Interferometric SAR observations of forested areas

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ABSTRACT

Properties of C-band repeat pass interferometric SAR (INSAR) information from forested areas in northern Sweden and from the Amazon rain forest are studied using data from the 3-day repeat cycle of ERS-1 in 1994 and from the ERS-1/ERS-2 tandem mission. Radar backscattering intensity is not sensitive to forest stem volume/biomass above a fairly low saturation level, and is limited in its use for forest/non-forest discrimination. Interferometric SAR has been shown to offer considerable improvement for mapping properties of land surfaces, particularly in forested regions. For boreal regions, coherence shows a significant advantage over intensity for classification of forest and non-forest areas. In the Amazon region, despite generally low coherence, areas of higher coherence are still visible. If the forest coherence is high enough, the interferometric height of the forest (difference between a DEM and the elevation obtained from the interferogram) can be measured. To determine the relationship between the observables and forest properties a first-order model has been developed. The observational results are compared with the model.

Keywords: Interferometric SAR, forest, model, observations

1. INTRODUCTION

Forested areas are important from a remote sensing point of view as they cover large parts of the earth, and are important environmentally and economically. In particular microwave remote sensing is important to follow fast changes, due to its independence of sun illumination and relative independence of the atmosphere and clouds.

ERS-1 SAR was intended as an experimental satellite regarding land applications, while other operations like sea ice remote sensing were considered to be semi-operational. The problem with land applications is the large variability in space as well as time, and the many parameters affecting the radar signal. The advent of repeat-pass interferometry with ERS-1/2 increased the information content in the measurements and the ability to investigate land processes. By using interferometric SAR, INSAR, and combining information using the radar backscatter, , change in , and coherence over time periods for which we have a reasonable interferometric coherence, the information from an area has increased considerably. By combining measurements from different acquisitions, perhaps at different seasons, information is similarly increased. However, the interpretation of the temporal changes of land cover on shorter and longer time scales is often quite complex. We will in this paper present a status report on the potential of interferometric SAR in forestry. The areas studied are mainly in Sweden, but also some scenes over the Amazon rain forest.

2. INTERFEROMETRIC SAR PROPERTIES FOR FOREST APPLICATIONS
2.1 Interferometric coherence

Interferometric coherence, , is an important parameter for describing the quality of different interferometric pairs. It is defined as

$$\gamma = \frac{E\{g_1 g_2^*\}}{\sqrt{E\{g_1 g_1^*\}E\{g_2 g_2^*\}}} \qquad (1)$$

where g1,2 are the complex pixel values of image 1 and 2 respectively, and E denotes expectation value. As was shown in (Ulander and Hagberg, 1995, Askne et al., 1997) the coherence can be divided into several factors

$$|\gamma| = |\gamma|_{noise} \cdot |\gamma|_{slantrange} \cdot |\gamma|_{volume} \cdot |\gamma|_{temporal} \qquad (2)$$

where $|\gamma|_{noise}$ is the system noise power decorrelation, which is normally negligible, $|\gamma|_{slantrange}$is the baseline decorrelation which can be compensated for by filtering, (Gatelli et al., 1994), $|\gamma|_{volume}$is due to the decorrelation between scatterers within the volume illuminated by the pulse, and $|\gamma|_{temporal}$is the temporal decorrelation of the scatterers between the two images.

Coherence estimation is only unbiased if the average is performed over a large number of pixels. The bias primarily influences low values of coherence such as over lakes and forests, (Dammert, 1996). In our case the sea outside the coast was used as reference for a zero-coherence area, for which the bias is around 0.22-0.26 using a 5x25 pixel estimation window for ERS SAR SLC images.

The coherence over a certain area is often determined by the random phase variations, , within the averaging window. The coherence then decays like $e^{-\sigma_\varphi^2/2}$. may be caused by random height variations H, or by random displacements of the contributing scatterers, R. We may also have a random thickness change, l, of an intervening dielectric medium, like a snow layer, or the atmosphere, resulting in dielectric decorrelation. Assuming independent Gaussian random variables we have

$$\sigma_\varphi^2 = \left(\frac{4\pi B}{\lambda R \sin\theta}\sigma_H\right)^2 + \left(\frac{4\pi}{\lambda}\sigma_R\right)^2 + \left(\frac{4\pi}{\lambda}(\sqrt{\varepsilon}-1)\sigma_l\right)^2 \qquad (3)$$

B is the interferometric baseline normal to the line of sight, R is the slant range, and is the incidence angle. Either R=0.5 cm, l = 3.8 cm (with =1.3), or H=17 m (at B=100 m) will decrease the coherence by a factor of two.

