Multi-temporal analysis of ERS-1 and EMISAR C-band VV backscattering properties of forest and lake surfaces in the NOPEX region

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Abstract

Multi-temporal ERS-1 SAR data, consisting of seven acquisitions in 1994 and 1995, were analyzed to determine the potential of C-band VV polarization backscattering data to discriminate different surface types within the patchy boreal landscape of the NOPEX area. Based on an aerial photo analysis, four classes of forest density were distinguished. For independent comparison, also one fully polarimetric EMISAR C-band image, including the VV polarization signatures was analyzed. It was found that the differences between the classes were quite consistent throughout the seasons and therefore probably significant, at least in a relative sense. The same images were also studied to determine the sensitivity of backscattering properties of lake surfaces to regional winds. For this purpose the backscattering values of five lakes within the study area were analyzed. It was found that the five lake surfaces behaved very similar, except for one observation date. This behavior, therefore, seems to be dominated by regional scale wind fields, although local scale wind fields also may have an effect. Since regional and local scale wind fields are difficult to observe in a synoptic way, the use of radar might have potential for monitoring such wind fields in the Swedish boreal region, which is characterized by the occurrence of many lakes. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Synthetic aperture radar; Backscattering values; Forests; Lakes; Regional winds

1. Introduction

Because of its cloud-penetrating capabilities and its high sensitivity to water content and roughness properties of the observed bodies there is an increasing interest in the use of microwave instruments such as synthetic aperture radar (SAR) for monitoring physical properties of the Earth’s surface. Both empirical analyses and theoretical models have increased our knowledge of the backscattering properties of different surface types in terms of the partial contributions and effects of soils and soil moisture (Dobson and Ulaby, 1986; Oh et al., 1992), agricultural crops (Eom and Fung, 1984; Bouman and Van Kasteren, 1990; Chuah, 1994) and forests (Hoekman, 1985; Richards, 1990; Kuntz and Siegert, 1994; Imhoff, 1995).

Radar is especially useful for monitoring forest structure and forest biomass because of the strong volume scattering in vegetation canopies (Bernard and Vidal-Madjar, 1989; Dobson et al., 1992; Le Toan et al., 1992). Due to the fact that vegetation introduces relatively strong volume scattering in the
cross-polarization channels more recently a strong interest has been developed in fully polarimetric instruments such as the 'ElectroMagnetic Institute Synthetic Aperture Radar', EMISAR (Dall et al., 1995) and in theoretical and experimental research of polarimetric backscattering properties of a variety of land surface conditions (Durden et al., 1989; Ulaby and Elachi, 1990). Therefore, cross-polarization signatures are also a powerful tool to discriminate between vegetation and bare soil (Dubois et al., 1995).

In order to determine the sensitivity of radar backscattering to different land surface units, including lake surfaces, within a boreal forest environment, multi-temporal ERS-1 C-band VV images and one EMISAR C-band VV image were analyzed. The study area forms part of the NOPEX region (Halldin et al., 1999, this issue) of which a total of seven ERS-1 images and one EMISAR image were gathered between June 1994 and August 1995. The analyses were carried out as part of the EC-funded (European Community) project FOREST-DYNAMO (Van de Griend et al., 1997). The main reason for the analyses described in this paper was to determine the level at which forest stands of different tree density could be distinguished and in how far the differences in backscattering properties of the different units are maintained during the seasons. For this purpose a detailed aerial-photo interpretation (1 : 10.000) was conducted during the summer of 1994 in conjunction with field observations.

Contrary to the land surface, lake surfaces showed a strong temporal variability in the backscattering coefficient ($\sigma^0$). Wind effects may have a strong influence on the backscattering properties of open water (see e.g., Johannessen et al., 1998). These effects, however, have until now been studied predominantly with respect to sea surfaces (Unal et al., 1991; Rijckenberg et al., 1992; Poulter et al., 1995; Vachon and Dobson, 1996; Wackerman et al., 1996) whereas its application to lake surfaces has been limited. Winds may be due to local phenomena, especially for small lakes and along the borders of larger lakes under weak wind conditions. They may also reflect regional air mass movements related to large scale weather systems and therefore, the spatial distribution of backscattering values of lake surfaces may be indicative for large-scale wind patterns as well. In order to study the relation between backscattering properties of lake surfaces and regional winds five lakes in the Östfora area were selected for further analysis.

