FOREST VOLUME DENSITY ESTIMATION CAPABILITY OF ALOS PALSAR DATA OVER HILLY REGION

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ABSTRACT
In order to investigate the capability of PALSAR for forest volume density estimation in one warm temperate hilly forest test site in China, ground true data for Black Locust were collected through field work from May to June of 2008. The location of each stand was found according to its image feature in the high resolution CCD mosaic, and 1-4 plots were surveyed in each stand according to its size and forest structure. The volume density was calculated according to the forest plot data. The correlations of volume density to PALSAR backscattering coefficient of HH, HV, their ratio and multi-temporal mean, and some H-Alpha polarimetric decomposition parameters were analyzed. It shows that it is difficult to apply L-band SAR data for plot level forest volume density estimation in hilly regions, even after geometric and radiometric terrain correction.

1. INTRODUCTION
Forest biomass and its change over time have long been considered as key characteristics of ecosystems. The knowledge about the amount and distribution of biomass is important not only for understanding the carbon budgets, but also for forest management and other land surface processes related to water and energy budget. Most of the forest biomass in forests is in tree stems. Since large datasets on biomass measurements in forests are difficult to obtain, stem volume data from forest inventory data bases are widely used instead of forest biomass. Biomass can be estimated from volume by multiplying it with an appropriate factor or factors, referred to in this paper as biomass factors (BF). For example, forest stem volume (m³/ha) in boreal forests can be converted into dry above ground biomass (tons/ha) by multiplying the stem volume estimate by 0.6 [1], here the BF is 0.6. Because of the good relationship between volume and biomass, the capability of SAR for forest volume estimation will be studied instead of forest biomass.

Taking the advantage of synthetic aperture radar (SAR) for mapping forest volume or above ground biomass in big area, many studies have been carried out to extract forest parameters information from SAR data. The techniques suitable for forest volume or biomass extraction include C-band InSAR ([2], [3], [4]), L- and P-band intensity ([5], [6]) and L-band ([7], [8]) and P-band [9] polarimetric interferometry SAR (POLinSAR). C-band InSAR coherence has been observed using ERS Tandem data to have good correlation with volume density, and the higher the volume density the lower the InSAR coherence. However, the relationship between L-band InSAR coherence is much more complex and needs to be further investigated. C-band SAR intensity saturates at very low biomass level, so only L- and P-band intensity were thought as suitable for forest biomass estimation. In case of SAR intensity only, P-band is the best for biomass estimation with the highest saturation level. Normally, L-band intensity saturates at 120-160 ton/ha of biomass. In the case of POLinSAR technique, many successful observations have been carried out using L-band data. ALOS PALSAR can provide dual-polarization (HH, HV) intensity data and quad-polarization data, so the potential applications of these data for forest parameters extraction include dual-polarization intensity, multi-temporal dual-intensity, polarimetry, InSAR coherence and POLinSAR. In this test site, only one quad-polarization data was acquired till now, therefore POLinSAR was not covered in this
2. TEST SITE AND EO DATA

The test site is located in Taian district of Shandong Province. Its geographic coordinate ranges from N35°59′ to 36°5′ and from E117°13′to 117°25′. The forest covering area of the test site is Culai Mountain, whose forest coverage rate is above 80%. One regional remote sensing campaign has been carried out over this test site from April to June of 2005. The airborne sensor data acquired includes small footprint LiDAR, high spatial resolution color CCD and Hyper-spectral data. One ortho-rectified color CCD image mosaic for the whole test site was produced. The DEM in map scale of 1:20 000 (Figure1), and forest component maps for the test site have been constructed.

![Figure 1. DEM of the test site](image)

Four scenes of ALOS PALSAR level 1.1 data have been acquired. The major imaging parameters were listed in Table 1.

