SLU

Kartläggning av hyggen i svensk skogsmark Med satellitbilder från radarinstrumentet ALOS PALSAR

Mapping of clear-cuts in Swedish forest using satellite images acquired by the radar sensor ALOS PALSAR

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Jägmästarprogrammet

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Contents

Summary

This study presents results for observing forest changes in Sweden using multi-temporal L-band satellite data and is a part of the JAXA's ALOS Kyoto and Carbon Initiative. An extensive dataset of images acquired by the Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar (ALOS PALSAR) is investigated for clear-cut detection in boreal forests in northern Sweden (Lat. 64°14' N, Long. 19°50' E). Strong forest/non-forest contrast and temporal consistency were found for the Fine Beam Dual HV-polarized backscatter during unfrozen conditions. Thus, a simple thresholding algorithm that exploits the temporal consistency of pair-wise HV-backscatter measurements has been developed for detection of clear-felled areas. When applied to an image pair acquired during favorable weather conditions, the detection algorithm identified 76% of the clear-cut pixels within a reference layer, with zero erroneously detected pixels. With further refinement, the developed methodology can be an option to present operational alternatives for clear-cut detection.

Keywords: remote sensing, forest monitoring, algorithm, change detection, JAXA.

Sammanfattning

Studien presenterar resultat från kartläggning av skogsförändringar (föryngringsavverkningar i Sveaskogs regi) i Sverige, med hjälp av multi-temporala L-bands satellitdata och är en del av den Japanska rymdflygstyrelsens (JAXAs) ALOS Kyoto and Carbon Initiative. Ett stort dataset av bilder tagna av Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar (ALOS PALSAR) undersöktes för hyggesdetektion av boreal skog i norra Sverige (Lat. 64°14’ N, Long. 19°50’ E). En stark kontrast mellan skog och hygge och en temporal stabilitet upptäcktes för Fine Beam Dual HV-polariserad tillbakaspridning under sommarförhållanden. Således togs en enkel tröskelvärdesalgoritm fram för hyggesdetektion som tillvaratar den temporala stabiliteten av parvisa HV-tillbakaspridningsmätningar. Vid tillämpning på ett bildpar taget under goda väderleksförhållanden, identifierade detektionsalgoritmen 76 % av hyggespixlarna i ett referensskikt, med noll felaktigt detekterade pixlar. Med ytterligare förfining kan den utvecklade metodiken komma att bli ett värdefullt komplement till dagens operationella metoder för hyggesdetektering.

Introduction

Radar remote sensing for forestry applications

The increasing demand for wood products in all parts of the world puts pressure on the forests to produce even more viable raw material than today. This in turn puts stress on the need for strategically sound decisions about forestry and how preservation and protection of nature will be handled. In this context forest management planning is more important than ever. For planning purposes the old typical approach of acquiring data through subjective surveying methods in the field are perhaps no longer enough, or as economical as other newer methods using remote sensing. Thus, economics in addition to the growing demand for forest products emphasizes the need for new methods of monitoring forest conditions in an efficient way. Clear-cuts are a good first step to focus on when studying forest change over time. As forest changes also can come suddenly, there is a need for a method that is continuous and able to gather and transmit data to users on a timely basis.

Using data from satellites that view the Earth from above is one way of ensuring that these requirements are met. Optical satellite images have a long history of being used in forestry and other remote sensing applications (e.g. land surveys or land use mapping). However, as weather conditions and other atmospheric disturbances make these images prone for errors it may not be adequate to use optical images of the forest if the sky is not relatively clear (Lillesand et al., 1999). Optical systems are dependent on the sun supplying light as a source of reflection for image acquisition. In contrast, the Synthetic Aperture Radar (SAR) technique is independent of cloud cover and the cycling of light conditions and is in this respect superior to light dependent systems (Lillesand et al., 1999).

There are many different wavelengths available for usage among today's SAR sensors. The SAR sensors of different satellite systems include a broad range of wavelength configurations, designated X (λ = 1 cm), C (λ = 6 cm), S (λ = 10 cm) and L-band (λ = 24 cm). There are comparative studies made that indicate that longer wavelengths will result in a higher contrast between forest and non-forest such as clear-cuts (Watanabe et al., 2007). This makes L-band satellite SAR systems highly interesting for large-area mapping of forest changes as it is at present the longest wavelengths available from satellite SAR systems. On the other hand, today's L-band satellite SAR images do not have as high spatial resolution as for instance TerraSAR-X (X-band) or various optical instruments, but further developments are being made in this field to improve the resolution of L-band satellite images (Börner et al., 2007; Rosenqvist et al., 2007). There have been several airborne and spaceborne missions conducted with L-band SAR systems (e.g. AIRSAR, E-SAR, Seasat, SIR-A/B/C, JERS-1, ALOS PALSAR), which have indicated the potential usefulness for forest applications (Rignot et al., 1997; Salas et al., 2002). Therefore, this study suggests that images acquired from the ALOS PALSAR L-band SAR sensor are suitable for detection of changes in the boreal forest landscape.