2. Test site and data description

The Östfora test site lies within the NOPEX study area. The NOPEX study area forms part of a patchy landscape consisting of a mixture of numerous lakes, forest stands and agricultural fields, typical for large parts of the Swedish boreal zone (Halldin et al., 1999, this issue). The landscape is slightly undulating with marine clay deposits in elongated depressions and glacial till deposits with huge blocks covering the hills. The clayey soils are almost without exception used for agricultural practice, whereas the till soils are covered with production forest.

The test site of Östfora is one of the intensive study sites along the flight-triangle which was used for intensive remote sensing studies during the concentrated field efforts of NOPEX (for its location see: Halldin et al., 1999, this issue). The Östfora site is covered with mixed forest dominated by Norwegian Spruce (Picea abies) and Scots Pine (Pinus sylvestris) and consists of different stands of typically 0.05 km². Differences in surface elevation within the study area are small with a maximum difference of less than 15 m over the 4 km² area of the Östfora test site. In Fig. 1 the top of the canopy of the forested area of Östfora is shown as observed from the meteorological tower at a height of approximately 20 m above the surface.

The lakes used in this study were selected from the larger lakes within an area of approximately 10 km by 10 km surrounding the Östfora site (see Fig. 2) The lakes are tabulated in Table 1.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Surface area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siggeforasjon</td>
<td>0.67</td>
</tr>
<tr>
<td>Helsoarna</td>
<td>0.18</td>
</tr>
<tr>
<td>Dysjön-left</td>
<td>0.09</td>
</tr>
<tr>
<td>Dysjön-right</td>
<td>0.16</td>
</tr>
<tr>
<td>Savjan</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Fig. 1. The top of the forest canopy in the Östfors test site (picture taken by the group of Dirk Hoekman, Agricultural University of Wageningen).

Fig. 2. Map of the Östfors area with the Östfors forest site, the agricultural area (within the thick line east of Östfors) and the lakes analyzed in this study; distance between grid lines is 2 km.
2.1. ERS-1 SAR data

The ERS-1 SAR is a single frequency polarization radar operating at C-band (5 GHz) and VV-polarization. The spatial resolution of the instrument is approximately 25 m although the data are delivered with a pixel spacing of 12.5 m. The look angle of the instrument at the center of the swath is 23°. For the current analyses we used seven ERS-1 images collected during the time frame between June 1994 and August 1995 (see Table 2) of which two were ascending (A) and five descending (D). ERS-1 data were provided by the European Space Agency for analysis within the framework of the 'European Multi-sensor Airborne Campaign,' EMAC-94/95 (Attema and Wooding, 1997).

2.2. EMISAR airborne SAR data

The EMISAR is a full-polarimetric SAR developed and operated by the Technical University of Denmark (Dall et al., 1995). The EMISAR data used within this study were also collected as part of EMAC-94/95 (Attema and Wooding, 1997). Parts of the NOPEX area were mapped in 1994 (C-band) and 1995 (C- and L-band). In 1994 only one data set became available, namely a C-band (5.3 GHz) full polarimetric data set acquired on 23 June. The look angle range is from 35.9° near-range, 52.0° mid-range to 60.2° far-range.

2.3. Wind data

Wind data at the time of radar acquisition were gathered at the NORUNDA site from the main meteorological tower in the NOPEX area (Lundin et al., 1999a, this issue). The NORUNDA tower is located approximately 20 km northeast of the Östfora site (Fig. 2). The data were extracted from SINOP, the information system (database) within NOPEX (Lundin et al., 1999b, this issue). The data we used were taken from a height of 58 m above the surface at which wind speed and wind direction are dominated by the regional wind field with limited influence of local effects. Wind data have been included in Table 2.