2.2 Differential SAR interferometry

If a DEM is available of the imaged area, it is possible to generate a simulated phase image and a differential interferogram. This will display all differences between the real interferogram and the real DEM and can be used for measuring the interferometric effective tree height over forested areas. However, there are several problems with this technique. The DEM is often in a national map co-ordinate system while the SAR interferograms are in the slantrange-azimuth domain. Without having a detailed model of the sensor viewing geometry, it is not possible to accurately coregister the image and the simulated image over a large area. However, over smaller areas of approx. 20x10 km2 a polynomial co-ordinate transformations and a set of tiepoints in the DEM and in the SAR interferogram can be used.

An interferometric pair from the winter season 1994 over an area in northern Sweden has been compared with a DEM in this fashion. Pixel mismatch (i.e. co-ordinate mismatch) is believed to be not larger than the pixel size of 20x20 m2. Using this differential interferogram, two things can be accomplished. First, measurements of the effective forest height and, second, measurements of how accurate the interferometric DEM is. The accuracy of interferometric DEMs, in the repeat-pass case and over high-coherence areas, is limited by variations of atmospheric radar wave propagation path delays (Tarayre, 1996), and also by snow layer variations.

3. FOREST INTERFEROMETRIC SAR MODEL

In the direct remote sensing problem we describe in a model the major effects of various in situ parameters on the measured signal. The radar scattering aspect is described in varying detail by e.g. the water cloud model, (Attema and Ulaby, 1978), or the MIMICS program, (Ulaby et al., 1990; McDonald and Ulaby, 1993). In the interferometric SAR case the phase aspects are important as described by Eq (3), including shifts of the scatterers due to winds, but also dielectric changes due to temperature changes, rain etc.

Geometrical Properties	Temporal Properties	Dielectric Properties
shape of trees size distributions and orientation of stems, branches etc. ground roughness vegetation area-fill	wind freezing/thawing water content snow cover rain	r of stems, branches etc. attenuation of vegetation

Table 1 Describing some parameters which affect a INSAR images from a forest area.

In (Askne et al., 1997) the water cloud model was used to model the scattering. The parameters of the water cloud model can be obtained by more exact models, but the model describes the essential feature; saturation at high stem volumes. As the ground and vegetation back scattering may vary over the year, some forest and open field sites with known properties should be used for reference (Pulliainen et al., 1966). In the model the extinction coefficient is assumed to be proportional to the number of scatterers, and hence to the stem volume. The extinction through the canopy layer varies with temperature, particularly for temperatures above and below the freezing point. The area fill or canopy closure at 23 incidence angle, represents the percentage of the area covered by forest canopy. This is an important parameter for sparse forests like the boreal forest in northern Sweden. Values of the area fill and the extinction were estimated in (Askne and Smith, 1996) from measurements reported by (Pulliainen et al., 1994).

The stability of the scatterers due to the wind has to be estimated, and in (Askne et al., 1997) a decrease with height was assumed. No experimental values on such stability factors are known and other height variations can also be argued for. For simplicity a constant variation has been used in this paper, resulting in minor changes compared to earlier analyses. This is a consequence of the high attenuation of the signal at C-band, which limits the back scattering to a thin layer at the tree tops.

The interferometric effective height of the forest and the coherence are related, as the height is determined from the phase factor of the complex coherence. This is illustrated in Figure 1 where the ground term (reference height) is combined with the vegetation part from the upper part of the forestry canopy. The two terms are combined and determine the effective height.

