THE USE OF ENVISAT ALTERNATING POLARIZATION SAR IMAGES IN AGRICULTURAL MONITORING IN COMPARISON WITH RADARSAT-1 SAR IMAGES

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ABSTRACT:

In this paper Envisat alternating polarization SAR images were used in the agricultural monitoring and yield damage assessment. The main advantage of using synthetic aperture radar (SAR) is that satellite images can be acquired frequently at user-specified times from the target area, even through clouds. Consequently, agriculture has been considered as one of the most promising civilian application areas of SAR imagery. Our test area is located in the Western Finland near the city of Seinäjoki. The test area is one of the northernmost consistent agricultural areas in the world and it is situated approximately at the latitude of 63° north. The main food crops are barley and oats, however, small areas of wheat and rye are also cultivated. A corresponding agricultural monitoring project was carried out in summer 2001 in the same test area using Radarsat-1 Fine beam SAR images, therefore, a comparison of the usability of Envisat ASAR and Radarsat-1 SAR images in the agricultural monitoring can be made. In order to carry out the research, altogether 16 Envisat ASAR images were requested from the summer 2003. The image request was possible in the framework of ESA's Envisat announcement of opportunity (AOE-488). In order to collect reference data, ground survey campaigns were organized for the selected set of test parcels simultaneously with each image acquisition. The ground surveys consisted of measurements of soil roughness, soil moisture and crop height, as well as general notes about growing stage and possible yield damages caused by drought or lodging. First results of the suitability of Envisat SAR images in the agricultural monitoring will be presented, as well as a projection of the usability of SAR images in the yield estimation will be made.

1. INTRODUCTION

Synthetic aperture radar (SAR) is an active imaging instrument, i.e. SAR sends a pulse of electromagnetic radiation and then records the amplitude and phase of the radiation coming back from the target. The backscattering coefficient, σ^0, is a measure describing the strength of the recorded radar signals from the target per unit area. Advantage over the optical satellite images, such as Landsat and SPOT, is that SAR uses cloud-penetrating microwaves having wavelength of few centimetres to even metres. Thus, it is possible to have satellite SAR images from the target at user-specified times, which is important in agricultural monitoring where satellite images are needed regularly and the time window for image acquisition is narrow. Although it is evident that cloud-penetrating SAR has great potential in agricultural remote sensing, the exploitation of the SAR backscattering, for example, in crop yield estimation is still non-existent. Instead, optical satellite images have channels revealing information of the photosynthetically active radiation of the vegetation, and thus, there is a well-established connection between satellite information and vegetation biomass.

There have been several agricultural studies concerning the temporal change of the SAR backscattering from agricultural fields during a growing season (ESA, 1995), but the estimation of the crop yield or vegetation biomass has proven to be a very difficult and is still an unresolved problem. According to previous studies the most useful frequency range for crop biomass estimation would be the C-band, i.e. the wavelength of about 5 cm, which is comparable with the size of the crop leaves and stems. Skriver et al. (1999) found out that at the end of the growing season C-band backscattering was dominated by volume scattering from crop vegetation. Brown et al. (2003) proposed that HH-VV amplitude difference of the backscattering in C-band could be a good measure for estimating the biomass of the crops. There have also been promising results of the use of repeat-pass SAR interferometric coherence with one day offset for the vegetation biomass estimation, but at the moment there are no suitable SAR satellite systems available for this purpose (Blaes et.al., 2003).

In general, crop yield estimation using remote sensing is an inverse problem (Ulaby, 1998), which means that recorded SAR backscattering is a function of several physical properties such as soil moisture, soil surface roughness, vegetation biomass, vegetation moisture, crop species, land slope and seed row direction. In crop yield estimation one would like to estimate the vegetation biomass, but its inversion from the recorded SAR backscattering is very complicated since other parameters are usually unknown. On the other hand, direct problem solving (Ulaby, 1998), where the SAR backscattering is modelled from the actual physical parameters (simulation), is still needed to find optimal SAR parameters (wavelength, polarization and look angle) for biomass estimation. Simulation is also needed to gain understanding of complex scattering mechanism of the microwaves from crop vegetation.