2.4. Rainfall and antecedent precipitation index

Rainfall was taken from the station Vittinge ~10 km south–southwest of Östfora. In order to account for the influence of rainfall preceding the day of observation we calculated the antecedent precipitation index (API) for Day \( n \), which is defined as

\[
API_n = \sum_{i=1}^{n} P_{n-i} k^i
\]

where \( P_n \) is the precipitation on Day \( n \) and \( k \) is constant, set equal to 0.75. Precipitation and API data are also included in Table 2.

2.5. Forest ground data

In order to identify different forest units, a stereoscopic aerial photo reconnaissance (Scale 1 : 30.000) was carried out at the beginning of the 1994 field campaign (De Ruiter et al., 1994). Based on this aerial photo survey the Östfora site, a 6 km × 6 km area north of lake Siggeforasjön, was divided into 221 uniform land surface compartments. The Östfora site

---

Table 2

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Sensor</th>
<th>Date</th>
<th>A/D</th>
<th>Wind speed (m/s)</th>
<th>Wind direction</th>
<th>P (mm)</th>
<th>API (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EMISAR</td>
<td>23/06/94</td>
<td></td>
<td>9.0</td>
<td>300</td>
<td>0.4</td>
<td>12.2</td>
</tr>
<tr>
<td>2</td>
<td>ERS-1</td>
<td>24/06/94</td>
<td>A</td>
<td>1.8</td>
<td>100</td>
<td>–</td>
<td>9.5</td>
</tr>
<tr>
<td>3</td>
<td>ERS-1</td>
<td>07/07/94</td>
<td>D</td>
<td>2.9</td>
<td>98</td>
<td>–</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>ERS-1</td>
<td>02/04/95</td>
<td>D</td>
<td>5.1</td>
<td>270</td>
<td>–</td>
<td>7.8</td>
</tr>
<tr>
<td>5</td>
<td>ERS-1</td>
<td>07/05/95</td>
<td>D</td>
<td>5.9</td>
<td>350</td>
<td>–</td>
<td>4.6</td>
</tr>
<tr>
<td>6</td>
<td>ERS-1</td>
<td>11/06/95</td>
<td>D</td>
<td>3.3</td>
<td>240</td>
<td>10.3</td>
<td>7.6</td>
</tr>
<tr>
<td>7</td>
<td>ERS-1</td>
<td>11/07/95</td>
<td>A</td>
<td>4.9</td>
<td>65</td>
<td>–</td>
<td>1.5</td>
</tr>
<tr>
<td>8</td>
<td>ERS-1</td>
<td>16/07/95</td>
<td>D</td>
<td>6.6</td>
<td>105</td>
<td>–</td>
<td>0.4</td>
</tr>
</tbody>
</table>

aA: ascending; D: descending.
was subsequently surveyed during early summer 1994 to map forest parameters such as tree height, crown coverage and crown structure. These observations were used in combination with the data archive of the local forest authorities. During the ground survey a total of 57 out of all 221 compartments were visited and described in terms of mean height and dominant species. Based on this information all compartments were subsequently classified into the following four photo interpretation classes: dense forest, intermediate dense forest, open forest and clear-cuts (see Table 3). Finally, in 15 compartments a quadrant of 100 m × 100 m was randomly selected for additional estimations of the average crown cover. Crown cover was estimated by statistical sampling of the fraction of visible sky by looking upwards through a vertical cylinder and estimation of the covered fraction by branches and needles in a small viewing circle. In each of the 15 quadrants a total of 40 estimates were made along two perpendicular lines of 100 m length at intervals of 5 m. The results for the 15 compartments are shown in Table 4. A summary of the results is presented in Table 5. During the summers of 1994 and 1995 the area was surveyed by Baker and Luckman, 1999, this issue) to determine stem biomass at several locations, and surveyed by Lindroth et al. (1994) who measured leaf area index. These data (included in Tables 4 and 5) were gathered in only a few of the compartments distinguished in this study, are therefore difficult to regionalize and give probably no more than an indication of those properties for the classes distinguished in this paper.

