Spaceborne SAR for detection of boreal wind-thrown forest and clear-cuts

L.E.B. Eriksson\textsuperscript{a}, J.E.S. Fransson\textsuperscript{b}, M.J. Soja\textsuperscript{a}, M. Santoro\textsuperscript{c}

\textsuperscript{a} Chalmers University of Technology, Department of Earth and Space Sciences, Gothenburg, Sweden

\textsuperscript{b} Swedish University of Agricultural Sciences, Department of Forest Resource Management, Umeå, Sweden

\textsuperscript{c} Gamma Remote Sensing AG, Gümligen, Switzerland

Abstract

A controlled experiment simulating wind-thrown forest was carried out at a hemi-boreal test site in Sweden. The simulation was done by manual felling of trees in September 2009. The trees were left on the ground until November 2009 to ensure image acquisitions after the simulated storm. SAR data from the satellites TerraSAR-X, RADARSAT-2 and ALOS were acquired before, during and after this period. The backscatter signatures were analyzed to evaluate possibilities to detect wind-thrown forest and clear-cuts. TerraSAR-X HH-polarized backscatter showed a significant increase when the trees were felled and the difference to selected reference forest stands was 1.2 dB to 2.0 dB. The corresponding differences for RADARSAT-2 were 0.2 dB to 1.2 dB for HH-polarization and 0.1 to 1.1 dB for HV-polarization. When the trees were felled, the ALOS backscatter decreased to 1.6 dB below the reference forest for HH-polarization and 0.4 dB to 0.8 dB for HV-polarization.

Shadowing effects in fine resolution TerraSAR-X and RADARSAT-2 data showed a high potential for detection of wind-throw with separation to the reference forest backscatter of
between 4.9 dB and 9.2 dB. For clear-cut detection ALOS proved to give the most suitable
data.

**Keywords:** SAR, Forestry, Wind-thrown forest, Storm damage, Clear-cut, X-band, C-band, L-band

1. **Introduction**

Each year storms and hurricanes cause destruction in many areas around the world. In Europe, an annual average of 35 million m$^3$ wood was damaged by natural disturbances during the period 1950 to 2000, and storms were responsible for 53% of the total damage (Schelhaas et al., 2003). In 2005 and 2007 devastating storms hit Scandinavia causing large damage to forested areas. In Sweden it was estimated that about 70 million cubic meters of timber were blown down in 2005 (Anon., 2006) and about 12 million cubic meters in 2007, to a value of billions of Euro. At such occasions, rapid mapping of wind-thrown forests is crucial in order to salvage timber values and prevent insect outbursts that could kill the remaining standing trees. After a severe storm, it is also of high importance to get a fast overview to assess the roads that should be cleared from wind-thrown trees as well as to detect power lines that are broken. Due to the large geographical extent of forests, rapid monitoring and mapping of forests can in practice only be done efficiently by means of airborne and spaceborne remote sensing methods. Synthetic aperture radar (SAR) has the potential of being a useful tool due to its independence of weather and sun illumination that allow rapid and frequent acquisitions, but few results have been published about detection of wind-thrown forest..

Fully polarimetric airborne SAR campaigns following acute storm damages have been performed with the Japanese Pi-SAR platform to study forest damages on the Hokkaido Island after the Songda typhoon in September 2004 (Wang et al., 2010) and the Canadian CONVAIR platform to study ice storm damages in the Ottawa region in January 1998 (Touzi et al., 1999). The first study compared polarimetric L-band data collected before and after the typhoon and observed changes in double-, volume- and surface scattering of respectively 27.5 dB, -0.20 dB and -20.3 dB. The classification
accuracy of the generated damage map was 77.7%. The second study indicated that a polarimetric parameter could detect differences between pre and post storm data that could not be seen in the normal linear or circular polarizations. Storm damage detection has also been studied using the Swedish airborne VHF-band platform CARABAS-II (Fransson et al., 2001; Fransson et al., 2002; Ulander et al., 2005; Ulander et al., 2006, Fransson et al., 2007). Operating at very low frequencies (20-90 MHz) and HH-polarization, CARABAS-II gave a response from horizontal trees that was significantly higher than from vertical trees, provided the horizontal trees were not lying directly on the ground and their axes were parallel to the flight track within about ±30° (±22° for single trees). In addition to the capability to detect areas where all trees have been wind-thrown, CARABAS-II also showed a potential to detect storm-felled trees in stands with standing forest and near borders with high trees. A method for automatic detection of wind-thrown forest in VHF SAR images is described by Folkesson et al. (2006). The method use autocorrelation functions to identify elongated structures created by fallen trees. However, due to the relatively low coverage, high expenses and long deployment time for airborne platforms, spaceborne systems are preferable for mapping and monitoring of large areas.