In the present study the objective is to verify if L-band satellite SAR data can be used to detect clear-cuts in Swedish forest. This study should be seen as a first step towards exciting developments foreseen in the future within this area. Clear-cuts are one of the most easily discernible patterns in the forest landscape and as such they are a good starting point when trying to develop and validate a method for monitoring forest conditions. If the developed method is proven to be successful it could be implemented as an operational tool for mapping of clear-cuts (e.g. by the Swedish Forest Agency).

The Swedish Forest Agency

The Swedish Forest Agency is the Swedish government's agency responsible for ensuring that laws and regulations concerning forests and forestry are upheld (Anon., 1999). One part of that work is in the form of monitoring fellings and to monitor that the amount of cutting is in agreement with the governmental goals. Furthermore, the Swedish Forest Agency has two goals set out in law that sets an environmental goal equal to one about sustainability and economy (Anon., 1999). To ensure that monitoring is done in the best way possible, the Forest Agency uses satellite imaging in its work (Ekberg et al., 2007). The images they use today are optical SPOT satellite data accessible via their sponsoring of the Swedish National Land Survey's (Lantmäteriverkets) project SACCESS (Anon., 2000). In Swedish law it is stated that every felling of a size larger than 0.5 hectare is subject for approval by the Swedish Forest Agency (Anon., 1999).

After due processing, the felling can commence. To ensure that everything is done according to laws and regulations the Forest Agency uses remote sensing to detect all the fellings performed in the country. This is published as a map of clear-cuts. This map can then be used for inventory of regrowing forest. The map production is done continuously and is updated every week on their webpage's (Anon., 2000). One suggestion is that radar images could be used as a complement to that work and help further substantiate their findings. It could be especially useful in the event of illegal loggings, to get a first estimate of the total extent of damages and maybe storm fellings to some extent. As an example of the usefulness of radar systems, the radar system CARABAS was used in the aftermath of the large storm Gudrun (January, 2005) in the southern parts of Sweden in the beginning of the year 2005 (Ulander et al., 2006). Even though CARABAS is an airborne system, it strengthens the argument about the usefulness of radar systems for forestry applications.

Collaboration between JAXA and SLU

In 2004, the Swedish University of Agricultural Sciences (SLU) and the Japan Aerospace Exploration Agency (JAXA) signed a contract, for collaboration. This collaboration is a part of JAXA's project ”ALOS Kyoto and Carbon Initiative” and the idea behind are in particular about sharing data and results between different independent projects. SLU will by access to ALOS PALSAR data (free of charge), share information and results gathered from mapping forest changes in two Swedish counties, i.e. Västerbotten and Västra Götaland. The methodology and approach taken by SLU in this work will then be shared to other projects that could stand to be gained by this sharing of information. The present study includes analysis of one of two available test sites. Remningstorp and Krycklan located in the south and north county, respectively, with analysis made of the north test site. Both test sites are described more in detail under the section of Material and methods.

ALOS

The Japanese satellite ALOS was launched in January, 24, 2006. After an initial phase of commissioning, a number of calibrations were performed with different international partners all over the world (Ulander et al., 2006; Börner et. al., 2007; Eriksson et al., 2007). This was done to assess the quality of the data acquired by the onboard sensors of the satellite. The satellite carries three advanced sensors for data gathering, such as the optical sensors Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) and Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2), and the radar sensor Phased Array type L-band SAR (PALSAR) (Rosenqvist et al., 2007). Sweden's part in these calibration and validation projects has been in relation to the PALSAR sensor (Ulander et al., 2006). The calibration was performed using on ground deployed corner reflectors and PALSAR images acquired in high-resolution and polarimetric modes, at the test site Remningstorp in southern Sweden (Ulander et al., 2006; Eriksson et al., 2007).