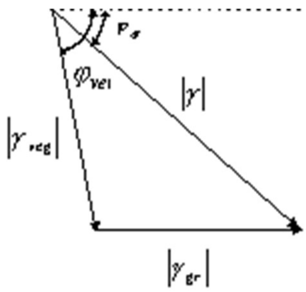


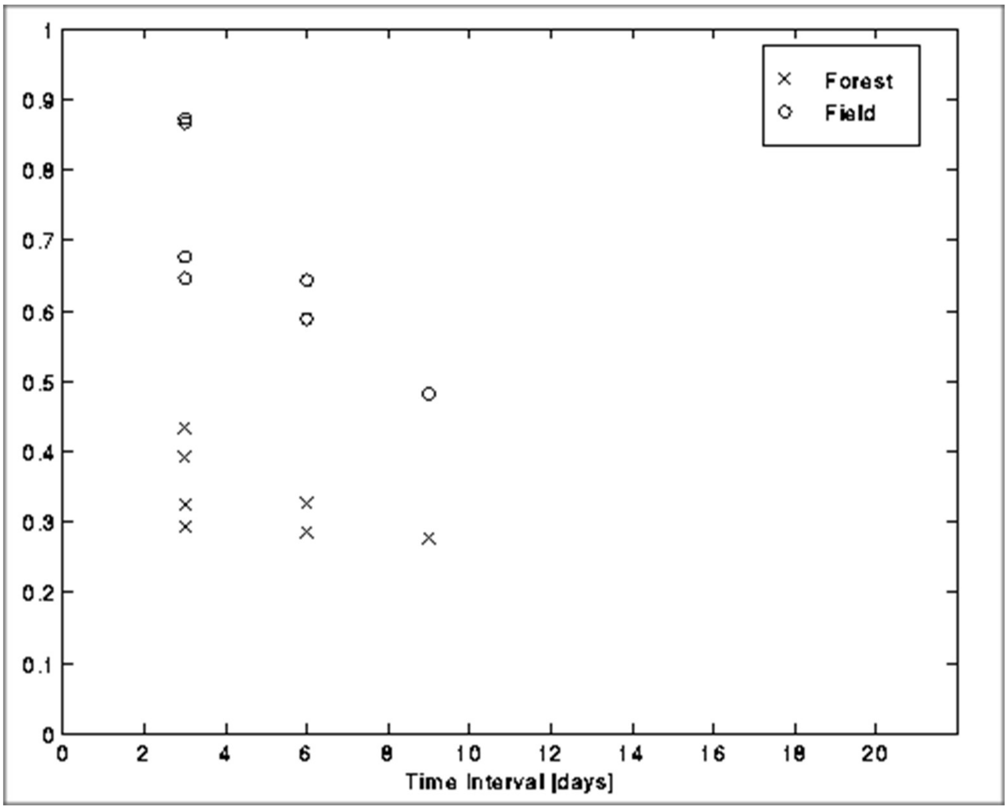
Fig. 1 Illustrating the coherence and effective height as combined by ground and vegetation components, from (Askne et al., 1997).

4. OBSERVATIONAL RESULTS

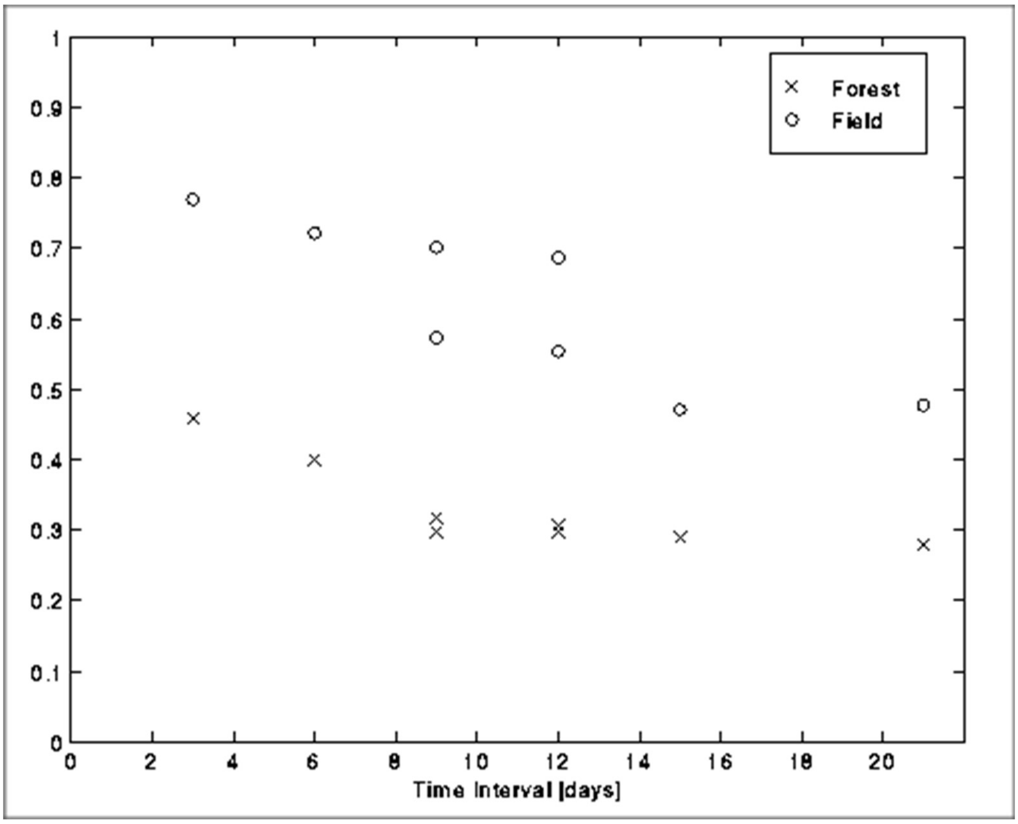
The results are concentrated to an area around Hökmark in northern Sweden using data from the 3-day repeat cycle of ERS-1 in February and March 1994. Looking at the weather statistics, melting temperatures (dielectric decorrelation) were often accompanied by strong winds (geometric decorrelation). Some results are also obtained from the Amazon rain forest not far from Manaus.