Table 3
Overview of photo interpretation classes giving area (km² and %) and number of compartments (N) identified

<table>
<thead>
<tr>
<th>No.</th>
<th>Class</th>
<th>Surface area (km²)</th>
<th>Surface area (%)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>dense forest</td>
<td>6.44</td>
<td>21.5</td>
<td>47</td>
</tr>
<tr>
<td>2</td>
<td>intermediate</td>
<td>11.06</td>
<td>37.0</td>
<td>53</td>
</tr>
<tr>
<td>3</td>
<td>open forest</td>
<td>7.11</td>
<td>23.8</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>clear-cuts</td>
<td>5.29</td>
<td>17.1</td>
<td>46</td>
</tr>
<tr>
<td>5</td>
<td>agricultural</td>
<td>(4.50)</td>
<td>–</td>
<td>(1)</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>29.91</td>
<td>100</td>
<td>221</td>
</tr>
</tbody>
</table>

Table 4
Results of canopy coverage, dominant species (s = spruce, p = pine, d = deciduous) and total needle area in the 15 compartments. Last column is filled only with measurements in the corresponding compartments (for location of compartment numbers see De Ruiter et al., 1994)

<table>
<thead>
<tr>
<th>Compartment No.</th>
<th>Density class</th>
<th>Dominant species</th>
<th>Estimated height (m)</th>
<th>Crown coverage (%)</th>
<th>Total needle area (m²/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>dense</td>
<td>s</td>
<td>18 ± 5</td>
<td>59 ± 26</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>dense</td>
<td>p</td>
<td>12 ± 3</td>
<td>65 ± 20</td>
<td>–</td>
</tr>
<tr>
<td>7</td>
<td>dense</td>
<td>s</td>
<td>16 ± 3</td>
<td>55 ± 25</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>dense</td>
<td>p/s</td>
<td>18 ± 4</td>
<td>51 ± 26</td>
<td>–</td>
</tr>
<tr>
<td>11</td>
<td>dense</td>
<td>s</td>
<td>16 ± 3</td>
<td>64 ± 18</td>
<td>–</td>
</tr>
<tr>
<td>27</td>
<td>dense</td>
<td>s</td>
<td>20 ± 3</td>
<td>56 ± 26</td>
<td>–</td>
</tr>
<tr>
<td>17</td>
<td>dense</td>
<td>o</td>
<td>10 ± 2</td>
<td>57 ± 23</td>
<td>–</td>
</tr>
<tr>
<td>52</td>
<td>interm.</td>
<td>s/p</td>
<td>18 ± 4</td>
<td>46 ± 26</td>
<td>2.8</td>
</tr>
<tr>
<td>56</td>
<td>interm.</td>
<td>s/p</td>
<td>14 ± 3</td>
<td>44 ± 23</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>interm.</td>
<td>p</td>
<td>10 ± 4</td>
<td>40 ± 26</td>
<td>–</td>
</tr>
<tr>
<td>14</td>
<td>interm.</td>
<td>s/p/d</td>
<td>13 ± 5</td>
<td>54 ± 26</td>
<td>–</td>
</tr>
<tr>
<td>12</td>
<td>interm.</td>
<td>s/p</td>
<td>18 ± 4</td>
<td>45 ± 25</td>
<td>–</td>
</tr>
<tr>
<td>57</td>
<td>interm.</td>
<td>s</td>
<td>18 ± 3</td>
<td>47 ± 32</td>
<td>–</td>
</tr>
<tr>
<td>25</td>
<td>open</td>
<td>p</td>
<td>20 ± 2</td>
<td>26 ± 26</td>
<td>–</td>
</tr>
<tr>
<td>21</td>
<td>open</td>
<td>s/p/d</td>
<td>7 ± 3</td>
<td>32 ± 28</td>
<td>–</td>
</tr>
</tbody>
</table>
3. Data processing and analysis

ERS-1 data were radiometrically corrected by Van Oevelen and Woodhouse (1996) as part of the EC-project FOREST-DYNAMO (Van de Griend et al., 1997) according to the procedure described by Laur (1992). The corrected data were linearly resampled to 25 m × 25 m ground resolution and subsequently converted to backscattering coefficients (dB) according to

\[ \sigma^0 = 10 \times \log \sigma^0_{\text{lin}} \]  

