ENVISAT/ASAR VV/HH BACKSCATTERING AND THE RADIATION CHARACTERISTICS OF SUBARCTIC BOREAL FOREST

Terhikki Manninen(1), Aku Riihelä(1)

(1) Finnish Meteorological Institute, Earth Observation, P.O. Box 503, FI-00101 Helsinki, Finland, Email:Terhikki.Manninen@fmi.fi

ABSTRACT
Surface albedo estimates based on optical and microwave satellite data were compared to corresponding ground based values in a Subarctic boreal forest test site. The ground based albedo values were derived from radiation measurements carried out at the forest floor using an albedo model and measured global and diffuse radiation data. The use of both optical and microwave satellite data turned out to produce more accurate surface albedo estimates than using only optical satellite data. The relative accuracy of the optical/microwave based near infrared and broad band albedo estimation was better than 10% for clear sky cases. The inclusion of microwave data improved the satellite based surface albedo estimation accuracy.

1. INTRODUCTION
The boreal zone land cover has very significant influence to northern hemisphere albedo and it is the main factor in northern hemisphere carbon budget. Surface albedo is also one of the Essential Climate Variables (ECV) that are largely dependent on satellite observations.

The surface albedo of forests is related to the leaf area index (LAI). It affects both the reflectance value and the bidirectional reflection distribution function (BRDF), the product of which constitutes the surface albedo. The BRDF of land cover is currently estimated for operational surface albedo products using optical satellite images and land use class information. Recently a method for boreal forest LAI retrieval using the ratio of the VV and HH polarization of ENVISAT/ASAR has been developed [1]. Preliminary results of a direct relationship between BRDF and the microwave signal have also been found [2, 3].

Because microwave instruments do not suffer from cloud cover and lack of sunlight, they enable regular updating of the description of the surface frequently enough in large areas to help improving the reliability of the climate change predictions. In addition, the optical BRDF is nowadays usually estimated from satellite data using NDVI as the vegetation descriptor. However, in boreal forests NDVI is very sensitive to the forest understory vegetation, which may deteriorate the forest BRDF estimation accuracy.

2. THEORY
2.1. Optical radiation
Vegetation absorbs most of the light in the visible part of the spectrum but is strongly reflective at near infrared band. The main part of the absorption takes place in the leaves (or needles). Thus the spectral response to visible and NIR wavelengths can be used for estimation of the leaf area index (LAI).

Canopy zero order (i.e. uncollided) transmittance in direct and diffuse radiation conditions can be expressed as [4]:

\[ t_0 = \exp(-G\beta L/\cos\theta) \]
\[ t_1 = \exp(-G\beta L)(1 - G\beta L)(G\beta L)^2 \text{Ei}(-G\beta L) \]

where \( L \) denotes the leaf area index, \( \theta \) is the solar zenith angle, \( G \) is the radiation extinction coefficient for a uniform leaf canopy, \( \beta \) is a clumping correction factor and \( \text{Ei} \) is the exponential integral. For coniferous canopies, the clumping of needles into shoots may be corrected for by putting \( \beta = 1 - p_{sh} \), where \( p_{sh} \) is the photon recollision probability within a shoot [5, 6]. For Scots pine (\textit{Pinus sylvestris} L.) the value \( p_{sh} = 0.47 \) is representative [7].

The photon recollision probability \( p \) is practically independent of the sun zenith angle [7].

Recently a model for the black sky spectral forest albedo \( \alpha \), i.e. the directional hemispherical reflectance DHR, based on the photon recollision probability was presented [4]. The model treats the albedo as a sum of four components:

\[ \alpha = \alpha_s + \alpha_a + \alpha_d + \alpha_w \]
The four components of the albedo are composed of: 1) photons transmitted through gaps in the canopy, first downwards and then upwards after being reflected from the forest floor \( (\alpha_{tt}) \), 2) photons scattered upwards from the canopy without reaching the forest floor \( (\alpha_s) \), 3) photons first scattered downwards from the canopy, then reflected from the forest floor and transmitted without interaction through the canopy upwards \( (\alpha_{st}) \) and 4) photons reflected from the forest floor and scattered upwards through the canopy \( (\alpha_{ss}) \). Notice that components \( \alpha_s \), \( \alpha_{st} \) and \( \alpha_{ss} \) all include multiple scattering from the crowns (photons that have interacted several times within the crowns), but the two added components \( \alpha_{st} \) and \( \alpha_{ss} \) in addition have interacted with the forest floor. In \( \alpha_{st} \) this has happened only once whereas \( \alpha_{ss} \) includes photons that may have been reflected several times from the forest floor before finally escaping the canopy.