The Finnish Geodetic Institute (FGI) has conducted research in the field of agricultural remote sensing since the beginning of 1990's. The early studies using CGMS (Crop Growth

Monitoring System by Joint Research Centre) in the FGI were based on weather data, historical crop yield statistics and optical low-resolution satellite images, and it turned out that cloudiness almost completely hampered the use of optical satellite images in Finland. The launch of ERS-1 satellite in 1991 activated vivid research on agricultural remote sensing using satellite SAR images (ESA, 1995). The excellent radiometric stability of the ERS-1 and ERS-2 SAR images enabled a long-term continuous monitoring of the agricultural fields. In 1997 agricultural SAR research was started in the FGI, firstly for crop species classification purposes, but later also for crop damage assessments and yield estimation purposes.

In 2001 FGI started a study in the test area near the city of Seinäjoki in Finland. The objective was to evaluate the potential of high-resolution high-repetition multitemporal SAR images in agricultural monitoring including aspects of the crop yield estimation and assessment of the crop yield damages. For the growing season in 2001 Radarsat-1 Fine beam satellite SAR images were used. The image delivery from the Tromsø Satellite Station took only few days, so near real-time agricultural monitoring was possible. Field surveys were made simultaneously with each of the image acquisition. The results were promising in some cases, for example flooded areas and cultivation practises were detected well, but the crop growth caused only weak change to the SAR backscattering and yield damages caused by lodging were detected only in very rare cases. Conclusion was that the HH polarization of the Radarsat-1 is not sensitive to the changes of biomass of small leaved crops, but on the other hand, it is sensitive to variation of the surface roughness and soil surface moisture. Example of the detection of the flooded area caused by snowmelt in the end of April is represented in Figure 1.

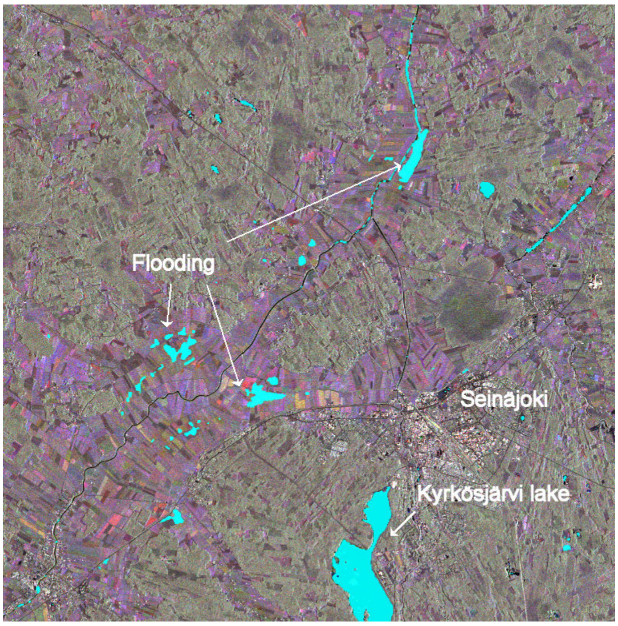

Figure 1. Snowmelt caused a minor flooding in April 2001. Original data © distributed by Radarsat International/TSS/Novosat Ltd. Processed by FGI.

In 2003 the study continued using Envisat SAR images, which were obtained in the framework of ESA's Envisat announcement of opportunity (AOE-488). We choose to have Envisat SAR images in VV/VH alternating polarization mode, which means that both VV and VH images are acquired simultaneously with some loss in the radiometric accuracy compared to one polarization imaging mode. Although two polarizations give more information about the research subject, a drawback with Envisat SAR in comparison with Radarsat-1 Fine beam SAR images is significantly worse spatial resolution. Envisat SAR has 30 m and Radarsat-1 SAR has 8 m spatial resolution. This paper describes our experiences of using satellite SAR images in the remote sensing of agricultural fields in Finland.