<table>
<thead>
<tr>
<th>Imaging Date</th>
<th>Polarization</th>
<th>Azimuth/range pixel size</th>
<th>Incidence Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 19, 2007</td>
<td>Quad</td>
<td>3.55/9.37m</td>
<td>23.8 deg</td>
</tr>
<tr>
<td>June 21, 2007</td>
<td>HH, HV</td>
<td>3.18/9.37m</td>
<td>38.7 deg</td>
</tr>
<tr>
<td>July 20, 2007</td>
<td>HH, HV</td>
<td>3.19/9.37m</td>
<td>38.7 deg</td>
</tr>
<tr>
<td>Sept 21, 2007</td>
<td>HH, HV</td>
<td>3.18/9.37m</td>
<td>38.7 deg</td>
</tr>
<tr>
<td>Oct. 20, 2007</td>
<td>HH, HV</td>
<td>3.18/9.37m</td>
<td>38.7 deg</td>
</tr>
</tbody>
</table>

In order to investigate the capability of PALSAR for forest structure information estimation, ground true data were collected through field work from May to June of 2008. The high resolution airborne CCD image mosaic was used to identify each forest stands through manual interpretation. One broad-leaved forest species Black Locust (*Robinia Pseudoacacia L.*) was selected as target. Some forest stands were selected for field plot data measurement. The location of each stand was found according to its image feature in the high resolution CCD mosaic and GPS, and 1-4 plots were surveyed in each stand according to the coverage size and the structure of it. The volume density, mean height \(H\) and mean diameter at breast height of 1.3m \(DBH\) of each plot was calculated according to filed measurement of \(H\) and \(DBH\) for each tree of one plot, which we defined as plot level ground true data. The average value of all the plots fallen into one stand was taken as the surveyed forest parameter for this stand, and this measurement is defined as forest level.

The paper only discusses the relationship between forest volume density of Black Locust and PALSAR data in plot level. Among all the plots surveyed, only the plots that can be thought as pure Black Locust forest were used for this study, the total plot number selected in this way is 66. Not all of the plots were really covered by the geo-coded terrain corrected SAR images, so the effective plot number can change from image to image acquired in different date, but there exist at least 50 plots for the smallest image coverage case.

3. SAR DATA PROCESSING METHODS

3.1. Radiometric Calibration

The sigma zero radiometric calibration function provided by JAXA is as follows:

\[
\sigma^0 = 10\log_{10} (I^2 + Q^2) + CF_i - C\]  \hspace{1cm} (1)

where, \(I\) and \(Q\) is the real and imagery part of the complex SAR image pixel value; \(CF_i\) and \(C\) are calibration constant, \(CF_i = -83.0, C = 32.0\).

We define \(K = CF_i - C\), and will not get the decibel (db) value of the radiometric calibrated intensity value until before analyzing the data. So we use equation (2) as the first step of our data processing.

\[
\sigma^0_i = (I^2 + Q^2) \cdot 10^{\frac{K}{10}} \]  \hspace{1cm} (2)

where, \(K = -115.0\), the subscript of sigma zero
means the sigma zero calibration result of each SLC pixel is in intensity domain, not decibel. For dual polarization PALSAR data, after this calibration, we get only intensity image of each polarization, phase information has been discarded.

For quad-polarization data, we only scale the amplitude of each element of the scattering matrix (S) using equation (3), the phase of each polarization was saved as it is.

\[
\begin{bmatrix}
S_{HH}S_{HH}^{*} 10^{\frac{k}{10}} \exp(i\phi_{HH})

S_{HV}S_{VV}^{*} 10^{\frac{k}{10}} \exp(i\phi_{VV})

S_{VH}S_{HV}^{*} 10^{\frac{k}{10}} \exp(i\phi_{HV})

S_{VV}S_{HH}^{*} 10^{\frac{k}{10}} \exp(i\phi_{HH})
\end{bmatrix}
\] (3)

where, the subscript for \( S \) and phase term \( (\phi) \) stands for different polarization; and \( \phi \) is computed from the original complex \( S \) matrix element of each polarization.

### 3.2. Multi-looking

Our finally aimed product is GTC and RTC SAR images in map coordinate of pixel size 20m*20m. So applying multi-look processing to the single look \( \sigma^0 \) image is reasonable for both depressing the speckle noise and reducing the size of the SAR data. The pixel size of the single look PALSAR data is 9.37 m in range and 3.18 m in azimuth. So we multi-look the \( \sigma^0 \) image with 10 looks in azimuth direction and 2 looks in range direction to produce one image of pixel size about 3.18*10=31.8m and 9.37*2/sin(38.7°)=30.0 m, taking the dual polarization data listed in table 1 as an example, the resulted image is denoted as \( \sigma^0_{IML} \).

