ABSTRACT

Ten ERS image pairs from the tandem period have been analyzed for two test sites in Sweden and the results have been compared with results based on 24 image pairs from two previously studied test sites. All four test sites represent boreal forests and include 338 forest stands with stem volumes up to 539 m$^3$/ha. With optimal environmental conditions (sub zero temperature, dry snow layer, moderate breeze) and large and homogeneous forest stands the relative RMSE is of the order of 20% while for less optimal environmental conditions the relative RMSE is of the order of 30%. The relative RMSEr is increasing with increasing number of small stands or stands with low stem volume. No saturation with stem volume is found. The consistency of coherence observations for a certain stand can be used to identify the potential of giving accurate estimates of stem volume. A baseline of the order of 200-250 m is favorable.

1. INTRODUCTION

Stem volume or biomass estimation is an important application for space borne SAR remote sensing due to its operational as well as climatological role. Optical satellites have been shown to be useful in operational applications in Finland and Sweden. In the microwave region the interest is presently focusing on P and L bands using polarimetry and interferometry However, much can still be done to improve our knowledge of the applicability of previous satellite missions. The aim of the present paper is to continue an ongoing evaluation of ERS-1/ERS-2 tandem data for boreal test sites. Repeat pass InSAR data have similarities with optical data in the sense that environmental properties influence the accuracy and that the dataset is calibrated by means of reference sites on the ground. One question is if the ERS-1/2 tandem data can give accuracies comparable to optical data.

The accuracy of stem volume estimates by means of remote sensing depends on many factors, the homogeneity of forest properties, the topography, the environmental influence, the sensitivity to different scattering mechanisms etc. The environmental influence is problematic in the sense that it varies from observation to observation as well as from stand to stand. These factors point at the importance for studies comparing large numbers of observations from several test sites before any conclusions on accuracy and usability are drawn.

For forest applications a major problem is to obtain accurate in situ data due to the intensive work associated with such data collection. In earlier work we have investigated data from the Swedish test site Kättbölö and the Finnish test site Tuusula, and will now consider two additional Swedish test sites, Remningstorp and Brattåker (in situ data courtesy Dr. Johan Fransson), see Fig. 1 for location.

Figure 1 Scandinavia with test sites marked.

In this paper the results from the two new test sites will be presented and compared with the previous test sites. Finally the properties and usefulness of ERS tandem data for stem volume estimates in boreal forests will be discussed.

2. METHODS

Radar data from five ERS-1/2 “tandem” pairs acquired between 1995 and 1996 for each of the two new test sites are processed by means of the Gamma InSAR software.

The model expression for coherence as function of stem volume is expressed by means of the Interferometric Water Cloud Model, IWCM, extensively presented elsewhere [1-3]. The model takes into account the decorrelation of the ground and the
vegetation layer including the volume decorrelation of which the phase plays an important role for larger baselines. For repeat pass interferometry the phase often is noisy, but also for the cases with large baselines studied below IWCM has been found to give a good basis for inversion of the observations. After model parameters have been derived using known forest stands for training of the model, the stem volumes of test stands are determined and the root mean square error versus in situ data relative the mean stem volume, denoted RMSEr, is determined.

For estimates of the accuracy of satellite observations, corrections for the uncertainties in in situ data should be applied. However, since such corrections are approximate they are not commonly done, and will not be included in this paper.

For simplicity we have used all the stands for training as well as testing. For statistical significance better methods are in use, but the simple method has been chosen in the belief that the results are mainly dependent on the variability of forest properties and environmental conditions.

An important aspect of microwaves is the independence of clouds and the possibility to acquire data regularly. A multitemporal combination of the observations weighted by the uncertainty of each observation and the percentage of stands within the model range [2] is an important way to compensate the environmental influence on each of the acquisitions.

### 3. TEST SITES AND INVESTIGATIONS

The investigated areas are covered mainly with typical boreal coniferous species, i.e. Scots pine (Pinus sylvestris) and Norway spruce (Picea abies); but some deciduous species are also present, the commonest being birch (Betula pendula).

A forest stand consists of relatively homogeneous forest properties and site conditions, and we will use the mean stem volume of the forest stands as the quantity of interest in this analysis. The stem volume is associated with the above ground biomass by a multiplicative factor. Some papers use the forest age as a substitute for stem volume/biomass, but for the test sites considered there is no clear relation between age and stem volume. The forest height is also of importance, in particularly for larger baselines (200 - 250 m) and an allometric expression introduced in [1] is used for the relation between stand mean height and stem volume. This relation is included in Fig. 2.

From Fig. 2 we see that the sites typically include some stands consisting of seed trees (large heights, small stem volumes). The deviation between the allometric $h(V)$ relation from the in situ observations may be used as an illustration of the site conditions.