The white-sky albedo corresponding to the diffuse radiation conditions differs somewhat from the black-sky albedo, but it can be derived using the same parameters \[4\].

The advantage of this forest albedo model is that it is based on only a few parameters. Only the LAI and forest floor albedo have to be estimated spatially. Other parameters can be derived from LAI or taken from the literature.

### 2.2. Microwave backscattering

In wide-band polarimetric radar inversion studies of vegetation layers it has been observed that at C-band the scattering is dominated by the smallest-scale, needle-like structures on the tree \[8\]. Backscattering is strongly dependent on the tree structure including the size, shape and orientation of the tree components. It has been suggested that the arrangement of needles can play an important role in the polarization behaviour according to the frequency used \[9\]. In addition, already in the early studies of electromagnetic wave scattering from vegetation, it was noticed that leaf shape affects VV and HH polarizations differently \[10\]. Thus it is probable that relevant leaf related information can be derived from the VV and HH polarization backscattering, or their ratio, which is less sensitive to calibration and weather conditions.

Since the needles are close to each other and their permittivity deviates markedly from that of air, the shoots have to be treated as dense medium. In addition, the highly ordered orientation of the needles in the shoots does not suggest that the interaction of all needles of a shoot would result in total scattering pattern resembling that obtained by summing all single needle scattering patterns. Thus from the scattering point of view the basic element of a Scots pine is the shoot, not needle. Also neighbour shoots interact, but if they are not very closely separated their contribution to scattering can be approximated by adding the signals of each shoot.

To understand the C-band microwave characteristics of Scots pine shoots the backscattering is simulated using the so-called discrete dipole approximation (DDA) \[11\] and they support the empirical result that the leaf area index is linearly related to the VV/HH backscattering ratio \[1\]. In addition, the shape of the scattering lobe of a single shoot resembles the previously simulated directional distribution of scattered photons for NIR wavelength \[7\] so that for perpendicular incidence the lobe is most elongated, especially for the HH polarization \[11, data not shown\].

It has been also empirically shown that the canopy leaf area index of boreal forest is essentially linearly correlated with the VV/HH backscattering ratio \[1, 12\].

### 3. MATERIAL

#### 3.1. Test site

The test site is in the immediate vicinity of the Arctic Research Centre of FMI, which is situated about 100 km north of the Arctic Circle (67.368° N, 26.633° E, 179 meters above sea level). It belongs to the NorSEN network \[13\]. The pure Scots pine (Pinus sylvestris L.) subarctic boreal forest in the area is relatively sparse and the maximum tree height is less than 15 m. The leaf area index (LAI) values of 265 plots had been measured in a regular grid with 50 m spacing in June 2006 \[14, Fig. 1\]. The topography of the test site is relatively flat: the height variation is about 22 m at the LAI measurement plots.

![Figure 1. The LAI measurement grid at the test site. The location of the albedo measurement points is a subset of the LAI points.](image-url)
3.2. Satellite data

One cloud free SPOT image (June 7, 2006) and altogether seven ENVISAT/ASAR SLC alternating polarization (VV/HH) images were acquired for the test site during summer 2006. However, this summer was extremely dry, in fact the driest summer ever measured in Finland since 1900. This was also manifested by the large amount of completely brown needles of the coniferous trees. Therefore the number of ASAR images fit for analysis was reduced from seven to two. Both images were of swath IS6. The first good image was taken in May 26 (descending pass) before the dry season and the other one in August 8 (ascending pass) right after a rain fall.

3.3. Radiation measurements

In August 2006 the incoming and reflected radiation was measured at about 1 m height at 81 points using a portable albedometer consisting of two separate pyranometers [Fig. 2]. The wavelength range of the instruments is 0.31 μm … 2.8 μm and the expected instrumental accuracy ±2%. The measured points were a subset of the grid for which the LAI values had been measured earlier in the summer. The measured effective LAI values varied in the range 0.27 … 1.65 at the radiation measurement points. The expected instrumental accuracy for the LAI measurements is ±1%.