After the hurricane Mitch hit Central America in November 1998, SAR data from the European ERS-1 and ERS-2 satellites were used together with optical SPOT images to assess the damage. The study showed that damaged forest could be detected when SAR images acquired before and after the hurricane were compared (Nezry et al., 2000). After the severe storm Lothar that hit France, Switzerland and southern Germany on the 26th of December 1999, a comparison of classification performance for selected airborne and spaceborne optical and SAR sensors was performed for an Alpine forest area (Steinmeier et al., 2002). This study showed that during the winter season, the optical images gave severe classification problems due to snow, long shadows and the fact that the spectral properties of forest without foliage resembled those of the wind-thrown forest. With SAR, the investigators were not able to detect the wind-thrown forest using only backscatter intensity. On the contrary, the interferometric coherence helped in detecting areas affected by storm damage. After Lothar, successful storm damage detection using SAR interferometry with the ERS-1 and ERS-2
satellites was also presented by Dwyer et al. (2000), Yesou et al. (2000) and Wiesmann et al. (2000).

Unfortunately, the ERS-1/2 constellation is no longer operational.

1 After the storm in Sweden in 2005, research activities for detection of wind-thrown forest with satellite images were initiated following the activation of the International Charter Space and Major Disaster, an instrument for rapid provision of images at catastrophic events. The usefulness of optical data was limited by the prevailing winter conditions (low sun-angle, extensive cloud cover and variable snow cover). The analysis of SAR data showed that with a limited number of backscatter intensity images from C-band SAR onboard the Envisat and Radarsat-1 satellites it was not possible to detect wind-thrown forests, except in the highest resolution Radarsat-1 images where in some cases changes in texture could be observed, primarily related to changes in shadowing from standing/fallen trees (Ulander et al., 2005).

The lack of sensitivity of C-band backscatter measurements to standing and wind-thrown trees at decametric spatial resolution can be explained as the felling of trees does not significantly change the total backscatter, since the needles and small branches are still present as a randomly oriented scattering volume. At coarse resolution, the speckle noise is also more extended compared with higher resolution SAR images, limiting the possibilities to detect wind-thrown forests. On the other hand, longer wavelengths are sensitive to larger structures like stems and large branches that change the general orientation when a tree is felled, which could improve the possibilities for detection of wind-thrown forest. Improved spatial resolution of satellite SAR images is also expected to improve the possibilities to identify forest damaged by a storm. Thus, to further explore the use of radar remote sensing to detect wind-thrown forest it is of interest to analyze images from satellite SAR systems with longer wavelength or finer spatial resolution than the SAR data from Envisat and Radarsat-1.

A preliminary investigation on the feasibility of mapping wind-thrown forest using data from the Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) was carried out as a controlled experiment, where trees were manual felled to simulated wind-thrown forest (Fransson et al., 2007). The experiment took place in 2006 at the test site.
Remningstorp located in the south of Sweden. When comparing the reference forest stand with the wind-thrown stands, the backscatter intensity decreased about 1.6 dB for ALOS PALSAR acquired in Fine Beam Single polarization (FBS) images with look angle 34.3° and HH polarization.

This paper presents results from a second experiment that was conducted in Sweden in 2009. The aim was to evaluate the possibility to detect forest change caused by storm felling (primary goal) and clear cutting (secondary goal) using multitemporal SAR data from three satellites, TerraSAR-X (X-band), RADARSAT-2 (C-band) and ALOS (L-band). Preliminary results based on visual interpretation of a limited number of co-polarized images acquired by these satellites are available in Fransson et al. (2010). In this paper a larger data set, including both co- and cross-polarized images, are analyzed and the first quantitative results are presented. The investigation is done by comparing the backscatter intensity of images acquired before and after a simulation of wind-thrown forest.

The test site and the available data will be presented in Section 2 and the experiment and the methods in Section 3. In Section 4 results are presented for each of the three satellites and a summary and discussion is given in Section 5.

2. Test site and data description

2.1 Test site

The Remningstorp test site is located in the southern part of Sweden (Lat. 58°30’ N, Long. 13°40’ E) and covers about 1,200 ha of productive forest land (Fig. 1). The test site is characterized by hemi-boreal coniferous forests and the dominant tree species are Scots pine (Pinus sylvestris) and Norway spruce (Picea abies). The dominant soil type is till (i.e. a mixture of glacial debris) with a field layer consisting of different herbs, blueberry (Vaccinium myrtillus), and narrowleaved grass (e.g. Deschampsia flexuosa). In denser old spruce stands the field layer is absent. The ground elevation is moderately varying between 120 and 145 m above sea level.
2.2 Satellite data

The SAR dataset consisted of TerraSAR-X images acquired in spotlight mode with 1.2 m and 1.1 m spatial resolution (slant range and azimuth) and RADARSAT-2 images acquired in ultra-fine beam mode with 1.6 – 2.4 m spatial resolution in range and 3 m in azimuth. The images were acquired in single polarization mode (HH-polarization for TerraSAR-X images, HH- or HV-polarization for RADARSAT-2 images). Both satellites were programmed to acquire data at different look angles and in both ascending and descending passes to study differences in the shadowing effects. For the satellite data that have been used in this study, acquisition dates and observation configurations are listed in Table 1 for TerraSAR-X and in Table 2 for RADARSAT-2.