After multi-looking, the look number of \( \sigma^0_{IML} \) was changed to about 20, which is still not big enough for the distributed target backscattering coefficient estimation. So the look number will be increased to a reasonable level during the resampling phase of the SAR image to the DEM map space.

### 3.3. Geocoded Terrain Correction

The Range-Doppler based SAR imaging model (RD model) was established for the geocoding of PALSAR slant range image. All the RD model parameters were extracted from SAR meta data file, so it can be used to geo-code the SAR image to the earth surface of one assumed ellipsoid such as WGS 84 ellipsoid without any information provided by the user, the geocoded product by this way is called Geocoded ellipsoid corrected SAR image (GEC). The GEC doesn’t need user to provide ground control points (GCPs) and DEM, so the location accuracy is too low to be used for quantitative application, especially in the mountain area, where the terrain caused geometric distortion can not be corrected without one DEM.

The scheme used for GTC processing based on DEM and RD model was illustrated with Figure 2. The RD model and the DEM were used to generate one simulated SAR image
corresponding to the real SAR image $\sigma_{\text{IML}}^0$.

Through automatic image to image registration, the simulated SAR image can be registered to the real SAR image with sub-pixel accuracy. We know the relationship between geographic coordinate of the input DEM denoted as $(x,y)_{\text{dem}}$ and the image coordinate of the simulated SAR image denoted as $(i,j)_{\text{sim}}$ through the simulating procedure. The relationship between $(i,j)_{\text{sim}}$ and the real SAR image’s coordinate denoted as $(i,j)_{\text{real}}$ can be easily established based on image to image registration model. So the relationship between $(x,y)_{\text{dem}}$ and $(i,j)_{\text{real}}$ can be solved, which was used to resampling the real SAR image ($\sigma_{\text{IML}}^0$) to the DEM coordinate space, the mean resampling method with 3 * 3 pixels window size was applied here. The produced SAR image is denoted as $\sigma_{\text{IGTC}}^0$. During the simulation procedure, the local incidence angle image ($\eta$), the layover and shadow mask image (LSM) and the terrain radiometric correction factor image ($F$) were also generated for assisting further image analysis.

![Figure 2 Illustration of the DEM based SAR image GTC processing method](image)

### 3.4. Radiometric Terrain Correction

Radiometric terrain correction (RTC) is to correct the effect of different effective backscattering surface area caused by the local topography and SAR imagery geometry. The same forest stand of size 20 m*20 m in different location of a hilly region should have similar backscatter coefficient level no matter where it is located. But in reality, the effective backscattering area has strong effect to the total backscattered power. RTC aims to correct this kind of effect by multiply the one RTC correction factor ($F$) with the $\sigma_{\text{IGTC}}^0$ image.

The pixel value of $\sigma_{\text{IGTC}}^0$ is derived from multi-looking the $\sigma_i^0$ computed using calibration function (2). The SAR incidence angle caused backscattering power changing trend from near to far range should be compensated during the data processing procedures to generate the SLC image. So we can derive the radar backscattering cross section $\sigma$ (BSC) with equation (4).

$$\sigma = \sigma_i^0 \cdot A = \sigma_i^0 \frac{\delta_r \delta_a}{\sin(\theta)}$$  \hspace{1cm} (4)

where, $A$ is the scattering area and $\theta$ is the incidence angle when taking the ground as one ellipsoid; $\delta_r, \delta_a$ is the resolution size of the SLC SAR image in range and azimuth direction respectively.