![Figure 2. Illustrating forest properties in for the test sites in the form of the relation between height and stem volume {dotted curve: allometric relation used $h(V) = (2.44 V^{0.46})$.}](image)

#### 3.1. Brattåker

Brattåker (lat. 64°16′ N; long. 19°33′ E) is a forest research park located in northern Sweden and managed by the Swedish forest company, Holmen Skog AB. It covers approximately 6000 ha. Elevations in the test site range from 160 to 400 m above se level and slopes up to 12° are common, and in one case 21°.

The in situ data include 53 stands carefully inventoried (at the 10% level) in 2000. Based on growth factors the status in 1996 was estimated. However possible thinning etc decrease the accuracy of the in situ data. We only include 48 stands for which the coherence values can be averaged over at least 24 pixels corresponding to 1.5 ha. If we also exclude stands with slopes exceeding 10° we have 41 left.

Five image pairs have been analysed, one from October 13/14 1995 (desc.) and four from 1996, namely February 27/28 (desc.), March 03/04 (asc.) and 17/18 (desc.), and April 02/03 (desc.). Since two of the pairs only covered half the investigated area and these pairs also showed serious decorrelation only three pairs will be further considered; October 13/14 1995 and two from 1996 March 03/04 (asc.) and 17/18 (desc.). For those acquired in March the temperature varied close to zero degrees during the day with risk for decorrelating changes of the snow layer. The best image pair is illustrated in Fig. 3. For the model fit we have used all 54 stands, and the figure illustrates the observations and the associated IWCM (solid line) and also an exponential model (dashed line).

The inversion result in the case of IWCM is illustrated in Fig. 4 in which the 54 stands are marked by a red cross. For these 54 stands we obtain RMSEr = 36%. 41 stands remain when stands < 24 pixels and
stands with slopes >10° are excluded are marked by a circle. In this case the RMSEr is 32%. Finally, if all slopes are included for stands with at least 24 pixels we obtain RMSEr = 33%, illustrating that the small stands cause larger uncertainties than large slopes.

3.2. Remningstorp

Remningstorp (lat. 58°30' N; long. 13°40' E) is a 1200 ha forest estate run by Skogssällskapet AB. This is a site with many ongoing forest research activities. Elevations in the test site range from 120 to 145 m above sea level.

The in situ data include 105 stands inventoried (at the 10% level). The inventory took place during 1997-2002. To decrease the uncertainties in the in situ values associated with unknown thinnings etc, we include stands that were inventoried not later than 2000 and used growth factors to estimate the status in 1996. A demand was also that the coherence values can be averaged over at least 24 pixels corresponding to 1.5 ha.

Five image pairs have been analyzed, all from 1996, namely March 05/06 (asc.) and 07/08 (desc.), April 09/10 (asc.), 11/12 (desc.), and 27/28 (desc.). Due to decorrelating weather conditions only the pairs from March 05/06, April 09/10, and 27/28 will be further considered.

The best image pair is illustrated in Fig. 3. For the April pairs the temperature at the acquisition is relatively close to zero degrees and the maximum temperature during the day was > 0° C. Some decorrelation could then be caused by the snow layer. In Fig. 6 we have illustrated the retrieved stem volume as function of the in situ values.

By excluding stands including less than 24 pixels we have 34 stands left with an RMSEr = 32% and if we also exclude those for which the inventory data are from 2000 we have 26 stands with RMSEr = 29%. Finally, if we include the stands with 18-24 pixels but exclude stands for which the inventory data are from 2000 we are left with 30 stands with an RMSEr = 26% (one stand, ID=2145, with suspicious in situ data excluded in all cases). Although differences are small this points at the importance of having in situ data close in time with
the acquisitions. Information on thinning etc will possibly be available in the future.

3.3. Tuusula

The test site Tuusula (lat. 60°N long. 25°E) consists of 210 stands of which eight stands were too small for estimates of backscatter and coherence. Elevations in the test site range from 35 to 90 m above se level. In situ data were collected in summer 1997 as part of the EUFORA project [4], and has together with InSAR data been analyzed in several papers cf. [5-7]. The best image pair is illustrated in Fig. 3.

37 stands were once selected as especially suitable for inversion for being large and homogeneous [5]. Here we divide the 202 stands in three groups of stand, type A, B, and C. A and B consists each of 18 of the large homogeneous stands. We now determine the multitemporally estimated stem volume for type A trained on B, type B trained on A, and the mean result of type C trained on either A or B. Results are shown in Fig. 7.

Figure 7 Illustrating the estimated stem volumes for all the 202 stands (red crosses) and with blue circles in a) for 36 large and homogeneous stands selected from in situ visit, and b) for stands including more than 4 pixels and with stem volume more than 100 m³/ha.