ALOS PALSAR data were acquired according to JAXA’s global observation strategy for ALOS (Rosenqvist et al., 2007), which for Sweden means summer and autumn acquisitions in Fine Beam Dual polarization (FBD) mode at 34.3° look angle in ascending pass. Compared to the ALOS PALSAR images in Fine Beam Single polarization (FBS) mode that were used in the study after the first storm simulation experiment in 2006 (Fransson et al., 2007), FBD mode provide images with HV polarization in addition to the HH images, but at the expense of a reduced spatial resolution of about 20 m. Acquisition dates and observation configurations for the used ALOS PALSAR images are listed in Table 3.

All SAR images were obtained in radar geometry, i.e. in range-azimuth coordinates and to reduce speckle noise multi-look processing was applied. The multi-look factors were determined based on the initial pixel size of the data and the desired output spatial resolution. Data were obtained in a form that only required application of a calibration constant to obtain calibrated sigma zero images. The calibration constants are given by the processing facilities. To allow inter-comparison between datasets, the images were geocoded to the Swedish
coordinate system RT90. For image geocoding, a Digital Elevation Model (DEM) acquired from the Swedish National Land Survey (Lantmäteriet) with 50 m posting was used. The DEM was oversampled to allow geocoding of the SAR images to the selected pixel sizes of 5 m for TerraSAR-X and RADARSAT-2 and 25 m for ALOS PALSAR. A lookup table that described the relationship between the radar and the map geometry was used (Wegmüller, 1999). The transformation described in the lookup table is set up based on orbital data. In case of inaccuracies of the orbital data, refinement of the lookup table is necessary. This is implemented in form of cross-correlation algorithm between the SAR image and a reference image for the output geometry. Matching features in the two images are used to detect possible offsets, which are directly related to errors in the geocoding transformation.

2.3 **In situ observations**

Meteorological observations, including temperature, precipitation and snow depth were obtained from a weather station located within the Remningstorp test area and managed by the Swedish Meteorological and Hydrological Institute (SMHI). For each day the maximum, minimum and average temperatures were available. Relevant observations for satellite acquisition dates are included in Table 1, Table 2 and Table 3. The temperatures in the tables are the daily averages, but in cases when the recorded minimum temperature was below 0º C at some point during the day, a note is given in the table. As precipitation might affect the moisture for the following days, information about rainfall has been included not only for the acquisition date but also for the day before the acquisition. In case of rainfall during several consecutive days, the total amount of precipitation during five days (including the acquisition date) has been indicated.

3. **Methods**
3.1 Experiment description

A controlled experiment simulating wind-thrown forest was carried out at the Remningstorp test site in the beginning of September 2009. The simulation was done by manual felling of trees and instead of stripping and removing the trees (as is done in clear-felling), the trees were left for a few orbit repeat cycles to ensure image acquisitions after the simulated storm. In total, four coniferous stands with a size of about 1.2 ha were used to simulate wind-thrown forest (Fig. 2, Fig. 3 and Fig. 4). The trees were felled in two directions to simulate two possible main wind directions during a storm. For two of the stands (T1 and T4 in Fig. 4) the trees were felled in 80° and for the others (T2 and T3 in Fig. 4) in 35° with the heading measured clockwise from north (0°). The felled trees were then harvested and removed from the forest in November 2009. In total, more than 2500 cubic metre of timber were felled. The stem volumes recorded by the harvester were about 650, 590, 330, 520 m³/ha for T1, T2, T3 and T4, respectively. The test areas were situated in forest stand with tree height of about 25 m.

3.2 Analysis of satellite data

In order to study changes of the forest backscatter after a severe storm, satellite datasets were divided in three phases:

- Phase 1: Before felling = mature forest
- Phase 2: Trees lying on the ground = simulated wind-thrown forest
- Phase 3: After trees were removed = clear-cut

In addition to the test areas T1 to T4 where the trees were felled, four reference areas were selected, two with mature forest, R1 and R2 (Fig. 4) and two in clear-cuts, R3 and R4 (Fig. 2).
The stem volumes for the reference areas R1 and R2 were estimated using laser scanning data in combination with in situ data to about 240 and 300 m³/ha with an average tree height of 18 and 21 m, respectively. R3 and R4 are two of the four forest areas that were felled during the previous storm experiment in 2006. The reference areas were included to avoid misinterpretation due to backscatter changes caused by rainfall or other environmental conditions not related to the storm experiment.

In the image analysis, each of the four test areas was divided in three smaller regions, one that was affected by shadowing during ascending passes, one that was affected by shadowing during descending passes and one that was outside the shadowed region for both ascending and descending passes. For T1, T2 and T3, these regions are shown in Fig. 5. The polygons that were selected for each region were used for all satellite images and the average backscatter values for each region and each reference area were measured. The backscatter values in the shadowed regions were significantly lower than for the surrounding areas, but in most cases a region that is brighter than the surrounding area can also be observed in each test area. This increase in backscatter is caused by layover from trees at the side of the test area opposite to the shadowed region. For ascending passes these areas roughly correspond to the regions that were defined as shadow for descending passes and in the same way the shadow regions for ascending passes can be used to estimate the backscatter for the layover areas for descending passes. To avoid biases specific for one test area, the backscatter values that are reported in this paper are averages of the values for each region type from all four test areas, and for both areas in the case of reference forest and reference clear-cut.