4.1 Coherence properties - Temporal decorrelation

For forests, a comparison of interferograms at different baselines, shows that decorrelation due to the baseline dependent volume scattering is unable to describe the difference between vegetated and non-vegetated areas (Smith et al., 1996). The differences seem to be related to the movement of scatterers (tree branches) on short time scales. This movement occurs so rapidly, that even decreasing the time interval between images to one day, as for the tandem mission, results in no observed increase in forest coherence (Askne et al., 1996). The authors believe that the decorrelation occurring over snow covered fields is a consequence of dielectric decorrelation resulting in phase shifts as well as amplitude shifts. This is a result of changing weather conditions, and usually occurs over a period of a few days. This is illustrated in Figure 2 for short baselines and medium baselines. The apparent differences between the decay of field coherence at different baselines is probably due to the weather conditions for the occasion of the short baselines being less stable than in the majority of medium baseline cases.



(a)



(b)

Figure 2 illustrating coherence decay with time for short baselines (21 and 30 m)in (a) and middle baselines (175 and 203 m) in (b).

4.2 Mapping of forests

A number of papers have suggested the use of SAR interferometry for improving the poor separation of forest and non-forest areas in ERS SAR backscatter measurements (Askne and Hagberg, 1993; Wegmüller and Werner, 1995b; Wegmüller and Werner, 1995a). To quantify the separability between different classes, we have used the Jeffreys-Matusita (J-M) distance (Jeffreys, 1948; Swain, 1978) to give a quantitative measure of the improvement available by including coherence information in a classification. The measure can be directly related to the probability of correct classification of Normally distributed data, for a maximum likelihood classifier (see Table 2, (Yatabe and Leckie, 1995)).

J	Probability of correct classification
0.0	0
0.4	0.60 0.84
1.0	0.75 0.94
2.0	1

Table 2

The results shown in Figure 3 demonstrate how the separability of forests and snow covered fields varies for interferometric pairs where the baseline for all of the pairs is less than 600m. It can be seen that the separability is generally much better using coherence information, although in one case (index number 11), the separation is as poor with coherence as with intensity. This interferogram corresponded to images straddling a period of changing temperatures, heavy snow fall and strong winds, resulting in the fields having as low coherence as the forests.

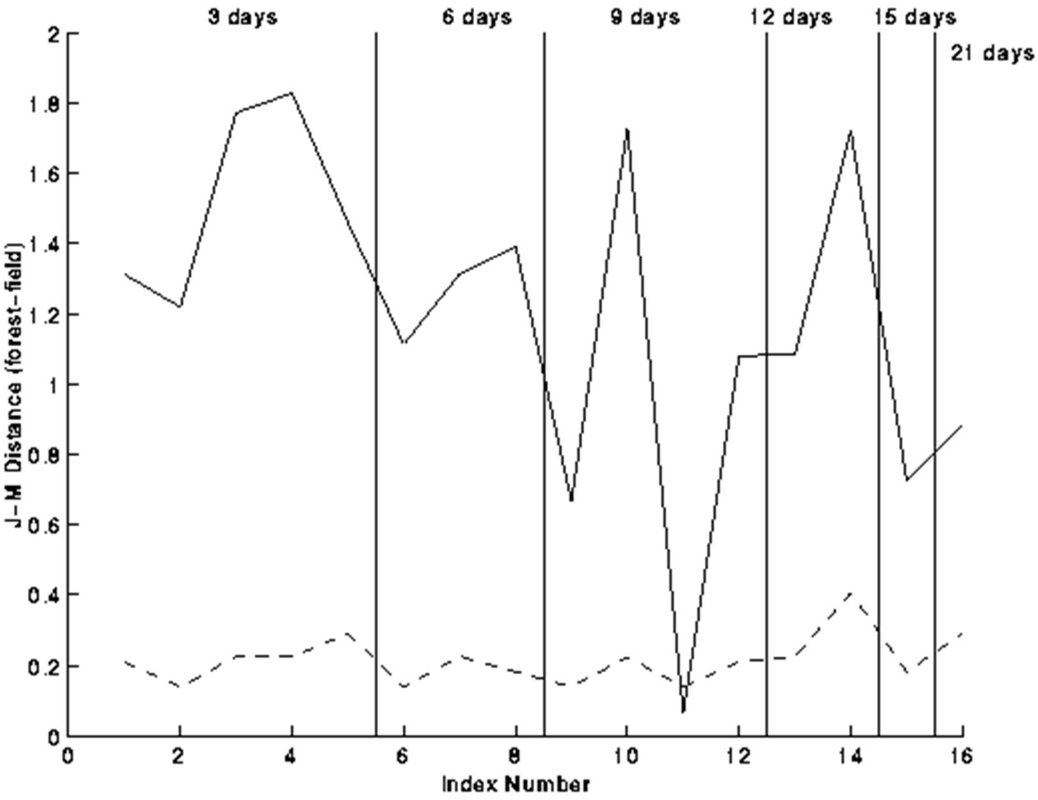


Figure 3 J-M Distance, Separability between forest and snow covered fields from Hökmark area. Solid line: using coherence; dashed line: using intensity.