2. TEST AREA AND DATA

2.1 The test area and satellite images

The test area near the city of Seinäjoki in Finland is located at the latitude of 63 degrees North and it is one of the northernmost consistent agricultural areas in the world. Percentages of different crop species in the arable land in 2003 were: oats 25%, barley 25%, grass silage 18%, fallow land 10%, turnip rape 5%, wheat 3%, rye 1%, potato 3% and the rest 10% comprises of sugar beet, grassland, pasture, garden etc (Tike, 2003). Cereal crops are mostly spring-sown varieties, except small amount of rye and autumn wheat. In 2003 the average crop yields in the Seinäjoki region were: oats 3.6 t/ha, barley 3.8 t/ha, wheat 3.5 t/ha and rye 2.8 t/ha (Tike, 2003). Crop yields are low compared with the yields in the southern regions of Europe. The river of Kyröjoki, which has been embanked in the last centuries, divides the test area, and nowadays there are no regular flooding in the springtime, but in some places floodwater from melting snow can stay on the low-lying fields for few weeks. The growing season in the test area lasts from 150 to 160 days a year. Sowing date is usually in the end of May or at the latest in the beginning of June. The harvesting of food crops occurs at the end of August or early September.

In 2001 altogether 20 Radarsat-1 SAR Fine beam images were used in the agricultural monitoring study. The description of the Radarsat-1 SAR images is given in Karjalainen et al. (2003).

In 2003 Envisat alternating polarization SAR were used. Altogether 16 SAR images were ordered in early spring 2003, but due to the problems in Envisat satellite and conflicts between commercial image orders, we were able to have 12 SAR images. All images were acquired from descending orbit, thus the local time was around 12:00 at the time of the acquisition. The SAR incidence angle varies from 23 degrees to 41 degrees. On the average, the time interval between image acquisitions was approximately two weeks, but in the most intensive growing period in the beginning of July there were even two image acquisitions in a week. The list of Envisat SAR images used is represented in Table 1.

Table 1. The list of Envisat alternating polarization (VV/VH) SAR images in 2003.

Image #	Date	PAF	Swath
1	15 June 2003	D-PAC	4
2	18 June 2003	I-PAC	3
3	21 June 2003	D-PAC	2
4	28 June 2003	I-PAC	6
5	04 July 2003	I-PAC	4
6	07 July 2003	UK-PAC	3
7	14 July 2003	I-PAC	6
8	23 July 2003	I-PAC	3

9	02 August 2003	UK-PAC	6
10	11 August 2003	D-PAC	3
11	24 August 2003	I-PAC	4
12	15 September 2003	UK-PAC	3

Unfortunately, the image delivery from ESA's Processing and Archiving Facilities took several weeks, thus it was not possible to make near real-time monitoring as in the case of Radarsat-1 SAR images in 2001. The Envisat SAR images were ordered in the precision image format, which means that the pixel's digital number corresponds to the amplitude of the recorded SAR backscattering. Firstly, all images were orthorectified into the Finnish uniform coordinate system using ground control points and image-to-image tie points. PCI geomatics software was used in the orthorectification. The residual error for the ground control points was 0.53 pixels in west-east direction and 0.82 pixels in south-north direction (the pixel size is 12.5 meters). The ground control points were originally digitized from the Finnish 1:20 000 basic maps. The rectification accuracy was also visually excellent, which guaranteed that parcel specific information could be derived from the time series of SAR images. In Figure 2 there is an example of multitemporal dual-polarization Envisat SAR image of our test area.

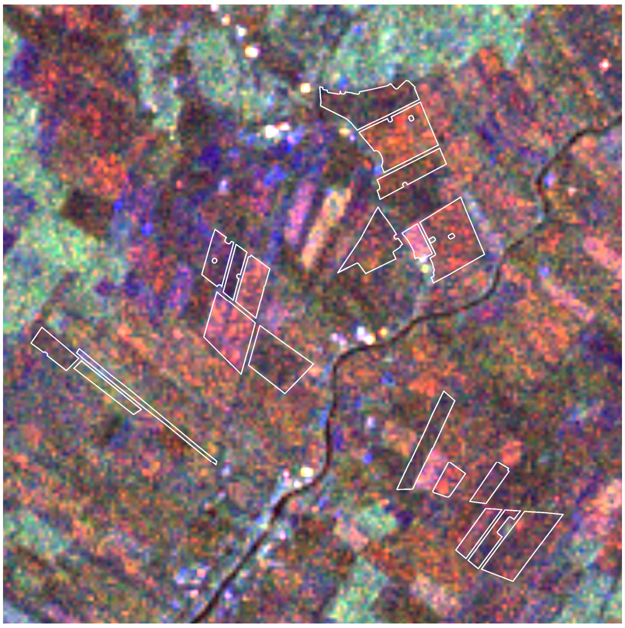

Figure 2. A multitemporal dual-polarization Envisat SAR image from the Seinäjoki test area in summer 2003. Original data © European Space Agency. Processed by FGI.