4. Results

The main objective of the analysis was to evaluate the detection of wind-thrown forest in the dataset of satellite images acquired during phase 2, i.e. from 2009-09-17 until November 2009. The
backscatter values from phase 3, i.e. from all images acquired during 2010, are included to permit an analysis of clear-cut signatures as a secondary objective.

4.1 TerraSAR-X

4.1.1. No shadow

For images acquired before the trees were felled, the backscatter values from the polygons that represent regions with no shadow were about 0.3 dB below the backscatter values from the reference forest and the temporal variability was identical (Fig. 6). This confirms that the forest in the test areas and in the reference areas were similar in terms of properties that are relevant for SAR backscatter at X-band. After felling, the backscatter values increased compared to the reference forest and the measured differences were between 1.2 dB and 2.0 dB. The backscatter values from the felled areas were also higher than those from the reference clear-cuts, but the differences were in most cases smaller than for the reference forest. Analysis of variance (ANOVA) was used for a statistical analysis. The null hypothesis tested was that the difference between backscatter values from test areas and reference forest were the same before and after the trees were felled. This hypothesis could be strongly rejected ($p < 0.001$). This implies that the observed differences are real and not coincidental.

For images acquired after the trees were removed, the variability of the backscatter from the test areas was larger, with a tendency towards higher values compared to the reference forest areas. At one occasion the difference with respect to the reference forest was 3.1 dB. This behaviour was also observed for the values from the reference clear-cuts during all three phases of the experiment.

Differences between the test areas and the reference clear-cuts during phase 3 were likely due to the fact that the reference clear-cuts are three years older, which has allowed some growth of vegetation. This young vegetation could be enough to give more moderate variations in ground moisture. Slight differences in topography and surface roughness should also have a larger effect on the backscatter from clear-cuts than from mature or wind-thrown forest. The occasions when the backscatter is higher for clear-cuts than forest is in most cases related to rainfall (see Table 1) and predominantly occur for
descending orbits, which could be explained by a more moist ground surface and vegetation during the early morning passes than during the late afternoon ascending passes.

4.1.2. Shadow and layover

The measured backscatter values for the shadow and layover regions are presented in Fig. 7 for ascending passes and in Fig. 8 for descending passes. For images acquired after the trees had been felled, the backscatter values in the shadow regions decreased from about -10 dB to around -19 dB. The backscatter differences between the shadow regions and the reference forest increased to values in the range from 7.8 dB to 9.2 dB for the ascending orbits and 6.5 dB to 8.6 dB for descending orbits. The backscatter in the layover regions increased and the backscatter difference between these regions and the reference forest was between 3.2 dB and 4.6 dB for ascending orbits and between 2.8 dB and 3.4 dB for descending orbits. The shadowing and layover appear when the trees are felled and remain as long as the trees that surround the test areas are still standing. This effect would in theory span both phase 2 and 3, but as shown in Fig. 7 and Fig. 8, the backscatter levels in correspondence of shadowing and layover disappear after the end of phase 2. When the felled trees were removed after phase 2, the forest manager at the Remningstorp estate decided to cut down a larger area, which included most of the trees surrounding the test areas T1 to T3 and all trees on the eastern side of T4.

4.2 RADARSAT-2

4.2.1. No shadow

The RADARSAT-2 backscatter shows many similarities with the TerraSAR-X backscatter, although some of the trends were not quite as clear. The values from test regions without shadow or layover were slightly lower than the values from the reference forest areas, but
followed the same temporal variations until the trees are felled. For HH-polarized data (Fig. 9), the test area values were between 0.3 dB and 0.8 dB below the reference forest values. For HV polarization (Fig. 10), the backscatter was either 0.1 dB above the reference forest or at most 0.7 dB below.

In Figures 9 and 10, two image acquisitions have been included from the period when the felling was on-going. These acquisitions have been included for completeness and represent a transition period when the trees in parts of the test areas had been felled. For images acquired after the trees were felled, the backscatter was slightly above the level measured for the reference forest. The backscatter difference was between 0.2 dB and 1.2 dB for HH polarization, thus being less than the in the TerraSAR-X case. For HV-polarization the difference was between 0.1 dB and 1.1 dB.

For images acquired after the trees were removed, the backscatter decreased and in three cases out of four (one for HH and two for HV), the separation between the test areas and the reference forest was over 3 dB. On the fourth occasion, 2010-10-29, the backscatter for the test areas was instead 0.4 dB higher than for the reference forest. At all four dates there was no or negligible amounts of rainfall (see Table 2). However, while the three first acquisitions were preceded by dry and relatively warm periods, the conditions before the last acquisition were different. During the period 2010-10-21 to 2010-10-24 Remningstorp received 29 mm of precipitation, partly as snow, and this was followed by two days with temperatures below the freezing point. It is likely that on the acquisition day, the ground surfaces of the clear-cuts were still wet. As for TerraSAR-X, the backscatter values for the reference clear-cuts showed large temporal variations, but for the RADARSAT-2 measurements on any given day, the backscatter from the reference clear-cuts never reach values that are higher than from the reference forest.
4.2.2. *Shadow and layover*

Five RADARSAT-2 images were acquired during phase 2. Two images were acquired in HH polarization and three in HV polarization. The HH images and two of the HV images are from ascending passes and only one HV image is from a descending orbit. The measured backscatter values from the HH images are presented in Fig. 11 and the HV backscatter in Fig. 12 (ascending) and Fig. 13 (descending).