It is also apparent from the figure that separability varies considerably between interferograms, but with a general trend towards decreased separability for increased time interval between the images of the pair. Again, this is a result of the coherence of the fields dropping as the time interval increases, and the forest (being already close to the bias level) remaining approximately constant.

In (Wegmüller and Werner, 1997) an accuracy of about 90% for the classification of forest area in an interferogram is reported for an area of mixed forest around Bern. This is consistent with the results shown here for boreal forests, although only for the better interferometric images. These images are generally characterised by high coherence for fields, which increases the separability as the forest coherence is almost always very low.

Extension of the work on forest mapping to identifying clear-cutting in the Amazon rain forest is currently being studied. Initial results indicate that areas of higher and lower coherence (believed to be signatures of clearings and forests) have been identified, and that the areas of supposed clearings appear consistently in all interferograms of the area. However, the separability between forest and open fields is not as good, see Figure 4, as in the Hökmark area.

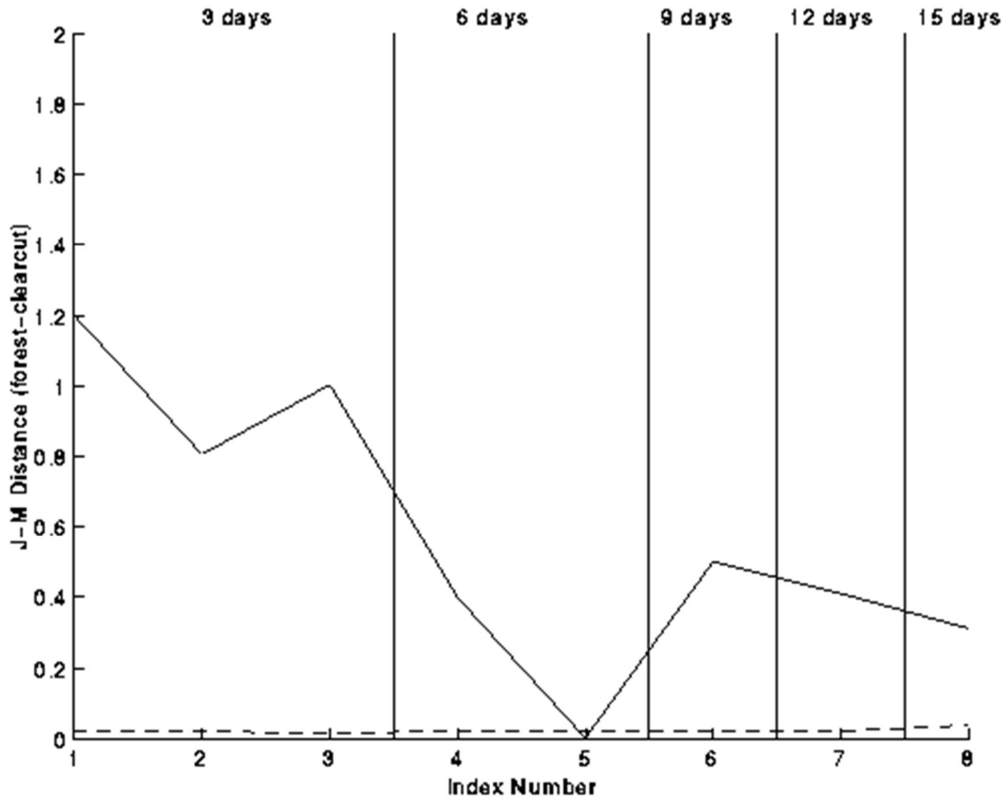


Figure 4 J-M Distance, Separability between forest and estimated fields in Amazon rain forest area. Solid line: using coherence; dashed line: using intensity.

4.3 Image segmentation and classification

A 10 by 10 km^2 area near Hökmark has been classified using coherence, image intensity, and intensity change between the image pair from March 8 and 11, 1994, and August 1 and 2, 1995, see Figure 5.