(2)

where \( \sigma^0_{\text{lin}} \) is the linear backscattering coefficient which is directly proportional to the radar brightness of the illuminated target. The original EMISAR complex data with a spatial resolution of 1.5 m × 1.5 m were ground range projected, amplitude detected, low-pass filtered and spatially resampled to 4.5 m × 4.5 m (Dall et al., 1995). For simultaneous analysis together with ERS-1 data the intensity values were also spatially resampled to 25 m × 25 m ground resolution and converted to backscattering coefficients in dB. In radar remote sensing the absolute precision of a pixel-value with respect to the target is low due to the effect of so-called speckle. In order to enhance the radiometric resolution, i.e. to reduce the speckle in the backscattering coefficient of the target, the backscattering coefficient of the distributed object (target) can be calculated by averaging the intensity values of a certain amount of pixels within the group of pixels that corresponds to the target (Laur et al., 1997). Therefore, the radiometric precision of a homogeneous target depends on the number of pixels included in the averaging process. According to Laur et al. (1997), the probability that the measured intensity of a uniform distributed target lies within error bounds of ±0.5 dB, at a 90% confidence level, requires approximately \( N \geq 240 \) pixels. This means that radar image interpretation cannot be done on a pixel by pixel basis as it can be done in the visible/near-infrared and thermal portions of the spectrum. With an original pixel size of 12.5 m × 12.5 m this means that a homogeneous target should be ~200 m × 200 m.

After radiometric calibration all images were geometrically corrected using a linear transformation and a nearest neighbor procedure and stored in an image processing system for easy extraction of signatures for selected units. For each of the land surface classes, defined in the compartment map, 10 sample areas were selected of ~200 m × 200 m. For each of the sample areas, average backscattering values (denoted \( \gamma \)) were calculated according to

\[ \gamma = \frac{\sum_{i=1}^{N} \sigma^0_i}{N} \]  

(3)

and extracted from all available images tabulated in Table 2. Lake surfaces tabulated in Table 1 were sampled from the open water bodies in order to avoid the effects from the bordering land surfaces (forests and agricultural fields) and small islands.

4. Results and discussion

4.1. C-band VV backscattering and forest density

Fig. 3a shows the course of ERS-1 \( \gamma \)-values over the sequence of dates (1994 through 1995) for the...
identified classes of forest density. Values of $\gamma$ are derived by taking the mean of $\gamma$-values of the 10 sampling areas per forest density class. The standard deviation (SD) of $\sigma^0$-values within the sample areas turned out to be $\sim 2$ dB, whereas the SD of the $\gamma$-values between the sample areas of the same density class was $\sim 0.45$ dB. The 2nd and 7th in sequence are ascending, the others descending. For an isotropic vegetation (randomly organized) the difference between ascending and descending $\gamma$-values should be small. By taking the average of 10 ERS-1 sampling areas for each density class, any preferential effects with respect to tree orientation or topography should therefore be substantially reduced.

The differences between the $\gamma$-values of different forest classes (dense, intermediate, open and clear cuts) over time are relatively small ($<0.5$ dB) which is about the precision of target identification for a sufficiently large uniform target. Taking account of the SD between the sampling areas of the same class ($\sim 0.45$ dB), the differences are hardly significant. The differences between the classes, however, are rather systematic when looking at the temporal variations. This indicates the high reproducibility of the areal mean in backscattering coefficients. If the differences in $\gamma$-values are significant they should, regarding the high frequency of C-band, primarily be related to features of the canopy, such as tree densities.

It has been reported in several ERS-1 evaluation studies that the C-band VV $\sigma^0$-values of forested areas tend to saturate at relatively low levels of trunk biomass (see e.g., Israelsson and Askne, 1995). This phenomenon of signal saturation was observed in this study with respect to forest density and crown cover. From Fig. 3a it could already be seen that the differences between dense, intermediate and open forest are relatively small. Fig. 4 shows the $\gamma$-values for the three bands of the full polarimetric C-band EMISAR (HH, VV and HV) for the four forest classes of Table 3 plus the agricultural area. The cross polarized signal (HV) seems to give the most systematic increase with increasing forest density, but regarding the fact that the backscattering values are computed as the mean of ten sampling areas - with a SD of $\sim 0.45$ dB between the samples and 2 dB within the samples, each sample consisting of the required $200 \times 200$ m – discrimination of density classes and their boundaries from radar images will be practically impossible. This is because discrimination of density classes would require a priori knowledge of the spatial distribution of approximately uniform areas of the required $200 \times 200$ m.