For the first HH image (2009-10-10) the backscatter values from the shadow regions are as low as -17.2 dB and the separation to the reference forest is 7.5 dB, while the backscatter value for the second HH image (2009-10-21) is -14.2 dB and the separation is only 4.9 dB. In addition to environmental differences between the two acquisition dates, a possible explanation to the difference could be that the smaller incidence angle of the RADARSAT-2 U3 observation mode that was used for the second acquisition gives less shadow within the shadow polygons than the larger incidence angle of the U25 mode that was used for the first acquisition. The difference between the backscatter levels from the regions with layover and the reference forest is 2.2 dB and 2.9 dB, which is lower than what was observed for the TerraSAR-X images.

The HV backscatter levels for the shadow regions range from -20.9 dB to -22.6 dB and the separation to the reference forest is between 5.9 dB and 7.0 dB. The HV images were acquired in the observation modes U14 and U16, so the differences in incidence angle are small and should not be the main cause for differences in the backscatter. The HV images cannot be compared with any TerraSAR-X data, but display a separation between layover and reference forest that is in the range 1.8 dB to 2.9 dB, which is on the same order as for the RADARSAT-2 HH data.
4.3 ALOS PALSAR

4.3.1 No shadow

The time series of ALOS PALSAR backscatter measurements in HH- and HV-polarization have been plotted in Fig. 14 and Fig. 15 respectively. Regardless of polarization, the values from the test regions without shadow and the reference forest only showed small differences (below 0.6 dB for HH-polarization and 0.5 dB for HV-polarization) during phase 1. For images acquired after the trees were felled, the backscatter of the test areas decreased compared to the backscatter level of the reference forest. The decrease was significantly larger for HH-polarization (1.6 dB compared to 0.4 dB and 0.8 dB for HV). For HH-polarization, the decrease in backscatter is likely due to removal of the double bounce component. The 1.6 dB decrease was in line with results from the experiment in Remningstorp in 2006 (Fransson et al., 2007). At HV-polarization, volume scattering is the main component and the scattering volume is still present when the trees have been felled. Conversely to the behaviour of the backscatter for the shorter wavelengths of TerraSAR-X and RADARSAT-2, at L-band the backscatter in phase 2 decreased with respect to the undisturbed conditions in phase 1. For images acquired after the trees had been removed, the backscatter from the test areas dropped with respect to the reference forest between 4.7 dB and 6.4 dB for HH-polarization and between 7.2 dB and 8.3 dB for HV-polarization. Compared to the backscatter measured in the reference clear-cut areas, the level of backscatter of the test areas was 1-4 dB lower. In general the separation between the reference forest and the reference clear-cuts is considerably larger than for TerraSAR-X and RADARSAT-2. This is in line with theory that states that longer wavelengths are more sensitive to differences in forest biomass and therefore should give a larger dynamic range between low and high biomass (e.g. Le Toan, 1992).
4.3.2. Shadow and layover

Due to the relatively coarse resolution of the ALOS PALSAR data, the polygons that had been defined for regions with ascending or descending shadow contained too few pixels to give reliable backscatter values for this sensor. However, a comparison with values from the polygons without shadow or layover gives a clear indication that shadow and layover do affect the backscatter significantly also for ALOS PALSAR images at this coarse resolution.

5. Summary and discussion

The backscatter signatures from mature forest, felled trees and clear-cuts have been studied with satellite SAR data from Terra-SAR-X, RADARSAT-2 and ALOS-PALSAR. A summary of the backscatter difference between reference forest and test regions without shadowing or layover is presented in Fig. 16. For TerraSAR-X the backscatter (HH) increased when the trees were felled while for ALOS PALSAR the HH polarized backscatter decreased. In both cases the backscatter differences between reference forest and felled forest without shadowing or layover were in the range 1.2 to 2.0 dB. For RADARSAT-2 (HH and HV) and HV polarized ALOS PALSAR images, only minor changes in backscatter levels were detected when the trees were felled.

The decrease in backscatter that has been measured for regions where shadowing appear after the trees are felled is significantly larger than the change in backscatter for areas that are not affected by shadowing or layover. This indicates that identification of new shadows gives a more reliable detection of wind-thrown forest, but after a real storm the shadows might be more diffuse than from the square test areas that have been used in the experiments in Remningstorp. In addition, a field or an open area will never create a shadow if the neighbouring forest is blown down and shadows will only appear if there are trees that remain standing after the storm. To increase the chance to find new shadows, images should be acquired in both ascending and descending passes when possible.
When a tree is felled by strong wind it is either uprooted or the stem breaks. Uprooting often occur for trees with shallow root systems, e.g. the spruce that is common in Northern Europe. The uprooted root system is often several meters in diameter and cause additional roughness and scattering surfaces that has not been possible to simulate in the experiment described in this paper. This difference between the conducted experiment and real conditions is expected to have a larger effect on the backscatter for longer wavelengths and might introduce double bounce scattering if the trees are felled in the same direction as the look direction of the SAR. This should be taken into account in case an operational system for detection of wind-thrown forest is to be designed.