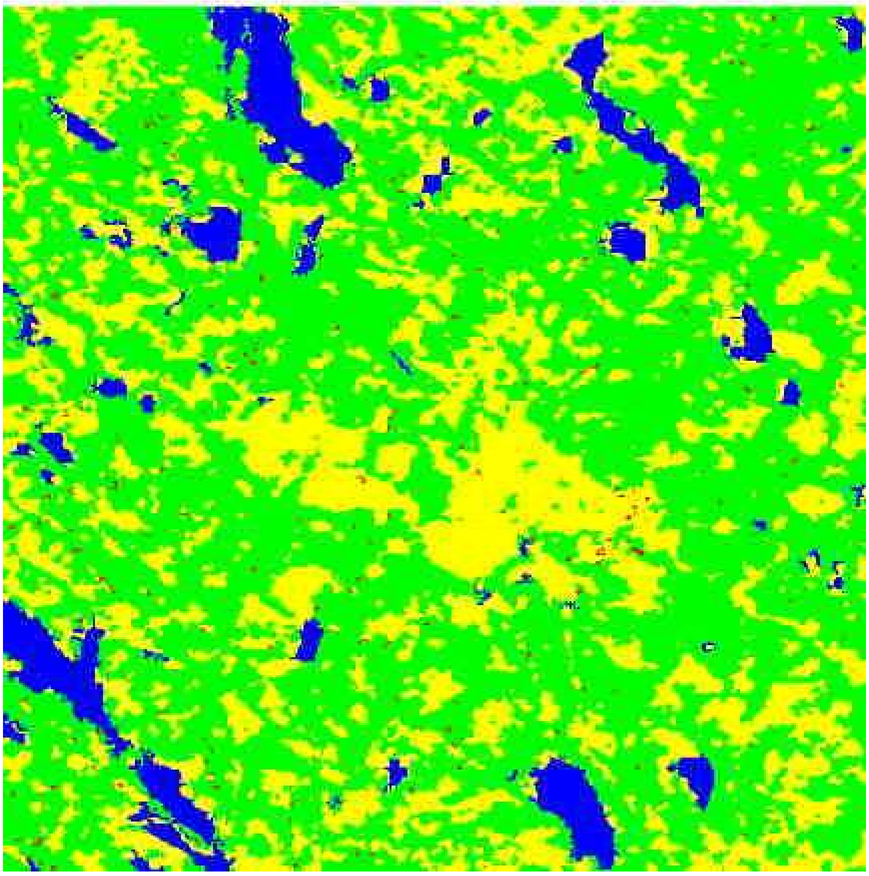


Figure 5: Classified image over Hökmark area: blue lakes green forests yellow open fields and clearcuts red buildings (Li et al., 1997).

By using an image pair from the summer period and another from the winter period, problems associated with frozen lakes can be eliminated and forests, open fields, lakes, and urban areas can be discriminated (Li et al., 1997). Such a classification has been used to determine a forest mask over the 617 km2 area studied below.

4.4 Interferometric effective tree height

Measurements over two small forest areas and surrounding fields in Hökmark are reported in Table 3. The forest coherence generally increases with the open field coherence while the effective tree height shows a more complex variation.

First date	Second date	Coherence	Effective tree height (m)	sigma zero (dB) First date	sigma zero (dB) Second date	Coherence adjacent open field	sigma zero (dB) adjacent open field
Feb 6	Feb 15	0.30	1.1	-7.4	-7.9	0.72	-10.9/-10.7
Feb 6	Feb 18	0.31	1.2	-7.0	-8.1	0.74	-10.6/-11.0
Feb 24	Feb 27	0.50	2.2	-8.1	-7.6	0.78	-10.6/-10.3
Mar 8	Mar 23	0.29	1.4	-8.7	-8.0	0.56	-10.9/-10.4
Mar 11	Mar 23	0.30	5.3	-7.9	-8.3	0.56	-10.2/-10.8
Mar 14	Mar 23	0.34	7.3	-8.1	-8.2	0.61	-10.3/-10.9
Mar 17	Mar 23	0.43	2.7	-8.0	-7.9	0.78	-10.5/-10.4

Table 3a Measurements over Forest 1

First date	Second date	Coherence	Effective tree height (m)	sigma zero (dB) First date	sigma zero (dB) Second date	Coherence adjacent open field	sigma zero (dB) adjacent open field
Feb 6	Feb 15	0.31	0.9	-7.0	-7.9	0.70	-12.5/-12-2
Feb 6	Feb 18	0.32	1.1	-6.6	-8.0	0.64	-11.9/-12.5
Feb 24	Feb 27	0.50	2.2	-7.8	-7.8	0.75	-12.7/-12.1
Mar 8	Mar 23	0.30	2.2	-8.5	-8.2	0.53	-12.6/-12.3
Mar 11	Mar 23	0.30	4.4	-7.7	-8.7	0.58	-11.5/-12.3
Mar 14	Mar 23	0.32	6.2	-8.0	-8.6	0.62	-12.2/-13.0
Mar 17	Mar 23	0.40	2.1	-8.2	-8.2	0.75	-12.4/-12.3

Table 3b Measurements over Forest 2

To create a large-scale effective tree height map, systematic phase variations over the image have to be removed. Using only the phase over fields and clear-cuts, this systematic phase variation can be estimated and, partly removed. A 2-D polynomial, up to a power of seven, fit to the field/clear-cut phase were carried out to see the large-scale phase variation. The phase variation is compared with the proposed phase fit in Table 4. (The topography in the area is below 100 m.)

The variations are believed to be partly due to mismatch between the DEM and the interferogram, and partly due to snow layer thickness variations. Another explanation is atmospheric artefacts over the image. To avoid such large scale effects an algorithm has been used to compare the forest height with close-by open fields. The observed heights are reported below.