After orthorectification, a pixel value corresponds to the amplitude of SAR backscattering. In order to be able to compare images from different dates, amplitude must be converted into the backscattering coefficient, which is usually given in decibels (dB). Backscattering coefficient was calculated using following formula (ESA, 2002):

$$\sigma^0 = \frac{(PixelValue)^2}{K} \sin(i) \qquad (1)$$

where σ^0 is backscattering coefficient (dB)
PixelValue is a digital number of a pixel
K is calibration constant
i is incidence angle

Calibration constant K varies from image to image and it can be found from the header information of the each image file. Incidence angle also varies from image to image, but also between each parcel, so incidence angle values were calculated for each parcel in every SAR image.

The true parcel boundaries for calculating SAR backscattering time series were obtained from the Land Parcel Identification System of Finland. Totally about 40000 base parcels were acquired from the Ministry of Agriculture and Forestry. Some of the base parcels can have one or more smaller parcels, so firstly we selected only those parcels that contained one base parcel i.e. one crop species and that had an area over 1 ha. This selection had 5571 parcels and for these an average SAR backscattering in VV and VH polarization was calculated. Averaging of the SAR image pixels inside a parcel was needed because of the SAR speckle. Finally, a time series of average SAR backscattering was acquired for major crop species in Seinäjoki area in Finland in 2003. The backscattering time series for test parcels are represented in Figure 3.

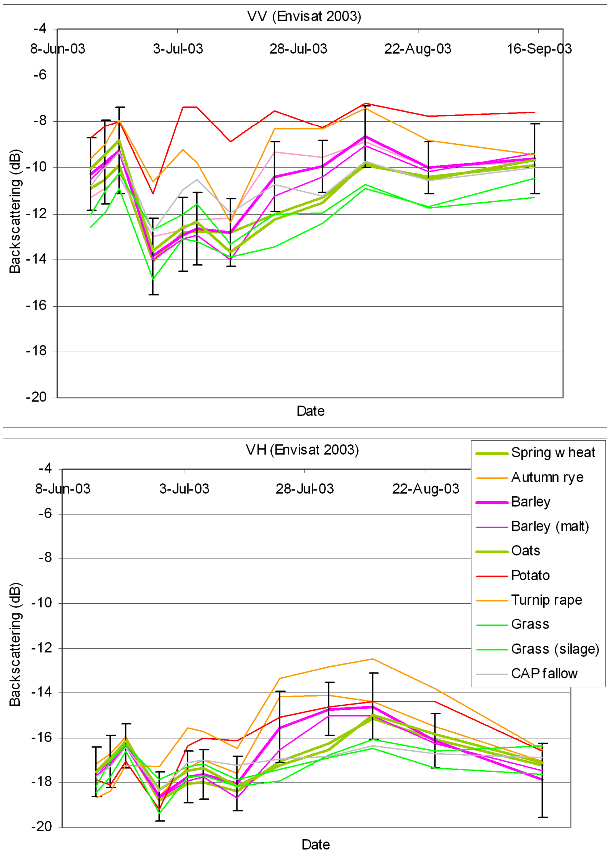

Figure 3. Time series of SAR backscattering in VV and VH polarizations for major crop species in 2003 in Finland.

The time series of SAR backscattering were then compared to the information acquired in field surveys in order to have more detailed information about temporal variation of backscattering against cultivation practises and crop growth.

