Monitoring of boreal forests with active and passive microwave sensors

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Abstract

New inversion methods are presented for active and passive satelliteborne microwave remote sensing. The objectives are biomass estimation, forest and land-cover type recognition in boreal forests. A new indirect inversion method for active sensors was developed for the forest block-wise stem volume estimation from satelliteborne radar images (e.g. JERS-1 and ERS-1 SAR). The inversion results with L-band and/or C-band SAR images showed promising accuracies: the relative retrieval rms error varied from 30 % to 5 % as the size of the forest area varied from 5 to 30000 hectares (the forest stem volume varied from 0 to 300 m^3/ha). The textural information of a seasonal set of satelliteborne radar images was studied with the first and second order statistical measures. The multitemporal approach was beneficial for the textural measures in forest and land-cover type recognition. Based on the SAR image texture, the overall classification accuracy for seven land-cover types was 65 % while with the SAR image intensity, the classification accuracy was 50 %, respectively. In the forest type classification based on the SAR image texture and intensity, the overall classification accuracy for four forest types was 66 % while with the intensity alone, the accuracy was 40 %, respectively. With the passive microwave sensor (e.g. satelliteborne SSM/I radiometer), the mixed pixel approach was employed for stem volume (biomass) and forest coverage fraction estimation. The results obtained, show that the pixel-wise fractions of water, non-forested, and forested area can be estimated with a rms errors of around 10 %-units. A new stem volume inversion method for wintertime SSM/I data achieved promising accuracies, the rms error was from 13 to 19 m^3/ha per pixel (25 km by 25 km) which was 15 to 16 % of the mean stem volume. In the test area, the stem volume ranged from 40 to 160 m^3/ha per pixel.

Keywords: Forest biomass estimation, land-cover and forest type classification, JERS-1 SAR, ERS-1 SAR, SSM/I

1 Introduction

The boreal forest belt covers large areas of Europe, Asia and North America forming the largest vegetation zone on Earth. The coniferous trees, such as pines and spruces, are the dominating tree species in this biotype. A large seasonal temperature variation is typical for the area. Therefore, the growing season is halted for winter when ground is frozen and covered by snow. The primary objects of our study are biomass estimation, forest and land type recognition from active and passive satelliteborne microwave images of boreal forests.

Active microwave sensors (e.g. Synthetic Aperture Radar, SAR) have a good spatial resolution, but their radiometric resolution is moderate, because of the coherent measurement method. In contradiction to the active sensors, passive sensor (e.g. radiometer) have a good radiometric accuracy and a wide coverage but the spatial resolution is moderate (tens of kilometres). Therefore, radiometers could be used for global monitoring while SARs provide more detailed local information.

1.1 Characteristics of radars images

The total backscatter of forest is a combination of the backscatter from ground and vegetation. Several studies (Dobson et al. 1991, Ahern et al. 1993, Pulliainen et al. 1996) have shown that the seasonal effects, such as soil freezing and thawing, snow cover and soil wetness, drastically change the level of the total backscatter in the boreal forest. Thus, the correlation between the biomass and the backscattering coefficient is also dependent on the above mentioned factors. Nevertheless, these seasonal effects may also benefit the inversion if suitable models are used with a multitemporal data set (Pulliainen et al. 1996).

The direct application of the backscattering coefficient for forest biomass inventory is limited by saturation (Dobson et al. 1992, Kasischke et al. 1994, Rignot et al. 1994). The lower SAR frequency bands (P- and L-band) are more suitable for biomass measurements than the higher one (C-band). The P-band would be the most promising for biomass measurements, but it is not available on satelliteborne sensors. The Japanese JERS-1 satellite has a L-band SAR which is the most useful of the satellite radars for forest biomass estimation. The higher frequency (C-band) is more suitable for the recognition of different forest and land types than the lower frequencies.