The L-band PALSAR is an evolution of the earlier Japanese Earth Resources Satellite-1 (JERS-1) SAR and is a fully polarimetric system. The sensor frequency is 1.270 GHz, which corresponds to a wavelength of about 24 cm. It has four different modes of operation (out of 72 possible modes): Fine Beam Single polarization (FBS), Fine Beam Dual polarization (FBD), Polarimetric mode (PLR) and ScanSAR mode (Fig. 1) (Rosenqvist et al., 2007). In FBS mode, PALSAR can be operated with either HH or VV polarization with a bandwidth of 28 MHz. In FBD mode, the polarization options are HH/HV or VV/VH (HH/VV not possible) at 14 MHz bandwidth. The look angle is variable in 18 steps between 9.9º and 50.8º off-nadir.

Out of the four operational modes available, two have been selected for analysis in the present study: HH polarization; 34.3º look angel (FBS34) and HH/HV polarization; 34.3º look angel (FBD34). These modes yield a swath width of 70 km and a ground resolution of 10×20 m^2 and 20×20 m^2 in HH and HH/HV polarization, respectively. The 34.3º look angle corresponds to an incidence angle range of 36.6º – 40.9º from near to far range (Rosenqvist et al., 2007).

Currently, more than 200,000 PALSAR scenes are being acquired annually through the observation strategy established by JAXA (Rosenqvist et al., 2003). Although gaps in the coverage inevitably will occur, this will nonetheless constitute a valuable global archive in which consistent time series of fine-resolution satellite data can be found for any arbitrary point or extensive region on the globe. (Rosenqvist et al., 2007).

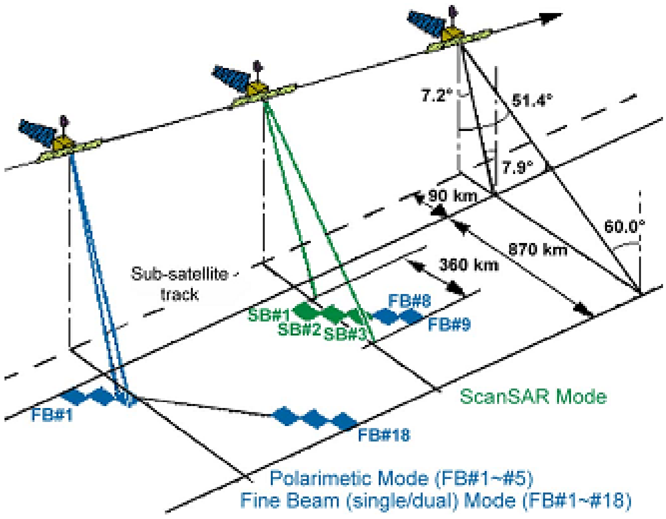

Figure 1. Different modes of operation of the ALOS PALSAR system.

Figur 1. *ALOS PALSAR systemets olika operationella moder (inställningar).*

(image courtesy of JAXA)

Previous and current research

There have been a number of studies performed since the start of the cooperation between JAXA and SLU most of them centered on forestry applications. Other studies have tried to discern what band (e.g. wavelength) that is most useful for detecting different properties of the forest. These have found L-band to be the best for clear-cut detection as the contrast between forest and non-forest was at its highest (Pulliainen et al., 1999). Before the launch of ALOS, it has been shown on numerous occasions that clear cut detection through the use of L-band data is possible using different methods (Yatabe et al., 1995).

Several studies have been performed by scientific groups in amongst others Japan, indicating that trough the use of backscatter values it is possible to monitor the forest landscape and detect changes such as fellings and also growing forest (Yatabe and Leckie, 1995; Bergen et al., 1998; Fransson, 1999). Using a combination of data from ALOS precursor JERS-1 and ALOS PALSAR data, a research team monitored forest over a period of 14 years. The results presented indicate a difference in backscatter value between forest and non-forest of about 3 dB, confirming that a felling has been performed (Watanabe et al., 2007). These results are substantiated by results from a research group in Sweden (Santoro et al., 2009). From using only PALSAR data the results show that a drop in backscatter value of about 3 dB indicates a clear-cut similar to the results obtained by Watanabe et al. (2007).

Detection and mapping of clear-cuts using L-band SAR backscatter data have been pursued primarily in boreal forest (e.g. Ranson and Sun, 1994; 1997; 2000; Ranson et al., 2001; 2003; Igarashi et al., 2003; Fransson et al., 2007; Magnusson et al., 2007; Santoro et al., 2009); nonetheless several examples have been reported for tropical and temperate forests as well (e.g. Ribbes et al., 1997; Rignot et al., 1997; Saatchi et al., 1997; Grover et al., 1999; Hoekman and Quiñones, 2000; Takeuchi et al., 2000; Salas et al., 2002; Almeida-Filho et al., 2005 and Thiel et al., 2006). Their findings indicate that L-band backscatter is typically lower in deforested areas compared to mature and regrowing forest. A decrease of about 1.5 dB was reported in Ranson and Sun (2000) for the British test site Kielder using JERS-1 (HH- polarization). A 3 dB difference with respect to mature forest was observed in Siberian boreal forest using JERS-1 Ranson and Sun (1997). These two studies are especially relevant as the conditions the trees are growing in are similar to conditions found in the north and south of Sweden.