4.2. Temporal variations of forest backscattering

The mean backscattering coefficients $\gamma$ of Fig. 3a show temporal variations which occur systematically

![Fig. 4. EMISAR C-band backscattering coefficients (HH, VV and HV) for five different surface cover classes in the Östfora area. The standard deviation between samples of the same class is approximately 0.45 dB (for explanation see text).](image-url)
for all surface classes. Although the significant increase in only a two weeks period between 24 June (2nd observation) and 7 July 1994 (3rd observation) might reflect the delayed but fast leaf growth of deciduous trees after an extremely cold and dry spring, the sudden decrease between 11 July (7th observation) and 16 July 1995 (8th observation) – a period of only 5 days can hardly be related to changes in vegetation properties. Moreover, the sudden increase at the beginning, and the sudden decrease at the end of the observation period, also occurs in the agricultural area within the Östfora test site. This suggests that the temporal variations might be determined by a regional phenomenon, for example related to precipitation or regional wind effects. An extensive study of ERS-1 backscattering values of tropical forest, carried out by (Van der Sanden (1997), page 202), recently revealed a comparable systematic temporal variation, which he could explain from antecedent rainfall in that rainfall on forest increases the backscatter. After an extended literature review we found that the thesis by Van der Sanden was the only work that referred to this phenomenon. Therefore, we also considered rainfall as a possible reason for the observed temporal variability of $\gamma$. Fig. 3b shows the antecedent precipitation index (API) and precipitation on the days of satellite observation for the NOPEX area as given in Table 2. It is shown that regional effects related to either soil moisture (API) or rainfall on the day of observation must be canceled out, simply because the strong variation in API for the sequential observation Days 3 (7/7/94), 4 (2/4/95), 5 (7/5/95) and 6 (11/6/95), with 12 mm of rainfall on Day 6, is not reflected in the backscattering coefficients. Since the temporal variations occur in all surfaces simultaneously – and beyond the precision of the instrument of ±0.5 dB (Laur et al., 1997) – no other possible explanations could be found for these variations. Therefore, in our opinion, a possible calibration or processing problem should not be canceled out a priori.

4.3. The effects of winds on backscattering from lakes

A possible explanation could be related to wind effects which together with precipitation and soil moisture are among the few mechanisms which could affect a larger region. Because winds have a strong influence on the $\sigma^0$-values of open water bodies, it is interesting to compare the temporal variations of $\gamma$-values of lakes with those of the land surface units. Fig. 5 shows the course of $\gamma$-values over time for the five lakes; the first date refers to EMISAR, all others refer to ERS-1 as given in Table 1. Although one might expect the different lakes to develop different wave spectra because of their different dimensions, different forms, different depths and different orientations with respect to the surrounding landscape (Heikinheimo et al., 1999, this issue) – and thus respond differently in terms of radar backscattering – the similar behavior over time is phenomenal except for the 3rd observation day (7 July 1994). All lakes react very similarly and it is most likely that the variations in time must be ascribed to wind effects. However, for comparing wind velocities with backscattering values of lakes, a series of other factors has to be considered as well, such as: (a) possible lake ice in winter and early spring, (b) azimuth angles of the radar beam, i.e. ascending or descending mode of ERS-1, and (c) the prevailing wind direction relative to the azimuth angles of the radar beam. Moreover, local wind fields on and around lakes may deviate from the regional wind due to local scale phenomena (Heikinheimo et al., 1999, this issue).