The global and diffuse incoming radiation is continuously measured at FMI-ARC. The reflected radiation of the forest is measured continuously at the meteorological mast 45 m above the ground level.

4. METHODS

4.1. Ground based albedo

The broad band forest floor albedo \( \alpha_b \) is the ratio of the reflected radiation to the incoming radiation measured at the forest floor and can be expressed as a weighted sum of the red and near infrared band albedo values, \( \alpha_{b1} \) and \( \alpha_{b2} \) respectively, [15]

\[
\alpha_b = k_1 \alpha_{b1} + k_2 \alpha_{b2}
\]

(5)

\[
\alpha_{b1} = \frac{\alpha_b}{k_1 + \frac{k_2}{k_1k_{12} + k_2}}
\]

(6)

\[
\alpha_{b2} = \frac{\alpha_b}{k_1k_{12} + k_2}
\]

where \( k_{12} = \alpha_{b1}/\alpha_{b2} \). A typical value for \( k_{12} \) in the measurement site was 0.33 [14]. The fraction of the incoming radiation in the visible and NIR wavelengths above the forest was assumed to be 5% higher than that of standard atmosphere to take into account the cloud cover mostly present [16]. However, the visible radiation is absorbed much more by the canopy than the NIR radiation. Therefore the fraction of visible and NIR band radiation is not the same at the forest floor, but must be determined iteratively requiring the model to be self consistent. Then the forest spectral albedo values are obtained as the ratio of the calculated reflected radiation to the incoming radiation at the forest top in the band in question. The clear sky formula is used for cloud free conditions and the diffuse sky formula for complete cloud cover. Fractional cloud cover cases are derived on the basis of the ratio of the diffuse incoming radiation to the global radiation, which are continuously measured in the test site.

By applying the albedo model [4] to the measured LAI and radiation values the ground truth values for the forest surface albedo are obtained. The accuracy of these values depends on the accuracy of the measured LAI and radiation values. The albedo model has been used to estimate the sensitivity of the forest albedo value to the measured input parameters of the model. The instrumental inaccuracy was estimated to cause the albedo value to vary on the average in the range 98% … 103% in the red band and 99% … 102% in the NIR band of the true albedo values at the measurement points. This should be about the accuracy in the case of full cloud cover. However, in the clear sky
The accuracy of the radiation measurements at the forest floor, especially that of the incoming radiation, is seriously affected by 1) immediate vicinity of tree trunks reducing the amount of radiation available, and 2) by larger gaps in the canopy that permit more than average amount of direct radiation to reach the albedometer without interaction with the canopy [Fig. 3]. An additional source of errors is the distance between the fixed locations of the global and diffuse radiation measurement (some hundred meters displaced from each other) and the varying location of the portable albedometer that could be about 1 km from the fixed measurement points. For this reason the radiation inputs for the model are not from the same column. The diffuse sky condition is the most reliable in testing the validity of the model. The incoming radiation calculated by applying the model to the measured LAI values and global and diffuse radiation measurements above the canopy is compared to the measured incoming radiation at the forest floor level [Fig. 4]. The measured and modelled values are quite similar. Linear regression to the corresponding scatter plot resulted in the relationship $I_{\text{model}} = 28 \text{ W/m}^2 + 0.71 I_{\text{meas}}$ ($R^2=0.69$) and the mean difference between the measured and modelled incoming radiation value at the forest floor was 34 W/m$^2$, the standard deviation being 27 W/m$^2$. The deviation caused by expected instrumental inaccuracy was estimated to be on the average ±4 W/m$^2$. The rest of the deviation is probably caused by the difference in the cloud cover thickness at the measurement locations of the forest floor measurement point and the diffuse and global (forest top) incoming radiation measurement points, which was of the order of a few hundred meters.