	Phase std.dev. (rad)	Height std.dev. (m)
Original field/clear-cut phase variation	0.201	1.66
Phase polynomial variation, field/clear-cut	0.182	1.50
Corrected phase variation, field/clear-cut	0.086	0.71

Table 4

4.5 Comparison with model

From field investigations five forest areas with average stem volumes of 140, 200, 240, and 345 m^3/ha (rough estimates due to large variability within each area) have been identified together with six clear-cuts with varying regrowth. The results for and the coherence (corrected for baseline decorrelation) are illustrated in Figure 5 for eight scenes and four image pairs.

For some of the results we will concentrate on observations from 24 and 27 February, due to the high forest coherence which simplifies the DEM comparison. In Figure 5 the observations are compared with the model results assuming an open field coherence of 0.9. The forest extinction is assumed to increase linearly with stem volume and equal 0.17 dB/m for a stem volume of 100 m^3/ha. The area fill is estimated to be about 70% for 100-200 m^3/ha forests.

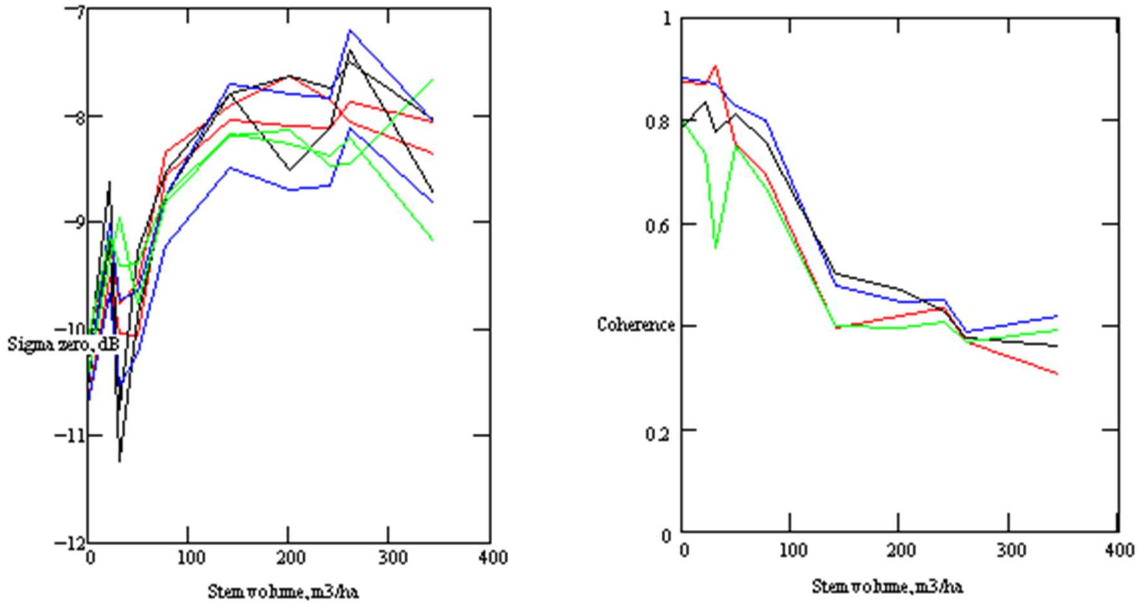
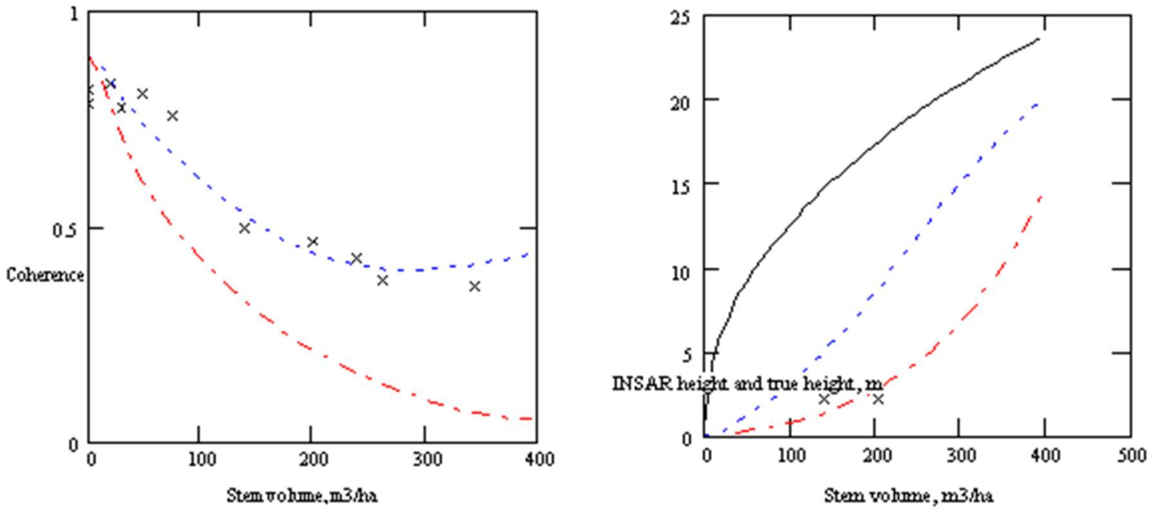
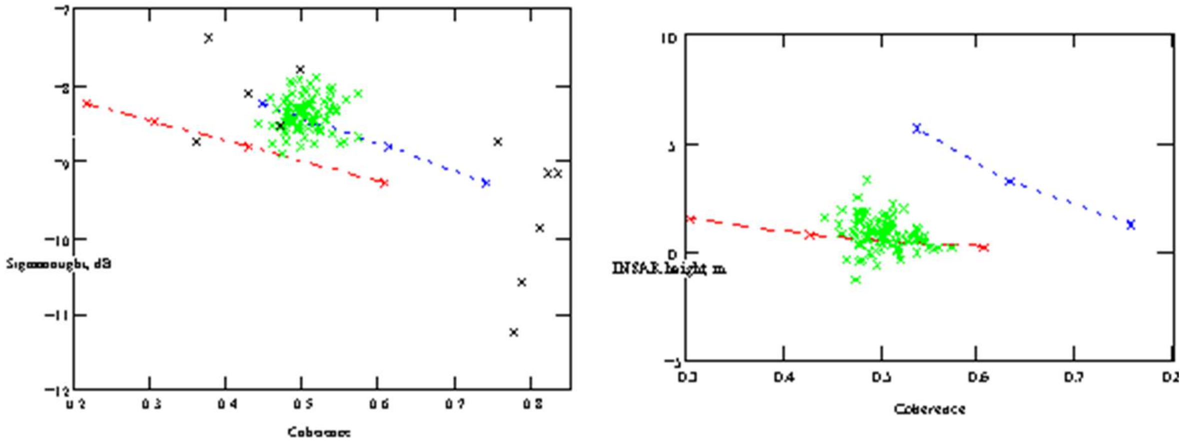