Fig. 6 shows a plot of $\gamma$ versus wind speed, observed at the NORUNDA tower at a height of 58 m and ~20 km northeast of the lake area. If we exclude the EMISAR because of the different angle of incidence, there exists a positive though weak correlation between $\gamma$ and wind speed ($r^2 = 0.304$). The scatter, however, is fairly large. The strong increase (Fig. 5) in
between 11 and 16 July 1995 is similar for all five lakes although the change in wind speed is only from 5–6.5 m/s. This large increase in backscattering might be due to the difference in wind direction with respect to the azimuth angle of the radar beam; i.e. ascending on 11 July, with a wind direction almost opposite to the radar beam, and descending on 16 July, with a wind direction almost perpendicular to the radar beam. The strong decrease between the 11 June and 11 July is also similar for all lake surfaces but goes together with an increase in wind speed, be it from opposite directions. Obviously, winds may direct the roughness elements of water bodies in one dominant direction, thus influencing the backscatter in the direction of the satellite, which makes the retrieval of wind speed a complex issue.

4.4. The effects of winds in backscattering from land surface

Comparison of the backscattering values of the lakes (Fig. 5) with those of the land surface units (Fig. 3a) shows that wind phenomena do not easily explain the sudden increase in land surface backscattering between 24 June 1994 (ascending) and 7 July 1994 (descending) and the sudden decrease in land surface backscattering between 11 July 1995 (ascending) and 16 July 1995 (descending). Both cases go together with a strong increase in lake surface backscattering, whereas the change in land surface backscattering between these cases is opposite for all land surface classes. Therefore, it is unlikely that the influence of wind is the proper explanation for the systematic short term changes observed in Fig. 3.

The effect of winds on the backscattering of vegetation can also be looked at on the basis of observed backscattering values during two successive days (23 June 1994 for EMISAR and 24 June for ERS-1) – the 1st and 2nd observation dates – with a strong contrast in regional wind speed. During the EMISAR flight of 23 June, there was a strong wind of 9 m/s, while during ERS-1 observation the next day (24 June) the wind speed was low again (<2 m/s). Direct comparison between both instruments should of course be done with great care because of the different instrument specifications, azimuth and incidence angles (50° and 23°, respectively, for EMISAR and ERS-1). Fig. 7 shows a plot of ERS-1 versus EMISAR C-band VV backscattering coefficients observed on the two dates. The figure indicates a strong similarity for all forest classes and a 1 dB difference for the agricultural area. Unless a potential wind effect would be counterbalanced by the effect of the different incidence angles for all forest density classes, this supports the conclusion that wind effects on the backscattering of forest is probably low.
Finally, it is interesting to see the difference between EMISAR and ERS-1/C-band VV for the agricultural area which may indicate enhanced information contribution by using a two-incidence angle radar system (e.g., the Canadian RADARSAT).

5. Summary and conclusions

A set of seven multi-temporal ERS-1 C-band VV-polarization images of the NOPEX boreal landscape were analyzed. An aerial photo survey and field observations were carried out to distinguish forest units of different tree density. It was found that the difference in backscattering for three different classes (dense forest, intermediate forest and open forest) were small (<0.5 dB). The differences were consistent throughout the seasons, indicating that they are significant, at least in a relative sense. However, the required large number of pixels (>240) to achieve a radiometric precision of ±0.5 dB does not allow spatial discrimination of the different classes and delineation of their boundaries.

In addition, the effect of regional winds on the backscattering of lakes was studied. For this purpose five of the larger lakes were selected and the backscattering coefficients were compared with wind data taken from a tower at a height 58 m above the surface, approximately 20 km from the center of the study area. Backscattering values of the lake surfaces varied between −24 and −9 dB. It was found that all five lakes behaved very similar, indicating that for the dates included in this analysis - the variations in backscattering were most probably dominated by regional wind fields, rather than by local winds. We found a positive correlation between backscattering and wind speed, however, with a substantial scatter. This has been ascribed to variations in wind direction with respect to the azimuth angle of the radar beam. Since large scale wind fields are difficult to observe in a synoptic way, the use of radar might have potential for monitoring regional wind fields in the Swedish boreal region, which is characterized by the occurrence of many lakes.

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References


Laur, H., 1992. ERS-1 SAR Calibration: derivation of the backscattering coefficient \( \sigma^0 \) in ESA ERS SAR PRI products, issue 1, Rev. 0, ESA-ESRIN, October 1992.