1.2 Characteristics of radiometer images

The interest towards microwave radiometers is growing because of the introduction of a 90 GHz channel which gives an approved spatial resolution (about 10 km). Moreover, ESA is planning to launch the Multifrequency Imaging Microwave Radiometer (MIMR) which will also have a 90 GHz channel. At the moment the SSM/I (Special Sensor Microwave Imager) is the only spaceborne sensor that can provide spaceborne data for the 90 GHz frequency band.

The seasonal snow cover causes relatively large changes on the brightness temperature in the boreal forests. The brightness temperature for forest vegetation is close to its physical temperature while the brightness temperature for dry snow is relatively low at frequencies above 20 GHz. Therefore, in winter the total brightness temperature is related to the forest canopy. Nevertheless, in wet and snow-free conditions this relation is weak because the emissivity of ground and that of forest vegetation are close to each other (Kurvonen et al. 1997).

The main limitation of the spaceborne microwave radiometry is its moderate spatial resolution; therefore, only few radiometry studies (Hallikainen et al. 1988, Neale at al. 1990) have been associated with the boreal forests. Moreover, these studies were mainly concentrated on land-type classification.

2 Test site and data

2.1 Test sites and ground truth

Two test sites were selected for the analysis of the SAR images. The test site SAR-1 (Porvoo) was in southern Finland and the test site SAR-2 (Sodankylä) was in northern Finland, see Table 1. The extensive ground truth set included rainfall distribution, temperature, snow, land-use and forest information. The SAR-1 has pine-, spruce- and birch-dominated forest stands, with relatively small age variations due to the industrial use. The test site SAR-1 is a good representative for the Scandinavian forests. The northern test site (SAR-2) is pine-dominated and the stands are more sparse and unevenly aged which is typical at those latitudes. The Finnish Forest Research Institute (FFRI) provided the forest measurements for the test sites.

The spatial resolution of spaceborne radiometers is tens of kilometres. Thus, the radiometer test site had to be relatively large to cover

Table 1. SAR test sites.

Test site number	Location	Centre latitude	Centre longitude	Size
SAR 1	Porvoo, southern Finland	60°30'N	25°30'E	100 x 100 km^2
SAR 2	Sodankylä, northern Finland	67°25'N	26°30'E	40 x 40 km^2

several pixels. Therefore, the whole Finland was used as a test site, but it was divided into sub-areas according to snow and temperature conditions. The Finnish National Forest Inventory Data Bank provided the forest information for the whole Finland.

2.2 Spacebore data

Twenty-two geo-coded ERS-1 PRI-images, 8 for Sodankylä and 14 for Porvoo, were used in the study. Respectively, seven JERS-1 images, five for the Porvoo test site (SAR-1) and two for the Sodankylä test site (SAR-2) were used. The applied radiometer (SSM/I) images covered whole Finland, the images were taken twice a day for 1 July 1993 through 30 June 1994.

3 Methodology and results

3.1 Land and forest type classification with multitemporal SAR texture

Due to resampling and spatial averaging ERS-1 PRI and JERS-1 (level 2.1) images are expected to have a low textural information. Nevertheless, the textural information of the seasonal set of ERS-1 and JERS-1 SAR images was studied with the first and second order statistical measures. For the forest and land type classification, the multitemporal textural measures showed a higher information value than the intensity. If a single image was used, the textural and/or intensity information was not adequate for a satisfactory classification. However, the textural measures from a multitemporal image set significantly improved the classification of land-use and forest types. Based on the SAR image texture, the overall classification accuracy for 7 land-cover types was 65 % while with the SAR image intensity, the classification accuracy was 50 %, respectively. Table 2 shows presents the classification for the 7 land-cover types. In the forest type classification based on the SAR image texture and intensity, the overall classification accuracy for 4 forest types was 66 % while with the intensity, the accuracy was 40 %, respectively. Table 3 presents the classification for the forest types. For more details, see Kurvonen et al. (1996) and (1998c).

