height.
5. CONCLUSIONS

A new method has been presented to show the capability of using multi-band polarimetric and interferometric SAR for tropical forest mapping and biomass type evaluation. This procedure compares backscatter, classification and biomass estimation before and after slope correction by using a digital elevation model (DEM) derived from InSAR data. This correction may not be optimal since the InSAR data has a multi-path error [8], however it could increase the classification accuracy slightly.

Backscatter and classification accuracy were improved utilising information on the topography of the study site in the image. The problem brought to image classification by the presence of topographic slopes can be solved. According [9], the effect in the radar cross section can be compensated by radiometric slope correction, using slopes derived from cross track interferometry or from DEM. The effect of the radar cross section as a function of the polarisation state can be corrected based on the orientation angle azimuth slopes. This could be explained by the fact that surfaces slope can change the radar cross section per unit image area and the polarization orientation.

The use of a direct empirical relationship for the biomass estimation in tropical forest area seems to be confusing because of the complexity of vegetation, frequent forest fire and terrain undulation. The relation between InSAR coherence with biomass is not fully understood yet. The possibility of using an indirect approach through classification of forest types as a first step like proposed in [7] was considered. Using additional information provided by Interferometric systems may also be beneficial. Topographic mapping and possible forest height estimations will further increase the accuracy.

In the near future some capabilities that are currently exclusive to airborne SAR may be available from spaceborne SAR. The ALOS PALSAR and possibly the TerraSAR L-band, are fully polarimetric and would give a boost to accurate monitoring for tropical forest mapping and biomass estimation. The combination with advanced C-band systems such as RADARSAT-2, ENVISAT and Shuttle Radar Topography Mission (SRTM) to provide DEM would even increase the capability.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