Figure 6 Illustrating in figure to the left and coherence in the figure to the right for eight scenes in February and March 1994. values vary quite a lot particularly over clear-cuts.



a

b



c d

Figure 7 Results from observations. Model results are shown with blue dashed lines for $_{veg}$=0.55, and red dash-dot lines, $_{veg}$=0.1. Solid line: estimated true height for forest as function of stem volume, x marks observations.

While coherence measurements in Figure 7c,d indicate values for $_{veg}$ = 0.55 and stem volumes around 175 (stem values for 50, 100, and 150 m^3/ha marked along the model lines), the INSAR tree heights are much lower and rather in agreement with $_{veg}$=0.1 and with a stem volume of 75 - 100 m^3/ha. At present we have no field measurement of the entire area. There are many error sources in the case of interferometric heights derived using a DEM including the effects of a snow layer. The area fill factor used in the model is based on measurements in another area and believed to be too high for the area studied here. Although reasonable fits between the modelled and measured heights have been reported, (Askne et al., 1997) the results are rather sensitive to the exact location of where the measurements have been done. This indicates problems in estimating the forest effective height over large areas, and this problem will be studied further.

5. DISCUSSION AND CONCLUSION

Decorrelation mechanisms have been investigated for forest and snow covered open fields as function of time delays between pairs and baseline. Wind decorrelation is assumed to dominate for forest, and dielectric and geometric decorrelation phenomena for snow covered fields. The results show that coherence differences between fields and forest make a discrimination with high accuracy possible for image pairs acquired with less than twelve days in between them as long as no major storm or temperature variation around the freezing point occurs.

Observations and model results show decrease of coherence with stem volume, with the strongest variations for stem volumes below 200 m3/ha. This is an interval where also shows large sensitivity to stem volume. However, this is also an interval where we may experience large temporal variations, particularly of . This illustrates a potential to map stem volumes in this interval as long as temporal variations can be taken into account by the use of known reference areas.

All interferometric height measurements are lower than model predictions. The measurements are performed relative to nearby snow covered open fields. The uncertainty in snow cover thickness makes these results uncertain, and interferometric effective heights should also be determined during summer time. However, this limits the study to the tandem mission, where the baselines were generally too small for reliable height estimates. Atmospheric and snow layer artefacts also influence the accuracy of the height measurements as well as the accuracy in the DEM simulated interferogram. The height estimates are dependent on the estimated area fill and extinction coefficients, for which more experimental information is necessary, in particular as function of stem volume.

The major conclusion is that the sensitivity of the ERS SAR sensors to differentiate between forest and open fields using coherence information it better than using backscatter measurements. Examples from the Amazon demonstrates that this is also possible in areas with dense forests. The time interval between the images should not exceed 3 days.

6. ACKNOWLEDGEMENTS

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