3.2 Stem volume estimation with SAR

An indirect inversion method was developed to estimate a forest-stand-wise stem volume from JERS-1 and ERS-1 SAR images. The method is based on a semi-empirical backscattering model by Pulliainen (1994). The model presumes, that the backscattering of a forest canopy is determined by (a) stem volume, (b) soil moisture and (c) vegetation moisture. In the inversion process, the area of interest is divided into training (10 %) and test areas (90 %). The stem volume for the training areas has to be known. The inversion algorithm has three steps and it is carried out as follows,

Table 2. Confusion matrix for the land-cover type classification. The rows present the results of the classification in percent and the columns are from the land-use map. The classification is based on the texture and intensity of the ten SAR images.

	Water	Agricul-tural land	Gravel	Clear-cut	Forest	Mire	Open bog
Water	96.7	5.1	0.6	1.9	2.0	1.0	1.0
Agricultural land	0.6	38.7	2.2	1.9	0.7	0.6	0.1
Gravel	0	1.7	67.0	0.4	0.6	0	0.1
Clear-cut	0.5	18.4	6.9	27.2	6.4	4.8	4.2
Forest	1.4	27.3	23.0	47.0	76.0	22.3	12.2
Mire	0	7.0	0.4	15.4	9.5	61.5	19.9
Open bog	0.7	1.8	0	6.3	4.8	9.7	62.5
Number of pixels	6 443	2 901	1 632	17430	141 416	16 895	38 216

Table 3. Confusion matrix for the forest type classification. The rows present the results of the classification in percent and the columns are from the land-use map. The classification is based on the texture and intensity of the ten SAR images.

	Coniferous	Deciduous	Mixed forest	Mire
Coniferous	74.1	42.4	36.8	23.1
Deciduous	12.1	41.0	12.3	10.5
Mixed forest	6.6	9.4	44.3	4.8
Mire	7.2	7.3	6.6	61.6
Number of pixels	111 390	27 111	2 915	17 072

1) For the training areas, the soil and vegetation moisture is estimated from the backscattering coefficient and the stem volume with the model. The soil and vegetation moisture parameters are interpolated to cover the whole area of interest.
2) For the whole area of interest, the stem volume is estimated with the model from the backscattering coefficient and the moisture parameters.
3) If several SAR-images are used, the stem volume estimates are combined with the multiple linear regression. The regression equation is defined from the stem volume estimation and ground truth of the training areas.

The results for the stem volume estimation using L-band and/or C-band SAR data showed promising accuracies: the relative rms error varied from 25 % to 6 % as the size of the forest area varied from 10 to 30000 hectares (the forest block wise stem volume varied from 0 to 300 m^3/ha), see Figures 1 to 4. For more details, see Kurvonen et al. (1996) and (1998b), Pulliainen et al. (1997).

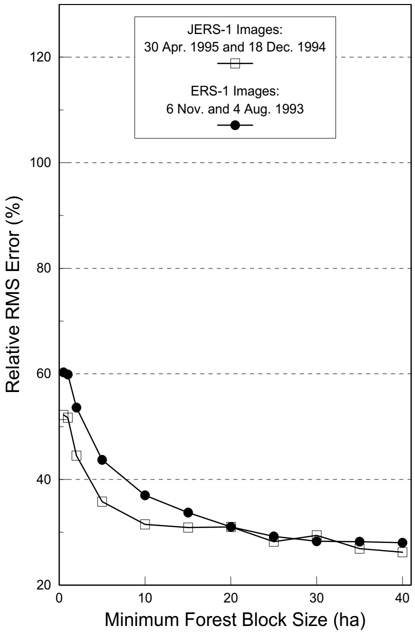

Figure 1. Relative rms error of the stem volume estimations vs. minimum forest block size.