2.2 Field surveys

In 2003 field surveys were organized similarly as the field surveys in the Radarsat-1 study in 2001. Purpose of the field surveys is naturally to have reference data for the analysis of SAR backscattering time series. Due to the limited time window, which in our case was ±3 hour compared with actual image acquisition, we had to select a small set of test parcels for more detailed research. Thereby 24 parcels was chosen and following information was surveyed for each of the parcel:

- Soil surface roughness
- Seed row direction
- Soil surface moisture
- Crop height and growth stage
- Possible crop yield damages

Soil surface roughness was measured using Leica laser distometer only once in the beginning of the growing season and after that roughness was assumed to be constant during the growing season. Soil surface moisture was measured using ThetaKit TK2-BASIC soil moisture measuring device, which measures volumetric moisture into the depth of 6 cm. Crop height was simply measured using measuring tape. Crop yield damages were mapped as they were found during the field surveys. Time series of the soil surface moisture for the 24 test parcels are given in Figure 4.

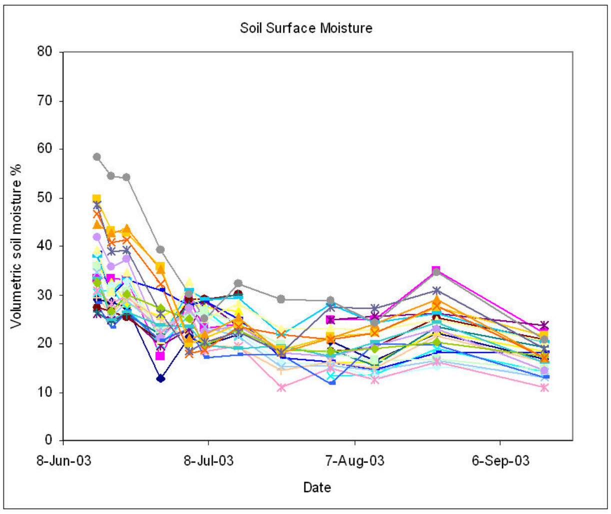

Figure 4. Volumetric soil surface moisture for test parcels in summer 2003.

3. RESULTS

3.1 Envisat SAR backscattering time series in 2003

In Figure 3 is represented the Envisat SAR backscattering time series in VV and VH polarizations for all major cultivated plants in the test area in summer 2003. Similar results were obtained for Radarsat-1 SAR in HH polarization in summer 2001 (Karjalainen et.al., 2003). Naturally results from years 2001 and 2003 are not directly comparable due to the changing weather conditions, but nevertheless, a general comparison of the usability of Radarsat-1 and Envisat SAR images in agricultural monitoring can be made.

In the beginning of the growing season, before sowing, ploughed fields had relatively rough soil surface and consequently backscattering values were higher than in sowed fields. According to Radarsat-1 results in 2001, HH backscattering for ploughed fields was approximately from –8 to even –4 dB. Backscattering variation was high in ploughed fields due to the surface roughness and soil moisture variations. After sowing, backscattering decreased, because sowing made the soil surface smoother compared to the ploughed fields. After sowing, VH backscattering was near –18 dB, but VV backscattering was still as high as –10 dB, and reason for this most likely is that VV polarization is more sensitive to the soil surface moisture, which at same time is around 40% of volumetric moisture. Soil surface moisture rapidly decreased by the beginning of July as can be seen in Figure 4, and simultaneously VV backscattering decreased to it minimum around –14 dB for cereal crops.

It should be noticed that the noise equivalent σ^0 for Envisat alternating polarization images is from –19 to –22 dB depending on the antenna look angle (ESA, 2002). From backscattering time series in Figure 3, can be seen that in the beginning of the growing season VH backscattering was close to the noise equivalent σ^0 and VH backscattering started to increase only after the middle of July, which implies that the early crop growth from emerging to 50 cm cannot be seen using Envisat cross-polarization images.

For cereal crops both VV and VH backscattering gradually started to increase in the middle of July when crop height was approximately 50 cm. After this point of time soil surface moisture stayed relatively constant from 10% to 30% of volumetric moisture, thus the average increase in SAR backscattering seemed to be caused by the increase of the vegetation biomass. Similar results were obtained for Radarsat-1 HH polarization SAR images in 2001. The increase of SAR backscattering was from 2 to 4 dB depending on the crop species and SAR polarization. According to these results it seemed that cross-polarization i.e. VH polarization might be the best choice for biomass detection in Finland for cereal crops, but noise equivalent σ^0 in Envisat SAR images is too high for detecting crops with low biomass. Also, it should be emphasized that averaging of relatively large areas of same crops is needed since the radiometric accuracy of alternating polarization images makes it hard to see backscattering changes for individual parcels with small area compared to the spatial resolution of 30 m.