When local topography is considered, the effective backscattering area ($\int dA$) of each DEM pixel size can be computed precisely according to the RD model and satellite orbit data. Then the terrain radiometric correction can be applied to the $\sigma_i^0$ image using the following functions:

$$\sigma_T^0 = \sigma / \int dA = \sigma_i^0 \cdot \frac{A}{\int dA} = \sigma_i^0 \frac{\delta_r \delta_a}{\sin(\theta)} / \int dA$$  \hspace{1cm} (5)

where,

$$\int dA = \frac{\delta_r \delta_a}{\cos(\psi)}$$  \hspace{1cm} (6)

where, $\psi$ is defined as the angle between the local surface normal vector ($\hat{n}$) and the normal vector of the imaging plane defined by the azimuth direction line ($R_{az}$) and the range direction line ($R_{rs}$) as illustrated by Figure 3. Earth center is located in point O, S is the position of SAR sensor, $R_s$ is the position vector of the sensor. T is the location of one target. $R_t$ is the position vector of T. The vector from T to S is defined as $R_{ts} = R_t - R_s$. The
local incidence angle $\eta$ can be computed from (7) and $\psi$ from (8).

$$\cos(\eta) = \frac{\hat{n} \cdot R_{\text{ts}}}{|\hat{n}||R_{\text{ts}}|}$$  \hspace{1cm} (7)

$$\cos(\psi) = \frac{\hat{n} \cdot (R_{\text{ts}} \times (R_{\text{ts}} \times R_{\text{t}}))}{|\hat{n}||R_{\text{ts}} \times (R_{\text{ts}} \times R_{\text{t}})|}$$  \hspace{1cm} (8)

Combining (5) and (6),

$$\sigma_{0}^{0} = \sigma_{0}^{0} \cos(\psi) \frac{\cos(\psi)}{\sin(\theta)} = \sigma_{0}^{0} \cdot F$$  \hspace{1cm} (7)

where, $F$ is the so called terrain radiometric correction factor. Because $F$ is one correction factor not an absolute area, so (7) can also be applied to multi-looked SAR image as (8).

$$\sigma_{\text{TRC}}^{0} = \sigma_{\text{GTC}}^{0} \cdot F$$  \hspace{1cm} (8)

4. RESULTS AND ANALYSIS

4.1. The effect of topography on backscattering coefficient

The local incidence angle as defined in equation (7) is computed from radar imaging geometry and the DEM. In flat region, local incidence angle equals common incidence angle ($\theta$). But in uneven region, local incidence angle changes with the slope and the aspect of the local DEM facet. Taking the July PALSAR image as example, we show the local incidence angle image as Figure 4. The forest distributes in the inner part of this figure, where it is mountainous region of very rough relief. In the forest region, there is large number of pixels with blue and red color, so the effect of local topography to their image backscattering values should be evaluated before relating volume density to SAR backscattering coefficient.

![Figure 4: Local incidence angle image (upper) of the test site and its histogram (lower)](image)

Before applying the terrain radiometric correction factor $F$ to the GTC image, backscattering coefficient of the 66 forest plots is highly correlated with local incidence angle as shown in Figure 5 (a) for HH polarization and Figure 5 (b) for HV polarization.
Normally H polarization wave has higher canopy penetrating capability than V polarization wave, so HH is much more affected by local topography than HV, leading to higher R value of HH to local incidence angle than HV to it.

After terrain radiometric correction, the correlation between backscattering coefficient and incidence angle decreased to one level of being not significant as shown in Figure 6 for HH (a) and HV (b) polarization respectively.

![Figure 5. Relationship between local incidence angle and SAR backscatter before applying radiometric terrain calibration](image)

![Figure 6. Relationship between SAR backscatter and local incidence angle after applying radiometric terrain calibration](image)

4.2. The sensitivity of backscattering coefficient to volume density

4.2.1. Dual polarization PALSAR data

Four scenes of PALSAR dual-polarization (HH and HV) (Table 1) have been radiometric and geometric terrain corrected. But here we only show the relationship between SAR backscatter and forest volume density in plot level taking the JUNE image as an example. Another reason for doing so is that the JUNE image is also the closest one to the ground true data collection date.

From Figure 7 we can find that HH correlates with volume density much well than HV (R for HV is -0.11, and R for HH is -0.30) on the condition that the relationship between the backscattering coefficient in DB is linearly related with volume density. Many publications have shown that both HH and HV backscattering coefficients increase with volume density (m³/ha) or biomass (ton/ha) and saturate in a certain level of forest parameters, which is defined as the saturation point. The results shown in Figure 7 seem to be very different from the common conclusions of past publications. Both HH and HV have decreasing trend with the increasing volume density.