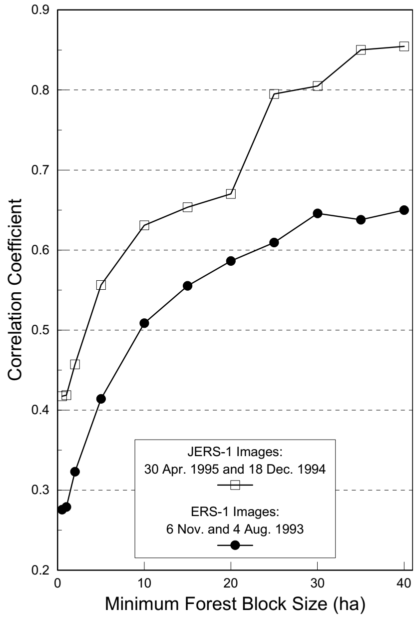

Figure 2. Correlation between the estimated stem volume and the ground truth vs. minimum forest block size.

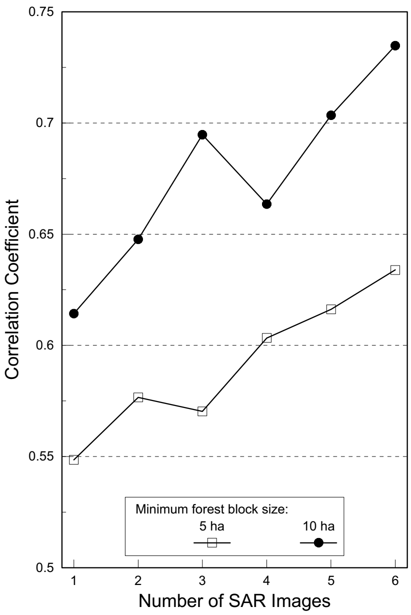

Figure 3. Correlation between the estimated stem volume and the ground vs. the number of employed SAR images. Correlation coefficients are presented for forest blocks larger than 5 ha or 10 ha.
1 SAR image: JERS-1 for 15 March 1995,
2 SAR images: JERS-1 for 15 March 1995 and 23 May 1993,
3 SAR images: JERS-1 for 15 March 1995 and 23 May 1993, and ERS-1 for 6
4 SAR images: November 1993, JERS-1 for 15 March 1995, 18 December 1994 and 23 May 1993, and ERS-1 for 6 November 1993,
5 SAR images: JERS-1 for 15 March 1995, 18 December 1994 and 23 May 1993, and ERS-1 for 4 August 1993 and 6 November 1993,
6 SAR images: JERS-1 for 15 March 1995, 18 December 1994 and 23 May 1993, and ERS-1 for 4 August 1993, 2 October 1993 and 6 November 1993.

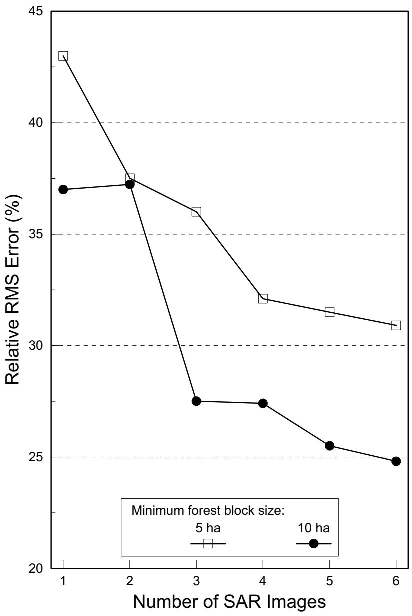

Figure 4. Relative rms error of the stem volume estimations vs. the number of employed SAR images. The rms errors are presented for forest blocks larger than 5 ha or 10 ha.
1 SAR image: JERS-1 for 15 March 1995,
2 SAR images: JERS-1 for 15 March 1995 and 23 May 1993,
3 SAR images: JERS-1 for 15 March 1995 and 23 May 1993, and ERS-1 for 6
4 SAR images: November 1993, JERS-1 for 15 March 1995, 18 December 1994 and 23 May 1993, and ERS-1 for 6 November 1993,
5 SAR images: JERS-1 for 15 March 1995, 18 December 1994 and 23 May 1993, and ERS-1 for 4 August 1993 and 6 November 1993,
6 SAR images: JERS-1 for 15 March 1995, 18 December 1994 and 23 May 1993, and ERS-1 for 4 August 1993, 2 October 1993 and 6 November 1993.