The backscatter difference between clear-felled and mature forest is larger for cross-polarized data because of the much weaker surface scattering component (Santoro et al. 2009). For a test site in the state of Rondonia, Brazil, Grover et al. (1999) reported a HV-backscatter difference between primary forest and cleared forest of 8 dB with the Spaceborne Imaging Radar-C (SIR-C) (L-band) SAR system. For Siberian boreal forest the HV-backscatter difference reached 5 dB using the SIR-C sensor (Takeuchi et al. 2000). Artifacts in the form of enhanced backscatter can, however, disturb image quality in the case of clear-cuts where trunks and woody debris are lying on the ground at the time of image acquisition.

Recent analyses of felled areas revealed that clear-cuts present a drop in PALSAR L-band SAR backscatter (Fransson et al., 2007; 2008; Santoro et al., 2009). Average differences in the order of 2 to 3 dB for HH- and HV-polarization were found, with stronger contrasts at HV-polarization. Moreover, the dynamic range for FBD34 HV-polarized data was 8-9 dB during unfrozen conditions compared to 6-7 dB for HH-polarized data (Santoro et al., 2009). Thus, clear-cuts seem to be detectable using PALSAR data. However, significant variations in backscatter due to environmental conditions has also been noticed, which needs to be taken into account when developing a methodology for clear-cut detection.

Objectives

The objectives of the study are to develop and evaluate a method for detecting clear-cuts using ALOS PALSAR data and to investigate if clear-cuts can be delineated for areal estimation in Swedish forest. Furthermore, the goal is to get a fulfillment of clear-cut detection of at least 75% of the available stands supplied by Sveaskog.

Material and methods

Test sites

There are two test sites initially used in this study, Remningstorp test site (Lat. 58°30’ N, Long. 13°40’ E), located in the south of Sweden and Krycklan test site in the north of Sweden (Lat. 64°14’ N and Long. 19°40’ E) (Fig. 2). The Remningstorp test site is located in between the two largest lakes of the country, Vänern and Vättern (Fig. 3). The estate is managed by the Forestry Society’s Estate Management Company. Most of the forestry studies taking place here over the years have been defined and carried out by SLU.

Figure 2. Map showing the counties of Västerbotten and Västra Götaland and the test sites of Krycklan and Remningstorp.

Figur 2*. Karta som visar länen Västerbotten och Västra Götaland samt försöksområdena Krycklan och Remningstorp.*

The forest holding at Remningstorp covers about 1,200 ha of productive forest land divided into 340 stands (Fig. 3). The prevailing tree species are Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and birch (*Betula* spp.) with a few of the stands dominated by oak (*Quercus robur*) and beech (*Fagus sylvatica*).The dominant soil type is till, i.e. coarse and mainly podsolic soil of glacial origin, with a mineral content dominated by quartz. The field layer, when present, consists of different herbs, bilberry (*Vaccinium myrtillus*), and narrow-leaved grass (e.g. *Deschampsia flexuosa*). In denser old spruce stands the field layer is absent. The topography is fairly flat with some small variations ranging between 120 and 145 m above sea level. The prevailing tree species generate an annual growth yield of about 9 m^3 ha^{-1} $year^{-1}$.

Krycklan is a forest area managed mainly by the Swedish forest company Holmen, with about 6,800 ha of predominantly coniferous forests (Fig. 4). The Krycklan area is currently hosting a large number of forest research projects. The prevailing tree species is Norway

Figure 3. The Remningstorp test site outlined, situated between the two largest lakes in Sweden. The test site consists of 1,200 ha of coniferous forests in different stages of development.

Figur 3*. Försöksområdet Remningstorp, beläget mellan Sveriges två största sjöar. Försöksområdet är 1200 ha stort och består främst av barrskog i flera utvecklingsstadier.*

spruce and Scots pine, but some deciduous tree species, e.g. birch, are also present. The tree species composition is approximately 37% spruce, 47% pine, and 16% deciduous. The test site represents rather intensively managed boreal forest compared with other areas in the northern part of Sweden. The dominant soil type is till. The field layer consists of bilberry, cowberry, and different grass and herb species. The ground elevation varies from 160 to 400 m above sea level. The highest stem volumes are in the order of 320 m^3 ha^{-1}.