The study shows that the variations in backscatter levels are larger for clear-cuts than for mature forest, which can be explained by a larger sensitivity to changes in environmental conditions like moisture of the ground and vegetation. For TerraSAR-X the backscatter levels from the clear-cuts overlap those of mature forest, which imply that X-band SAR backscatter is not suitable for clear-cut detection or monitoring. With increasing wavelength the separation between backscatter levels from clear-cuts and mature forest increase (see phase 3 in Fig. 16) and the results from ALOS PALSAR confirm results from previous studies that have indicated that L-band SAR backscatter can be used for clear-cut detection.

This study has been limited to backscatter signatures. Further work will be focussed on possibilities to use texture measures for detection of wind-thrown forest. Available material could also allow a sensitivity analysis for incidence angles and deviations between tree trunk direction and orbit direction, which has shown to influence detectability of wind-thrown forest for fine resolution low frequency airborne SAR systems (Fransson et al., 2007). A limited number fully polarimetric ALOS PALSAR images from 2006 and Radarsat-2 images from 2009 might also allow an evaluation of the usefulness of spaceborne SAR polarimetry for detection of shifts in scattering components when trees are felled.

Acknowledgments
This work was financially supported by the Swedish National Space Board and the Hildur and Sven Wingquist’s Foundation for Forest Research. ALOS PALSAR data have been provided by JAXA EORC within the framework of the JAXA Kyoto & Carbon Initiative. Data from RADARSAT-2 were granted within the Canadian program for Science and Operational Applications Research for RADARSAT-2 (SOAR), project number 3931 and data from TerraSAR-X were provided by the German Aerospace Center (DLR) under the agreement for proposal LAN0126. Meteorological observations from Remningstorp were available through a license agreement with SMHI. A. Pantze is acknowledged for his contribution to the planning of the storm simulation. G. Sandberg, Chalmers University of Technology is acknowledged for advice on the statistic analysis.

References


Tables

**Table 1.** List of the TerraSAR-X data, including information about acquisition date, observation mode (HS = High resolution Spotlight), track number (incidence angles: 2 = 43.6°, 55 = 49.5°, 78 = 34.0°, 146 = 41.4°), flight direction (Asc = ascending, Desc = descending), polarization (HH = horizontal co-polarized) and environmental conditions (T = temperature, PD = previous day) at and before the acquisition.

<table>
<thead>
<tr>
<th>ID</th>
<th>Acquisition date</th>
<th>Obs. mode</th>
<th>Track</th>
<th>Flight direction</th>
<th>Polarization</th>
<th>Environmental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>2009-08-24</td>
<td>HS</td>
<td>146</td>
<td>Asc</td>
<td>HH</td>
<td>T≈16 °C; Dry</td>
</tr>
<tr>
<td>X2</td>
<td>2009-08-26</td>
<td>HS</td>
<td>2</td>
<td>Desc</td>
<td>HH</td>
<td>T≈15 °C; Rain: 2 mm + 3 mm PD</td>
</tr>
<tr>
<td>X3</td>
<td>2009-08-29</td>
<td>HS</td>
<td>55</td>
<td>Asc</td>
<td>HH</td>
<td>T≈13 °C; Rain: 4 mm + 16 mm PD</td>
</tr>
<tr>
<td>X4</td>
<td>2009-08-31</td>
<td>HS</td>
<td>78</td>
<td>Desc</td>
<td>HH</td>
<td>T≈14 °C; Rain: &lt; 1 mm</td>
</tr>
<tr>
<td>X5</td>
<td>2009-09-04</td>
<td>HS</td>
<td>146</td>
<td>Asc</td>
<td>HH</td>
<td>T≈13 °C; Rain: 4 mm + 13 mm PD</td>
</tr>
<tr>
<td>X6</td>
<td>2009-09-06</td>
<td>HS</td>
<td>2</td>
<td>Desc</td>
<td>HH</td>
<td>T≈14 °C; Rain: 22 mm PD</td>
</tr>
<tr>
<td>X7</td>
<td>2009-10-03</td>
<td>HS</td>
<td>78</td>
<td>Desc</td>
<td>HH</td>
<td>T≈6 °C; Rain: 19 mm</td>
</tr>
<tr>
<td>X8</td>
<td>2009-10-07</td>
<td>HS</td>
<td>146</td>
<td>Asc</td>
<td>HH</td>
<td>T≈9 °C; Rain: 6 mm PD</td>
</tr>
<tr>
<td>X9</td>
<td>2009-10-09</td>
<td>HS</td>
<td>2</td>
<td>Desc</td>
<td>HH</td>
<td>T≈4 °C; Rain: 9 mm PD</td>
</tr>
<tr>
<td>X10</td>
<td>2009-10-12</td>
<td>HS</td>
<td>55</td>
<td>Asc</td>
<td>HH</td>
<td>T≈4 °C; Rain: 7 mm + 1 mm PD</td>
</tr>
<tr>
<td>X11</td>
<td>2009-10-14</td>
<td>HS</td>
<td>78</td>
<td>Desc</td>
<td>HH</td>
<td>T≈-1 °C; No precipitation</td>
</tr>
<tr>
<td>ID</td>
<td>Acquisition date</td>
<td>Obs. mode</td>
<td>Track number</td>
<td>Flight direction</td>
<td>Polarization</td>
<td>Environmental conditions</td>
</tr>
<tr>
<td>----</td>
<td>------------------</td>
<td>-----------</td>
<td>---------------</td>
<td>------------------</td>
<td>--------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>X12</td>
<td>2009-10-18</td>
<td>HS</td>
<td>146</td>
<td>Asc</td>
<td>HH</td>
<td>T~2 °C; Frozen at night; No precip.</td>
</tr>
<tr>
<td>X13</td>
<td>2009-10-20</td>
<td>HS</td>
<td>2</td>
<td>Desc</td>
<td>HH</td>
<td>T~5 °C; Rain: 2 mm + 2 mm PD</td>
</tr>
<tr>
<td>X14</td>
<td>2009-10-23</td>
<td>HS</td>
<td>55</td>
<td>Asc</td>
<td>HH</td>
<td>T~5 °C; Rain: 1 mm</td>
</tr>
<tr>
<td>X15</td>
<td>2010-08-22</td>
<td>HS</td>
<td>146</td>
<td>Asc</td>
<td>HH</td>
<td>T~15 °C; Rain: 4 mm PD</td>
</tr>
<tr>
<td>X16</td>
<td>2010-08-24</td>
<td>HS</td>
<td>2</td>
<td>Desc</td>
<td>HH</td>
<td>T~14 °C; Rain: 9 mm + 5 mm PD</td>
</tr>
<tr>
<td>X17</td>
<td>2010-08-27</td>
<td>HS</td>
<td>55</td>
<td>Asc</td>
<td>HH</td>
<td>T~12 °C; Rain: 6 mm, 5 days: 47 mm</td>
</tr>
<tr>
<td>X18</td>
<td>2010-09-02</td>
<td>HS</td>
<td>146</td>
<td>Asc</td>
<td>HH</td>
<td>T~10 °C; Dry</td>
</tr>
<tr>
<td>X19</td>
<td>2010-09-04</td>
<td>HS</td>
<td>2</td>
<td>Desc</td>
<td>HH</td>
<td>T~8 °C; Dry</td>
</tr>
<tr>
<td>X20</td>
<td>2010-09-07</td>
<td>HS</td>
<td>55</td>
<td>Asc</td>
<td>HH</td>
<td>T~12 °C; Dry</td>
</tr>
</tbody>
</table>