Figure 8 Illustrating the RMSEr for increasing number of stands sorted after decreasing estimated stem volume. In the case of the blue curve stands less than 4 ha and for which the estimated stem volume is less than 200 m³/ha have been excluded leaving 65 stands with an RMSEr = 33%.

Fig. 7 illustrates the scattered results associated with the 202 stands (red crosses) and for all we obtain RMSEr = 58%. In a) we have marked the results for the two groups A and B, using the other for training. We obtain for these 36 stands RMSEr = 20%. In b) we have excluded stands less than 4 pixels and also those with in situ stem volume less than 100 m³/ha. For the remaining 85 stands we obtain RMSEr = 26%.

In the case of Tuusula we have a large number of stands and the RMSEr analysis for all the stands end up in 58%. This raises questions about the possibility to select stands in such a way that the RMSEr is in a range of interest for practical applications i.e. up to 30%. We have illustrated such selections above, including only large and homogeneous stands based on inspection on site, or disregarding small stands and stands with small stem volumes, Fig. 7. We have also studied possibilities to sort the stands after the retrieved stem volume, Fig. 8. It can then be shown that RMSEr is highest for stands with small stem volume and lowest for stands with high stem volume, see Fig. 8. Based on backscatter studies C band is found to saturate for relatively low stem volumes with low estimation accuracy as a consequence. Also for coherence saturation is expected to happen, but for higher stem volumes and from the analysis of the stands in Tuusula including stands up to 539 m³/ha this is not seen, see Fig. 9. On the contrary it is stands with stem volumes < 100 m³/ha that have the largest relative errors.

Stands can be sorted after decreasing area, decreasing stem volume or after increasing Outlier value. The Outlier concept in [8], based on the spread of coherence values between different image pairs. In these cases the RMSEr is typically found to increase with increasing number of stands included, cf Fig. 8. Such sorting mechanisms can be used to identify stands for which stem volume can be estimated with highest accuracy.

3.4. Kättbölö

Kättbölö (lat. 60°N long. 17°E) was the first test site analyzed [2, 9]. Elevations in the test site range from 75 to 110 m above se level. Accurate in situ data were collected 1995 and 1996 and those from 1995 corrected
by growth factors. The image pair for which the estimated stem volume is most accurate is illustrated in Fig. 3 (baselines 218, 55, and 66 m). Using all stands for training as well as testing the RMSEr of these three pairs are 20%, 32%, and 38% respectively. The multitemporal combination of all nine pairs results in 19% for the 42 stands, cf. Fig. 10.

![Timeline](image.png)

**Figure 10** Estimated stem volumes in Kättbölle.

### 4. CONCLUSIONS AND DISCUSSIONS

We have considered in total 34 ERS-1/2 tandem pairs including 24 from previous publications. The four test sites represent examples on Scandinavian boreal forest – three of them at the southern edge. They are managed by different organizations/companies and forest properties of the in total 338 forest stands have been determined by foresters, for two sites (Kättbölle and Tuusula) within one year and for the other two within two to four years time difference to the ERS tandem observations.

Repeat pass interferometry is influenced by environmental effects, and the list in Tab. 1 illustrates the weather conditions for the three image pairs for which the RMSEr of the retrieved stem volume is highest. Best conditions are obtained when temperature is a few degrees below the freezing point, with a dry snow layer on the ground (characterizing high ground coherence) and a wind speed characterized by at least moderate breeze (for low vegetation coherence). Such conditions were obtained in Kättbölle and Tuusula, while it happened that the low temperature situation in Brattäker occurred before the first winter pair.

We have used a multitemporal combination of observations to reduce retrieval errors associated with noise and environmental effects and we have also shown how a multitemporal filtering can be used to identify the relative contribution of various stands to the relative RMSE of the estimated stem volume.

The analysis has illustrated that the retrieval accuracy is related to:

- **Stand size**: at least 1.5 ha (large and homogeneous stands give best agreement with in situ data)
- **Stem volume**: small stem volumes cause accuracy problems; higher relative accuracy is obtained for larger stem volumes
- **Baseline of image pair**: Somewhat large baselines are typical for “good” conditions. Of the 34 image pairs studied seven had baselines in the range 200 – 250 m. Four of these belong to the best twelve image pairs. This result is obtained using the Interferometric Water Cloud Model.