Figure 4. The Krycklan test site outlined, situated north west of the city of Umeå. The test site consists of 6,800 ha of coniferous forests in different stages of development.

Figur 4*. Försöksområdet Krycklan, beläget nordväst om Umeå. Försöksområdet är ca 6800 ha stort och består av barrskog i flera utvecklingsstadier.*

Data acquisition

ALOS PALSAR images have been acquired regularly over the test sites since the validation phase started (in May, 2006) (followed by the operational phase in October, 2006) until August, 2008. PALSAR images from two modes of operation, i.e. Fine Beam Single and Fine Beam Dual were available for the study. For the analysis, however, FBD34 images were chosen as they seemed especially suitable for clear-cut detection (Table 1).

Table 1. List of PALSAR images used in the analysis with acquisition date and mode, RSP (Reference System for Planning) number and environmental conditions. All images were acquired in ascending orbital track and during unfrozen conditions

Tabell 1*. En lista på PALSAR-bilderna använda i analysen med bildtagningstillfälle, mode, RSP (referenssystem för planering) nummer och väderleksförhållanden. Alla bilder registrerades i uppåtstigande satellitbana och temperaturer över 0* ºC

Acquisition date	*Imaging mode*	*RSP number*	*Environmental conditions*
2007-10-07	FBD34	614	T ≈ 7 ºC, 4 mm rainfall
2007-07-24	FBD34	615	T ≈ 15 ºC, < 1 mm rainfall
2008-04-25	FBD34	615	T ≈ 3 ºC, dry
2008-05-07	FBD34	613	T ≈ 8 ºC, dry
2008-07-26	FBD34	615	T ≈ 19 ºC, dry

Information about clear-felled areas in the form of vector layers were obtained from the Swedish company Sveaskog. The polygon layer consists of fellings made from January, 2006 until August, 2008. These are not done as proper clear-cuts but rather according to Sveaskog’s internal policies about practical forestry implementations. The policy states that on average 9% of the area subject to felling, should be left for nature conservation purposes. This means that both single trees and groups of trees or combinations thereof are left when performing a felling. The effect this can have in the analysis is that areas that are known clear-cuts, does not show up as such when applying the algorithm because of the disturbance effect caused by left trees. This is something that could present a problem when making analysis on a pixel based level but for larger areas this should be adequate.

There are some differences present when comparing the two layers over the southern and northern test site with each other. First there is a difference of size of the actual polygons as the layer over Krycklan often consists of polygons larger than five hectare in size. The polygons in the layer over Remningstorp are smaller and more often down towards two hectares. This could make a difference when interpreting results, but the two layers where generated using the same conditions, i.e. selecting clear-cuts of at least two hectares in size. Both layers are geographically evenly spread out over the test sites. The Krycklan layer consists of 1074 and Remningstorp of 666 polygons. Another difference is that the south of Sweden has over the last years been hit by a number of storms. Therefore, some of the polygons that are stated as clear-cuts for the south test site could be areas felled by storms, disturbances such as felled trees or remains from uprooted trees could therefore present a problem in the analysis. These events have not happened to the north of Sweden and here there are only conventional clear-cuts represented.

Image processing

PALSAR images have been processed by the consulting agency GAMMA Remote Sensing in Switzerland. Processing of the images has been performed to eliminate disturbances and effects of topography and to geo-reference the images to fit into the Swedish National Grid (RT90). The images obtained from GAMMA were geo-referenced, but not according to RT90. Therefore, as a starting point this was done in the raster software package ENVI. The Swedish system RT90 2.5 gon west was used to match the polygon layer supplied by Sveaskog. The geo-referencing of the images is important in order to geographically match the polygon layer used in the validation procedure.

Selection of test site and image data

In the start up phase of analysis, data Remningstorp was discovered to be problematic since the vector layer of clear-cuts and the PALSAR images had negligible overlap, meaning that no data could be gathered via an overlay of the polygons on the images. Therefore, the test site Remningstorp was excluded from further analysis, and all results presented below are for the Krycklan test site only. In Fig. 5 the mean HV-polarized backscatter for the reference forest stands at different acquisition dates is plotted. The plots depict temporal consistency of HV-polarized backscatter for unaffected stands during unfrozen conditions (cf. Santoro et al., 2009). Due to differences in SAR data coverage for different dates there are an unequal number of reference stands available for each image pair. As the clear-cuts stand out, the plots also indicate that HV-polarized backscatter alone can be used for clear-cut detection, at least under favorable weather conditions. The environmental conditions at image acquisitions are presented in Table 1.