Table 2. List of the RADARSAT-2 data, including information about acquisition date, observation mode (U = Ultra-fine resolution beam with the following elevation angles to inner edge of beam: U3 = 27.8°, U14 = 35.0°, U16 = 36.2°, U25 = 40.9°), track number, flight direction (Asc = ascending, Desc = descending), polarization (HH = horizontal co-polarized, HV = cross-polarized) and environmental conditions (T = temperature, PD = previous day) at and before the acquisition.
<table>
<thead>
<tr>
<th>ID</th>
<th>Acquisition date</th>
<th>Obs.</th>
<th>RSP</th>
<th>Flight direction</th>
<th>Polarization</th>
<th>Environmental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>R8</td>
<td>2009-09-16</td>
<td>U25</td>
<td>259</td>
<td>Asc</td>
<td>HH</td>
<td>T≈10 °C; Dry</td>
</tr>
<tr>
<td>R9</td>
<td>2009-09-30</td>
<td>U16</td>
<td>116</td>
<td>Asc</td>
<td>HV</td>
<td>T≈4 °C; Rain: 14 mm</td>
</tr>
<tr>
<td>R10</td>
<td>2009-10-07</td>
<td>U14</td>
<td>209</td>
<td>Desc</td>
<td>HV</td>
<td>T≈9 °C; Rain: 6 mm PD</td>
</tr>
<tr>
<td>R11</td>
<td>2009-10-10</td>
<td>U25</td>
<td>259</td>
<td>Asc</td>
<td>HH</td>
<td>T≈4 °C; Frozen at night; No precip.</td>
</tr>
<tr>
<td>R12</td>
<td>2009-10-21</td>
<td>U3</td>
<td>73</td>
<td>Asc</td>
<td>HH</td>
<td>T≈4 °C; Rain: 2 mm PD</td>
</tr>
<tr>
<td>R13</td>
<td>2009-10-24</td>
<td>U16</td>
<td>116</td>
<td>Asc</td>
<td>HV</td>
<td>T≈4 °C; Rain: 1 mm + 1 mm PD</td>
</tr>
<tr>
<td>R14</td>
<td>2010-09-08</td>
<td>U14</td>
<td>209</td>
<td>Desc</td>
<td>HV</td>
<td>T≈13 °C; Dry</td>
</tr>
<tr>
<td>R15</td>
<td>2010-09-11</td>
<td>U25</td>
<td>259</td>
<td>Asc</td>
<td>HH</td>
<td>T≈14 °C; Rain: 2 mm + 1 mm PD</td>
</tr>
<tr>
<td>R16</td>
<td>2010-10-02</td>
<td>U14</td>
<td>209</td>
<td>Desc</td>
<td>HV</td>
<td>T≈9 °C; Dry</td>
</tr>
<tr>
<td>R17</td>
<td>2010-10-29</td>
<td>U25</td>
<td>259</td>
<td>Asc</td>
<td>HH</td>
<td>T≈8 °C; Rain: 1 mm PD</td>
</tr>
</tbody>
</table>