3.3 Monitoring of boreal forests with spaceborne microwave radiometer

Due to the moderate resolution, the mixed pixel approach is used in the analysis of the radiometer data. The three possible mixed pixel approaches are: a) in each pixel spatial fractions of different areas types are known and their emissivities are calculated, b) in each pixel emissivities or brightness temperatures of the different area types are known (or modelled) and their spatial fractions are calculated c) the combination of a) and b).

First, the spectral emissivity behaviour for forest, non-forest and water areas was studied with the mixed pixel approach. In winter the effect of dry snow was obvious and the emissivity of forest separated well from that of non-forest. In summer the emissivity variation was determined by water areas, while in winter the dominating factors were forest canopy and snow covered ground, respectively.

Even during snow-free conditions, rough estimates for forest coverage could be retrieved with the mixed pixel approach. Nevertheless, the most accurate forest coverage estimates were retrieved during winter conditions. With the combination of summer and winter measurements, the coverage of water, non-forest and forest inside a pixel can be estimated with an rms errors around 10 %-units. See Figures 5 and 6.

An indirect inversion method was developed to estimate the pixel wise stem volume from the winter-time SSM/I data. The method is based on the fact, that in winter forest canopy and snow cover are the dominating factors of the emissivity. Nevertheless, the snow cover emissivity is dynamic; therefore, long term averages are used in the inversion. Additionally, the averaging diminishes the atmospheric disturbances and uncertainties with the physical temperature measurements. The area of interest is divided into a training set (20 %) and test set (80 %). The pixels around the weather stations, referred as training areas, were used as a training set while the rest of the data was used for testing the algorithm. The air temperature, the forest and non-forest coverage and the stem volume are known for the training areas. The inversion algorithm has five steps and it is carried out as follows,

1) The emissivity estimates of the two target types (forest and non-forest) are calculated with the mixed pixel approach from the training set. In the test case, the training set consists of the 15 weather stations and their surroundings. The calculated estimates represent the mean emissivities of the target types. In order to unfold the local variation in the emissivities, local emissivity estimates are also calculated by solving the mixed pixel equations separately for the surroundings of each weather station.

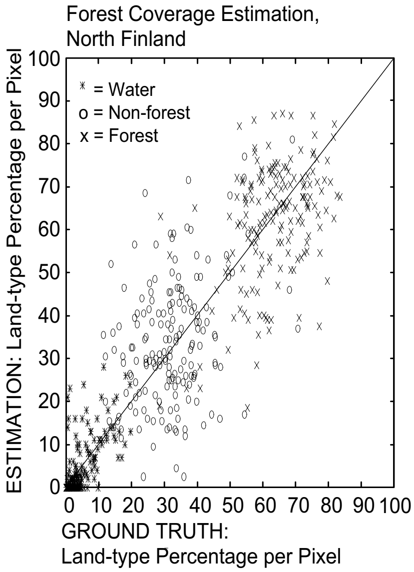

Figure 5. Pixel-wise land cover type estimation vs. ground truth. The estimation is based on SSM/I data for North Finland, July through September 1993 and January through February 1994.

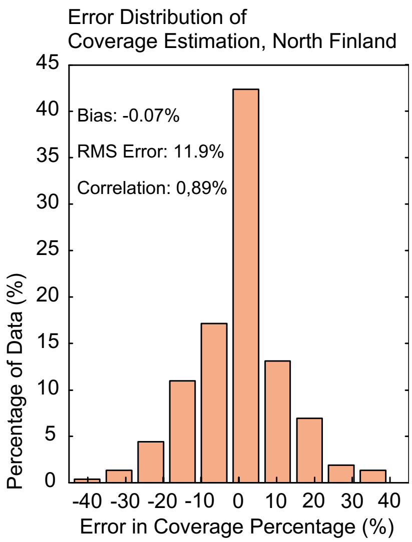

Figure 6. Error distribution of the land cover type estimation presented in Figure 5.