Algorithm

A thresholding algorithm working at pixel level on a given pair of PALSAR images were used to test the possibility to detect clear-cuts. First, the multi-look intensity images are filtered to suppress speckle (background noise and disturbance mostly) (Lopes et al., 1990). Any differences between the images due to different ground and weather conditions during image acquisition are assumed to be linear. To adjust for these differences and make the images comparable, a linear fit is used on all overlapping pixels in the image pair to find the scaling factor and offset. This method uses non clear-felled areas as a reference material. The linear-fit is done through taking the first and third quartiles of the two images being analyzed and synchronizing them. This can be seen as a rough and computationally cheap way of making the images comparable, nevertheless it works.

A threshold is then applied to the resulting difference image, generating an initial binary classification image. To suppress noise and delineate areas of change, two images are then produced by morphological opening followed by closing of the classification image. For the first image a small structuring element is used and for the other one a larger. The final classification is the pixel-wise multiplication of the resulting images. The larger structuring element used cancels noise and small area changes, whilst the smaller one keeps some details. A disk structuring element with a 3 pixel radius (1.16 ha in area) and a 3×3 structuring element were then used in the morphological operations to produce the final classification (the disc element is essentially a circle with a 3 pixel radius centered on each classified pixel).

Results

The algorithm was applied to the image pair corresponding to the bottom right plot in Fig. 5 (2007-07-24 vs. 2008-07-26). The two original 20×20 m^2 spaced FBD34 HV-polarized multi-look intensity images overlapped by approximately 400,000 ha and covered 155 reference stand polygons (1,800 ha) of which 51 stands (500 ha) were subject to felling between image acquisition dates. First an adaptive 3×3 Enhanced Lee (Lopez et al., 1990) filter was applied to both images. The linear multiplicative and additive offset between the images was found by comparing their first and third quartiles. A difference image was produced by subtracting values of the second date from the first (Fig. 6). This figure also shows the detection procedure being performed. Pixel values below one inter-quartile range from the first quartile of the difference image were then initially classified as change (corresponding to a backscatter drop in the order of 1 dB).

For the accuracy assessment only areas covered by the Sveaskog's stand polygons were used as reference as they constitute a reliable source for what are truly forest areas and whether they are clear-felled or not. This was the reason for not using a forest mask as earlier studies have done (e.g. Fransson et al., 2007; Santoro et al., 2009). The change detection accuracy at pixel level was 76.4% correctly detected pixels within the 51 clear-cut stands for the image pair of 2007-07-24/2008-07-26. Furthermore, zero false detected pixels were observed for this image pair (i.e. not a single falsely detected pixel within the 104 polygons of 1,300 ha not subjected to felling between the two acquisition dates).

In addition, the stand-wise detection accuracy can be seen in Fig. 7. If a partial pixel detection of at least 60% is required for a clear-cut detection, 80% of the clear-felled stands were found, whereas if only 30% partial pixel detection is required 90% were found. For the whole curve in Fig. 7 the error of commission is zero. 76.4% is the peak value where most pixels are correctly classified as clear-cut of the available pixels. That means that 76.4% of the felled areas are found as changed without getting any erroneously classed forest areas. In comparison the initial classification image, not processed with any speckle reducing tools, gave a result of 71% correctly classified pixels. The amount of erroneously classified pixels was much higher and reached about 30%. This is also seen as an argument towards the strength of the developed algorithm, as it generates results with a minimum of erroneously detected pixels.