### 4.2. Optical satellite based albedo

To correct the effect of the seasonal change the SPOT reflectance values were first multiplied by the ratio of the forest albedo at the time of the ground measurements and at the time of the SPOT acquisition measured at the meteorological mast above the forest. Then the reflectance values were corrected in order to take into account the daily variation assuming that the relative change is in the whole forest the same as at the mast. The spectral BRDF values were derived using the NDVI values calculated from the corrected red and near infrared channel reflectance values of SPOT [17]. Multiplying the BRDF values with the corresponding corrected reflectance values estimates for the albedo values of the red and near infrared band were obtained.

Currently the BRDF for forest in summer condition is calculated using the following formulas [18, 19]. The surface reflectances are first normalized to nadir sun, nadir viewing by

$$\rho(0,0,\phi) = \frac{\Omega(0,0,\phi)}{\Omega(\theta_s,\phi_s,\phi)} \cdot \rho_{\text{surf}}(\theta_s,\phi_s,\phi)$$

(7)
where $\rho_{sv}(\theta_s, \theta_i, \phi)$ is the observed surface reflectance, and $\Omega$ is the BRDF:

$$\Omega(\theta_s, \theta_i, \phi) = 1 + a_1 f_1(\theta_s, \theta_i, \phi) + a_2 f_2(\theta_s, \theta_i, \phi)$$  \hspace{1cm} (8)$$

where the $a$-terms are the canopy scattering parameters, dependent on NDVI, and $f_1$ and $f_2$ are the geometric and volumetric scattering kernels, respectively. The BRDF is described as multiples of nadir-viewed reflectance, hence the first term equals one. For forest, $a_1$ is zero and the geometric scattering term vanishes. The volumetric scattering terms for the 0.8-micron NIR channel are

$$f_2 = \frac{4}{3a_2} \left( \frac{\pi}{2} - \xi \right) \cos(\xi) + \sin(\xi) - \frac{1}{3}$$

$$\xi = \cos(\theta) \cos(\theta) + \sin(\theta) \sin(\theta) \cos(\phi)$$  \hspace{1cm} (9)$$

Optical BRDF is also directly related to directional-hemispherical albedo of the surface. The relation is

$$a(\theta_s) = \frac{2}{\pi} \int_0^\pi \rho(\theta_s, \theta_i, \phi) \cos(\theta_i) \sin(\theta_i) d\theta_i$$  \hspace{1cm} (10)$$

Numerical integration of the forest BRDF therefore yields the following relation [18, 19]:

$$a(\theta_s) = a_2 I_2$$  \hspace{1cm} (11)$$

where

$$I_2 = -0.0137 + 0.0370 \tan(\theta_s) + 0.0310 \tan(\theta_s) - 0.0059 \tan(\theta_s)$$  \hspace{1cm} (12)$$

The SPOT albedo was based on the NIR reflectance and existing BRDF formula parameterized with NDVI.

Although NDVI is sensitive to the leafing, it is not well suited to characterize the canopy LAI of boreal forest throughout the summer. In Sub-Arctic boreal forest actually the forest understorey vegetation, such as lichen, dominates the NDVI [14]. Therefore the variation of NDVI during the summer is not necessarily related to changes in the scattering behaviour of the canopy. This is a drawback in applying the formula of [19] in satellite based estimation of the surface albedo of boreal forest.

4.3. Optical/microwave satellite based albedo

It has been shown before that the VV/HH polarization ratio of ENVISAT/ASAR is linearly correlated fairly well with the leaf area index of boreal forest [1], also in the sparse Sub-Arctic forests [12]. The BRDF is theoretically parameterized with the LAI [18]. Thus the optical/microwave albedo should be related to the product of the corrected SPOT reflectance values and the VV/HH polarization ratio. At this stage, more complicated functional relationships were not studied.

5. RESULTS

The comparison of the measured/modelled forest albedo and the corresponding forest albedo derived using the SPOT reflectance values and ASAR VV/HH polarization ratio is shown for the near infrared channel in Fig. 5 for dominantly cloudfree (top) and dominantly cloudy days (bottom) of the albedo measurements. Corresponding comparisons using only SPOT for the albedo estimation are shown in Fig. 6. In these data sets 13 points out of 81 were excluded, because they were in the very sparse marsh area, in the immediate vicinity of roads or contained metallic reindeer fences, which are problematic for microwaves.