These local estimates are interpolated to cover the whole test area.

2) The spatial fractions of the target types (forest and non-forest) are calculated for each pixel with the mixed pixel approach by employing the measured SSM/I emissivities and the mean target emissivity estimates.
3) The emissivity of forest is calculated from the measured SSM/I emissivity in each pixel by employing the local non-forest emissivity estimate and spatial fractions of the target area types (results from the first and second step).
4) For the training set pixels, a multiple linear regression is calculated between the forest emissivity estimate and ground truth stem volume.
5) For the area of interest, the stem volume estimates are calculated from the estimated forest emissivity with the linear regression equation.

The inversion results for stem volume estimation with SSMI/I data show promising accuracies: the rms error was from 13 to 19 m^3/ha per pixel (25 km by 25 km) which was 15 to 16 % of the mean stem volume. In the test area, the stem volume ranged from 40 to 160 m^3/ha per pixel. These results confirm the assumption that spaceborne radiometer data could be used for large scale biomass estimation in the boreal zone, see also Figures 7 and 8. For more details, see Kurvonen et al. (1997) and (1998a).

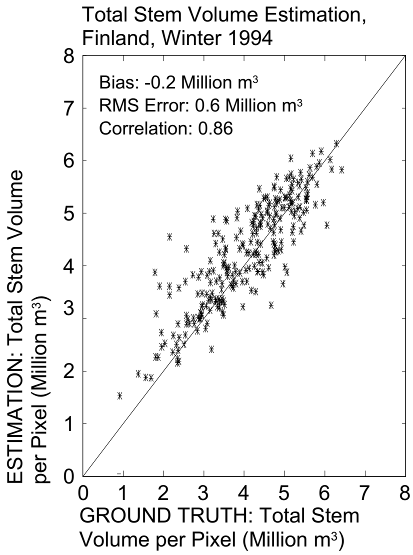

Figure 7. Pixel-wise total stem volume estimation vs. ground truth. The pixel-wise stem volume density estimation is based on the inversion of the SSM/I data covering Finland, January through February 1994. The pixel-wise forest coverage is based on the ground truth.

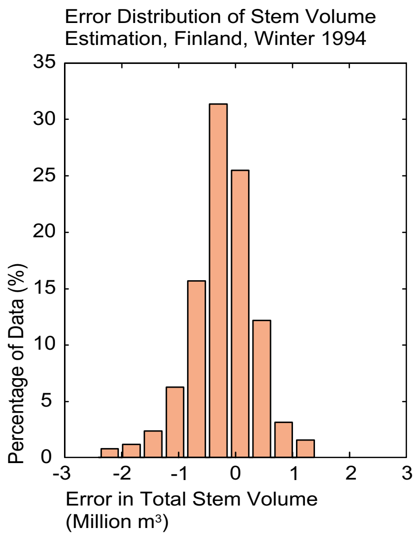

Figure 8. Error distribution of the stem volume estimation presented in Figure 7.

4 Conclusions

Due to resampling and averaging, textural information in ERS-1 and JERS-1 SAR images is expected be low. Nevertheless, based on the results of this study the textural measures had a higher information value than that provided by the intensity values for the land-cover and forest type classification. The multitemporal approach was beneficial for the textural measures and they significantly improved the classification of land-cover and forest types.

The new stem volume inversion method for radar images removed successfully the seasonal effects from a single SAR image and the stem volume inversion was accurate for the large-scale stem volume estimation. In the single image case, the estimation of small forest blocks is corrupted by speckle. However, the inversion results were improved significantly for small scale estimation when several estimations (based on different SAR images) were combined.

Rough forest coverage estimates can be retrieved from satelliteborne radiometer data with the mixed pixel approach. Moreover, the new stem volume inversion method for radiometer data achieved promising accuracies. Therefore, the results propose that satelliteborne microwave radiometry data has potential for large-scale biomass estimation in the boreal forest zone.

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