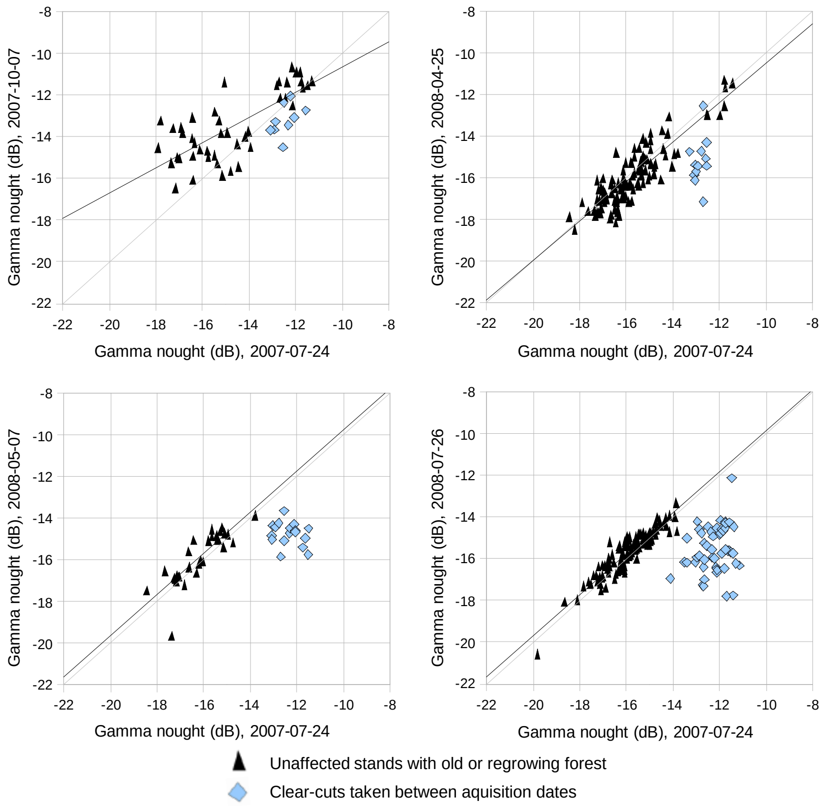

Figure 5. Bi-temporal scatterplots of average PALSAR FBD34 HV-polarized backscatter for forest stands at the Krycklan test site for four different acquisition dates with respect to a common date (2007-07-24). All images except one (2007-10-07, top left) were acquired during dry conditions (Table 1). The one-to-one line is shown in grey and a robust regression line based on unaffected stands in black.

Figur 5*. Bi-temporala plottar för medelvärdet av PALSAR FBD34 HV-polariserad tillbakaspridning av skogsbestånd kring Krycklans försöksområde, för fyra olika bildtagningstillfällen med utgångspunkt i ett gemensamt datum (2007-07-24). Alla bilder utom en (2007-10-07, övre vänstra) är tagna under torra förhållanden (Tabell 1). Ett-till-ett linjen är visad i grått och den robusta regressionslinjen baserad på ej påverkade bestånd är svart.*

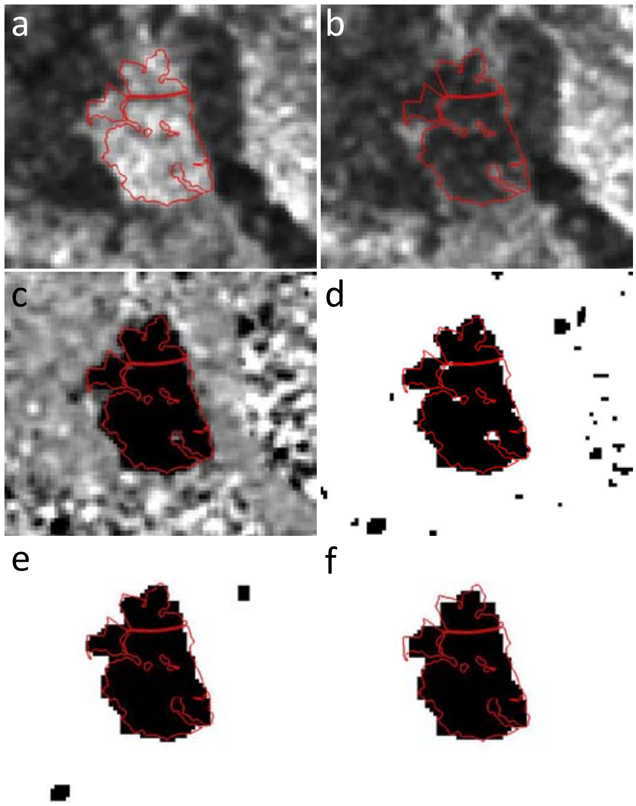

Figure 6. Illustration of the clear-cut detection algorithm with the boundary of a reference polygon shown in red. a) intensity image before felling, b) intensity image after felling, c) intensity difference image, (b)-(a), d) thresholded difference image, e) image after morphological opening and closing using a 3x3 structuring element and f) final detection image after multiplying (e) with the opening and closing of (d) using a disk structuring element with a 3 pixel radius.