**Table 3.** List of the ALOS PALSAR data, including information about acquisition date, observation mode (FBD34 = Fine Beam Dual polarization with look angle 34.3°), Reference System for Planning (RSP) number, flight direction (Asc = ascending, Desc = descending), polarization (HH = horizontal co-polarized, HV = cross-polarized) and environmental conditions (T = temperature, PD = previous day) at and before the acquisition.
<table>
<thead>
<tr>
<th>Station</th>
<th>Date</th>
<th>Code</th>
<th>Level</th>
<th>Phase</th>
<th>Temp (°C)</th>
<th>Rain (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A8</td>
<td>2009-10-08</td>
<td>FBD34</td>
<td>630</td>
<td>Asc</td>
<td>HH + HV</td>
<td>T≈5 °C; Rain: 9 mm</td>
</tr>
<tr>
<td>A9</td>
<td>2010-08-09</td>
<td>FBD34</td>
<td>629</td>
<td>Asc</td>
<td>HH + HV</td>
<td>T≈16 °C; Rain: 6 mm + 5 mm PD</td>
</tr>
<tr>
<td>A10</td>
<td>2010-08-26</td>
<td>FBD34</td>
<td>630</td>
<td>Asc</td>
<td>HH + HV</td>
<td>T≈13 °C; Rain: 8 mm, 4 days: 41 mm</td>
</tr>
<tr>
<td>A11</td>
<td>2010-09-24</td>
<td>FBD34</td>
<td>629</td>
<td>Asc</td>
<td>HH + HV</td>
<td>T≈15 °C; Rain: 9 mm</td>
</tr>
<tr>
<td>A12</td>
<td>2010-10-11</td>
<td>FBD34</td>
<td>630</td>
<td>Asc</td>
<td>HH + HV</td>
<td>T≈2 °C; Frozen at night; No precip.</td>
</tr>
</tbody>
</table>

2 **Figures**

3 ![Map of Northern Europe](image)

4 **Fig. 1.** The location of Remningstorp test site, shown on a map of Northern Europe.
Fig. 2. A mosaic of digital aerial photographs captured by a UAV (courtesy SmartPlanes AB) covering three of the simulated wind-thrown forest stands, each with a size of about $110 \times 110$ m$^2$.

Fig. 3. Photograph taken from the ground of one of the simulated wind-thrown stands.
Fig. 4. Location of test areas (T1-T4) and reference areas (R1-R4). R1 and R2 are reference forest and R3 and R4 are reference clear-cuts. The background image is a temporal average of four TerraSAR-X images with acquisition dates 2009-10-07, 2009-10-12, 2009-10-18 and 2009-10-23.
Fig. 5. The left image shows the division of the test areas T1, T2 and T3 into shadowed and non-shadowed regions for ascending passes (in this case the TerraSAR-X image from track 55 acquired 2009-10-23). The right image shows the regions that have been used for descending passes (exemplified by TerraSAR-X image from track 2, acquired 2009-10-09). The perimeters of the test areas are indicated with dashed lines, while polygons for shadow are marked with dotted lines and polygons for regions without shadow with solid lines.

Fig. 6. Time series of TerraSAR-X backscatter values for regions of the test areas without shadow. Includes all acquired images from both ascending and descending passes.
Fig. 7. Time series of TerraSAR-X backscatter values for regions of the test areas with shadow or layover. Includes all acquired images from ascending passes.

Fig. 8. Time series of TerraSAR-X backscatter values for regions of the test areas with shadow or layover. Includes all acquired images from descending passes.

Fig. 9. Time series of RADARSAT-2 backscatter values for regions of the test areas without shadow. Includes all acquired images with HH polarization. All images are from ascending passes.
Fig. 10. Time series of RADARSAT-2 backscatter values for regions of the test areas without shadow. Includes all acquired images with HV polarization from both ascending and descending passes.

Fig. 11. Time series of RADARSAT-2 backscatter values for regions of the test areas with shadow or layover. Includes all acquired images with HH polarization. All images are from ascending passes.
Fig. 12. Time series of RADARSAT-2 backscatter values for regions of the test areas with shadow or layover. Includes all acquired images with HV polarization from ascending passes.

Fig. 13. Time series of RADARSAT-2 backscatter values for regions of the test areas with shadow or layover. Includes all acquired images with HV polarization from descending passes.
Fig. 14. Time series of ALOS PALSAR backscatter values for regions of the test areas without shadow. Includes all acquired images with HH polarization. All images are from ascending passes.

Fig. 15. Time series of ALOS PALSAR backscatter values for regions of the test areas without shadow. Includes all acquired images with HV polarization. All images are from ascending passes.
Fig. 16. Differences in sigma nought between test regions without shadow and reference forest. The temporal spacing along the x-axis is not equidistant.