There is a fairly good correlation ($R^2=0.74$) between the product of the SPOT reflectance and ASAR VV/HH polarization ratio and the modeled/measured albedo value, when the ratio of the diffuse and global radiation is smaller than 0.2, as is the case normally in completely cloud free conditions in the test site at the season of the measurements. Increasing ratio of diffuse and global radiation decreases the coefficient of determination of the linear regression so that $R^2 = 0.56$ and $R^2 = 0.34$ for the upper limit values 0.3 and 0.5, respectively [Fig. 5]. The former regression was used to estimate the optical/microwave albedo values for the measured points. The two outliers in the lower image of Fig. 5 are due to the clearings [Fig. 7] and roads within the satellite pixels. Since the white-sky albedo does not depend on the sun zenith angle, the measured albedo has a very small dynamic range. As the SPOT reflectance corresponds always to a clear sky case, it is natural that the modeled SPOT/ASAR based albedo does not correlate with the albedo measured in diffuse conditions. Likewise the solely SPOT based albedo does not match well the measured albedo of the cloudy days.

The correlation between the optical satellite based albedo and the modeled/measured ground based albedo values is not as good as for the optical/microwave albedo estimate. The coefficient of determination is poor for all tested values for the upper limit of the ratio of the diffuse and global radiation, so that $R^2=0.2$ and $R^2=0.09$, for the limit values 0.5 and 0.2, respectively [Fig. 6]. The Point 305 in Fig. 6 was problematic for
The observed correlation between the ground based near infrared and broad band albedo values ($R^2=0.97$) was used to derive optical/microwave satellite based broad band albedo values.

It seems that the optical/microwave data combination can be used to obtain reasonable estimates [Tab. 1] for the forest surface albedo in near infrared channel. This supports the view that the C-band microwave scattering of the boreal forest is dominated by the needles as long as the canopy is not too sparse [1]. It is equally understandable that the correlation between the optical/microwave signal and the measured/modelled red band albedo values is practically nonexistent. The
Figure 7. The clearing causing the topmost outlier in the lower image of Fig. 5. The location of the LAI and albedo measuring instruments is marked with a stick and red and blue ribbons near the lower edge of the photo.

Figure 8. The albedo measurement point 305.

Table 1. The mean and relative mean difference between the satellite and ground based albedo values.

<table>
<thead>
<tr>
<th>Band</th>
<th>Satellite data</th>
<th>Mean difference</th>
<th>Relative mean difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIR</td>
<td>SPOT</td>
<td>0.038</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>SPOT/ASAR</td>
<td>0.017</td>
<td>8%</td>
</tr>
<tr>
<td>Broad band</td>
<td>SPOT</td>
<td>0.015</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>SPOT/ASAR</td>
<td>0.011</td>
<td>9%</td>
</tr>
</tbody>
</table>

reason is that in the red band the radiation is mostly absorbed, not scattered by the canopy. In addition, the red band albedo is small compared to near infrared band albedo, so that its estimation from broadband measurements is less accurate.

Obviously the optical satellite based albedo estimate suffers from the cloudiness, but also it needs larger statistics than the optical/microwave estimate to produce good results. This is probably partly due to the weak correlation of NDVI with LAI in the test data ($R^2=0.21$). The variation of the optical satellite based albedo estimate from point to point is clearly smaller than the variation of the ground measurements, but the trend is systematically the same. Thus the optical albedo results would most probably improve just by increasing the number of measurement points.

The correlation between the optical satellite based red band albedo and the measured/modelocked albedo was almost nonexistent, but the estimation accuracy of the red band albedo value from the ground measurements is assumed to be less accurate than the near infrared band estimate.

6. CONCLUSIONS

The near infrared channel reflectance of SPOT multiplied by the ASAR VV/HH polarization ratio turned out to correlate fairly well with the near infrared albedo of the forest obtained applying an albedo model to radiation measurements carried out at the forest floor. Both near infrared and broad band albedo estimation would benefit from combined use of optical and microwave satellite data.

7. ACKNOWLEDGEMENTS

The authors are grateful for Prof. Pauline Stenberg, Dr. Miina Rautiainen, Dr. Matti Möttus and Mr. Pekka Voipio for the LAI data. Support of various people from FMI-ARC is gratefully acknowledged. Thanks to the NorSEN network of European Regional Development Funds and EUMETSAT for financial support at various stages of the work.

REFERENCES