Figur 6*. Illustration av hyggesalgoritmen med gränslinjen av en hyggespolygon markerad i rött. a) intensitetsbild före avverkning, b) intensitetsbild efter avverkning, c) intensitetskillnadsbild, (b)-(a), d) tröskelvärdesbehandlad skillnadsbild, e) bild efter morfologisk öppning och stängning med användning av ett 3x3 strukturelement och f) slutgiltig detektionsbild efter att ha multiplicerat (e) med öppning och stängning av (d) med användning av ett skivstrukturelement med en radie på 3 pixlar.*

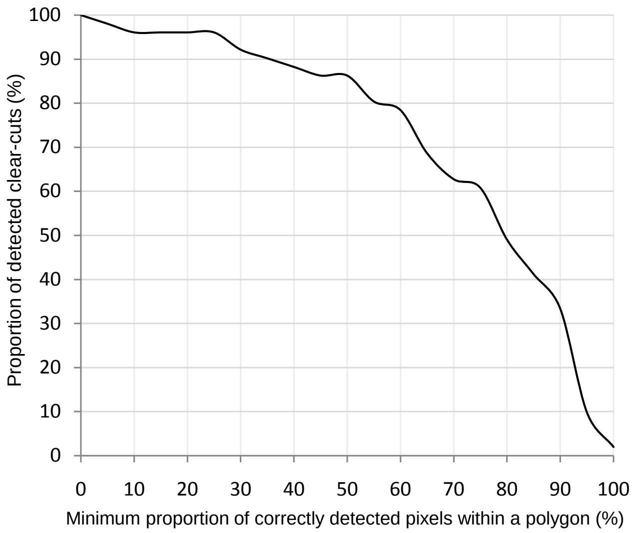

Figure 7. Proportion of correctly classified clear-cuts as a function of the minimum proportion of correctly detected pixels within clear-cuts.

***Figur 7**. Proportionen av korrekt klassade avverkningar som en funktion av minimum proportionen av korrekt detekterade pixlar inom hyggespolygonen.*

Discussion and conclusions

The objective of this study was to develop a method for detecting and delineating clear-cuts using ALOS PALSAR data. It was found that PALSAR HV-backscatter data acquired during unfrozen and dry environmental conditions were a stable data source for change detection of clear-cuts. As seen in the three plots of Fig. 5 corresponding to stable weather conditions, clear-cuts are clearly separated from regenerating or old growth forest. Conversely, the top left plot of Fig. 5 depicts an image pair where the images were acquired under different environmental conditions, i.e. dry and wet. This illustrates the problems caused by different weather conditions in conjunction with image acquisitions.

The results show that the thresholding algorithm, when applied to an image pair acquired under favorable weather conditions, was able to detect 76,4% of the clear-cut pixels within the reference stands, with zero falsely detected pixels. Furthermore, Fig. 7 shows the proportion of correctly classified clear-cuts as a function of the minimum proportion of pixels correctly classified as clear-cut. As an example, if at least 30% partial detection of the clear-cut reference stand is required, 90% of the available clear-cuts were found. As there were zero erroneously detected pixels there is a potential for improved detection accuracy through further refinement of the algorithm, still keeping the error small.
Previous studies have shown a forest/non-forest contrast in Swedish boreal and hemi-boreal forest of up to 9 dB for PALSAR HV-polarized backscatter (Santoro et al., 2009). In Fransson et al. (2007; 2008) and Santoro et al. (2009), it was observed drops in average backscatter in the order of 2-3 dB for stands that were clear-fellings. In this study, a threshold on the order of 1 dB was used to detect clear-cuts at pixel level for an image pair acquired during unfrozen and dry conditions. A threshold of this magnitude seems sufficient and is comparable to the average drop in backscatter presented in Fransson et al. (2007; 2008) and Santoro et al. (2009) for similar conditions.

As mentioned earlier several studies using L-band SAR backscatter data have been pursued in different boreal forests all over the world. A difference of up to 3 dB was observed in Siberian boreal forests Ranson and Sun (2001) and a 1.5 dB difference on the British test site Kielder Ranson and Sun (2000). These early findings are also in line with the results obtained by Igarashi et al. (2003) and Fransson et al. (2007). This study concurs with earlier findings in that L-band backscatter is typically lower in deforested areas compared to mature and regrowing boreal forests. Various disturbances such as artifacts taking the form of enhanced backscatter can, however, occur in the case of clear-cuts where trunks and woody debris are lying on the ground at the time of image acquisition. This could be the effect when dealing with fellings being performed simultaneously with image acquisition or woody debris being left behind for later use as an energy source for example.

As concluded, the difference in weather conditions at acquisitions affect image comparison and a more elaborate model than the linear one assumed here may improve the algorithm performance. Also, other speckle and small change suppressing techniques than Lee filtering and black and white morphological operations should be considered. When applying the crude morphological operations as described, narrow corridors and small clear-cuts have a tendency to be overlooked.

Future developments consist of refinement of the algorithm, possibly incorporating other image acquisition modes and textural analysis. A multi-temporal approach similar to the one presented in Santoro et al. (2009) may also be considered in a continuation. In addition, future investigations should include analyses of hemi-boreal forests in southern Sweden.

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