As shown in Figure 8, the variance of forest density is very large, this means the structure of the forest is very complex, one forest of a certain
volume density can own very different forest density, this can lead to large variance of backscattering coefficient both for HH and HV polarization. Figure 8 also shows the relationship of average forest height with volume density, apparently, the variance of forest height is large in any certain forest volume density level. These facts can explain in certain degree why we can not find good correlation of SAR backscattering to forest volume density in this test site in plot level.

4.2.2. Quad polarization PALSAR data

Backscattering coefficient of each of the four polarizations, the backscattering power ratio of HV to HH (HV minus HH in decibel), HH to VV power ratio, Anisotropy, Entropy and Alpha parameters from Cloude-Pottier H-Alpha-A decomposition are compared for their sensitivity to volume density (Figure 9). HH, VV, HV and HH/VV have negative correlation with volume density. HH is much more sensitive than VV and HV.

HV/HH, Entropy and Alpha are the three parameters with R bigger than 0.4 (Figure 9). The common characteristic of the three parameters is that they are all independent of SAR data calibration errors.
4.2.3. Multi-temporal dual polarization PALSAR data series with volume density

Normally people think multi-temporal remote sensing data series is useful for improving land cover or forest types classification accuracy, because different terrain type may has distinct spectral or backscatter changing behavior with temporal date acquiring the data. What does this means for forest volume density estimation? Assumed we are observing the same forest in different date of one year using the same SAR system, the major factors affecting the backscatter are these related to climate and local environment parameters, such as ground moisture, shrub under forest canopy, in addition to the canopy coverage and structure changes of forest stands. While, the way to collect ground true data of forest volume density is assumed that the volume density of one forest is not changed within the duration of acquiring the multi-temporal SAR data. So although the observed SAR backscatter changes from one date to another, the mean value of the multi-temporal data can be considered as the most appropriate estimation of the backscatter level of the forest stand.

For each plot, the backscattering value of HH and HV can be derived from the five images. The mean value and standard deviation of the five values were calculated and their relationships with forest volume density were analyzed. It shows that the mean value of HH has higher sensitivity to volume density ($R=-0.43$, Figure 11 top) than HV ($R=-0.178$, Figure 11 low), this is the same as each single date data where HH is always better than HV; while the standard deviation has very low relationship with volume density (HV standard deviation $R$ is 0.03, that of HH is -0.10). Therefore the best parameters using multi-temporal data to estimate Black Locust forest volume density in plot level is the mean HH backscattering coefficient of the data series. This conclusion tells us that if HH is the only polarization data we can obtained for an application, multi-temporal observation should has some benefits for volume density estimation than single time observation. However if we can get one date of dual polarization data such as PALSAR HH and HV data or quad-polarization data, we don't need to acquire multi-temporal data, because HV/HH ratio, entropy and alpha from Cloude Pottier H-Alpha decomposition of Quad-polarization data can even produce better result (Figure 9) than the temporal mean HH value.

![Figure 11. The relationship between temporal mean backscatter and forest volume density](image)

5. CONCLUSIONS

It has been observed that the backscattering coefficient of ALOS PALSAR data was strongly affected by the local topography changes in hilly region of tough relief, the correlation coefficient between HH backscattering coefficient and local
incidence angle was -0.75 and that for HV polarization was -0.54, so it is very important to do radiometric terrain correction before extracting forest parameters from SAR data. After RTC correction, the HH backscattering coefficient correlates with volume density much well than that of HV (R for HV is -0.11, and R for HH is -0.30), and both of the two polarizations have negative correlation with volume density. In the case of the quad-polarization data, HH, VV, HV, VH and HH/VV have negative correlation with volume density, HH is much more sensitive than VV and HV to volume density, and HV/HH, Entropy and Alpha are the three parameters with R bigger than 0.4. The mean HH backscattering coefficient of the multi-temporal dataset shows better correlation with volume density than the mean value of HV. The results were achieved using only plot level ground true data. The relationship between PALSAR backscattering coefficient and polarimetric parameters in forest stand level need to be analyzed in the future. However, the current results shows that it is difficult to apply L-band SAR data for forest volume density estimation in hilly regions, even after geometric and radiometric terrain correction.

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