### Table 1. Weather conditions during those three image pairs from each test site showing the best RMSEr.

<table>
<thead>
<tr>
<th>Date</th>
<th>Baseline m</th>
<th>Temp. °C</th>
<th>Wind speed m/s</th>
<th>Snow depth cm</th>
<th>Prec mm</th>
<th>RMSEr %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Brattäker</strong>, stem volume: &lt; 305 m³/ha, multitemporal RMSEr = 33%</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1995-10-13/14</td>
<td>219.7</td>
<td>+5.4/+8.4</td>
<td>5/10</td>
<td>0/0</td>
<td>0/0</td>
<td>42</td>
</tr>
<tr>
<td>1996-03-03/04</td>
<td>228.5</td>
<td>-2.7/-2.5</td>
<td>2/2</td>
<td>36/40</td>
<td>0/0</td>
<td>32</td>
</tr>
<tr>
<td>1996-03-17/18</td>
<td>84.3</td>
<td>-1.7/-2.6</td>
<td>2/2</td>
<td>33/33</td>
<td>0.1/0</td>
<td>32</td>
</tr>
<tr>
<td><strong>Remningstorp</strong>, stem volume: &lt; 494 m³/ha, multitemporal RMSEr = (32 or) 26%</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1996-03-05/06</td>
<td>250.2</td>
<td>-0.6/-1.2</td>
<td>1/1</td>
<td>8/7</td>
<td>0/2.3</td>
<td>46</td>
</tr>
<tr>
<td>1996-04-11/12</td>
<td>-89.1</td>
<td>-3.1/-3.1</td>
<td>5/5</td>
<td>0/0</td>
<td>0/0</td>
<td>45</td>
</tr>
<tr>
<td>1996-04-27/28</td>
<td>-84.5</td>
<td>-2.4/-6.6</td>
<td>5/5</td>
<td>0.8</td>
<td>0/0</td>
<td>44</td>
</tr>
<tr>
<td><strong>Tuusula</strong>, stem volume: &lt; 540 m³/ha, multitemporal RMSEr = 58%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1996-02-12/13</td>
<td>85</td>
<td>-14.9/-10.8</td>
<td>5/1</td>
<td>16/19</td>
<td>1.4/0</td>
<td>60</td>
</tr>
<tr>
<td>1996-03-02/03</td>
<td>76</td>
<td>-4.2/-5.5</td>
<td>4/3</td>
<td>32/32</td>
<td>0.1/0</td>
<td>74</td>
</tr>
<tr>
<td>1995-10-14/15</td>
<td>220</td>
<td>+8.6/+6.2</td>
<td>6/1</td>
<td>0/0</td>
<td>0/0</td>
<td>82</td>
</tr>
<tr>
<td><strong>Kättbölle</strong>, stem volume: &lt; 335 m³/ha, multitemporal RMSEr = 19%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1996-03-12/13</td>
<td>220</td>
<td>-4.9/-4.4</td>
<td>2.5/2.5</td>
<td>10/10</td>
<td>0/0</td>
<td>20</td>
</tr>
<tr>
<td>1996-03-17/18</td>
<td>66</td>
<td>-1.7/-2.8</td>
<td>1.7/0.9</td>
<td>10/10</td>
<td>0/0</td>
<td>38</td>
</tr>
<tr>
<td>1996-04-21/22</td>
<td>55</td>
<td>+12.8/+12.5</td>
<td>2.3/1.3</td>
<td>0/0</td>
<td>0/0</td>
<td>32</td>
</tr>
</tbody>
</table>
For the best environmental situations and for large homogeneous stands an RMSEer of 20% is obtained (correcting for in situ data errors 15% is reached), but for the two new test sites, for which we have only five image pairs and for temperature conditions close to zero degrees, the result is more like 30%.

Observations using other sensors have been performed for the same test sites, cf [9-12]. Results are not directly comparable but indicate that the results for ERS tandem pairs are comparable with optical images (SPOT and Landsat) reported to have RMSEer 24 – 38%. In the other end of the frequency range we find CARABAS, an airborne VHF-SAR, with much higher spatial resolution and with RMSEer 19 – 30% excluding stands with small stem volume. An ongoing investigation using CARABAS-II in Remningstorp has given RMSEer = 13% using a combination of 15 overpasses (courtesy Klas Folkesson). For standard methods like photo-interpretation one can find figures in the literature indicating accuracies such as 26 – 39%. The accuracy of in situ observations may vary 10 – 34% with a mean of 21.4% cf. [13] Other sensors are based on accurate height observations to determine stem volume and for laser scanning the RMSEer for Remningstorp is reported to 19 – 26% on plot level and 11% on stand level [14].

We have only considered estimation of stem volume and many other aspects may be added for deciding on the optimal sensor, but obviously C-band repeat pass interferometry is an interesting alternative for estimation of stem volume and biomass above ground in boreal forests from satellite with potential of accuracy comparable to standard methods.

5. ACKNOWLEDGEMENT

The ERS tandem pairs (obtained as an ESA Cat-1 project, ID 3121) and in situ data for Brattåker and Remningstorp (obtained from Dr Johan Fransson, Swedish Univ. of Agricultural Sciences) are gratefully acknowledged. Part of the work was supported by the Adlerbert Research Foundation and the Swedish National Space Board.

6. REFERENCES