The backscattering time series for cereal crops can be explained fairly well, but for other species it is more difficult. For example grass silage can be harvested many times per growing season depending on the weather conditions. Also turnip rape and potato have quite unique time series, which on the other hand makes classification or identification of crop species possible. For example potato fields have relatively high backscattering throughout the growing season in VV polarization most likely due to the much more rough soil surface than cereal crops have.

3.2 Detection of yield damages

In 2001, we concluded that crop yield damages caused by lodging could not be detected using Radarsat-1 HH polarization SAR images. Only one barley field out of totally 41 fields with lodging was possible to be identified from Radarsat-1 SAR images. We believed that HH polarization used in Radarsat-1 SAR images was not sensitive enough to see changes in the crop vegetation biomass. When Envisat SAR images were used in 2003, we detected 8 parcels where more than 50% of the crops where flattened by lodging. The lodging usually happens in August, when ripening begins. An example of lodging is represented in Figure 5, where an extensive area of lodging was detected on 24 July 2003. On the upper part of Figure 5 there is a multitemporal Envisat SAR image, which comprises of images taken on 14 July and 11 August 2003. Nearly 80% of the crops were flattened in the middle part of the parcel as can be seen in the photograph taken on 11 August 2003. The lodged area in the SAR image somewhat corresponded to the area what was mapped in the field surveys. Anyhow, the rest of the 8 lodged fields could not be detected from SAR images, accordingly it seems that it is not possible to see lodging reliably from Envisat SAR images. Most likely the reason for this is, again, that the spatial resolution and radiometric accuracy of Envisat SAR images is not enough compared to the small size of parcels in Finland.

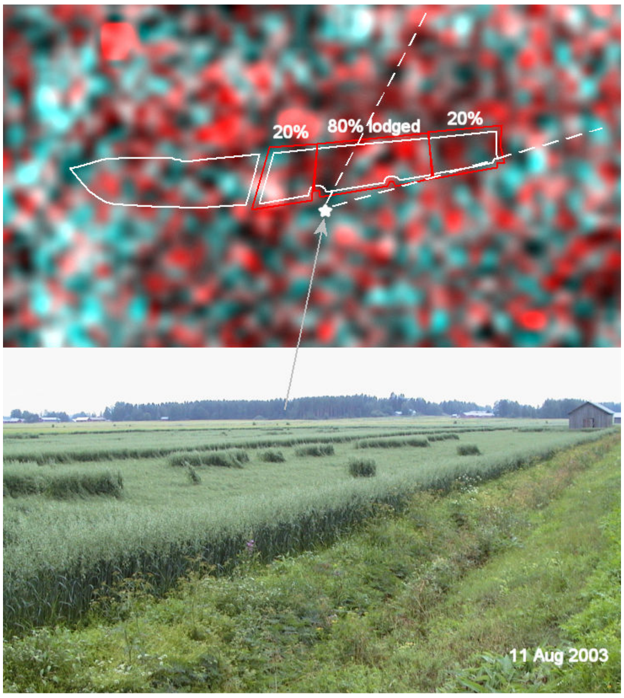

Figure 5. Yield damages caused by lodging in the test area in 2003.

3.3 Yield estimation using SAR images

Spring sown oats, barley and wheat are the major cereal crops in the Seinäjoki test area. Although, the crop yields are relatively low compared to the yields in the southern latitudes, there is interest in the crop yield estimation in Finland. Nowadays field agents of the Ministry of the Agriculture and Forestry prepare the crop yield estimation on a subjective basis. In Figure 3, in case of cereal crops, can be seen a slight increase (3-4 dB) in SAR backscattering from the end of June till the end of August when harvesting starts. At the same time soil surface moisture in Figure 4 seems to be relatively constant. The increase in the SAR backscattering seems to correspond to the increase in the crop height, which might make crop yield estimation indirectly possible. Problem is that the increase in SAR backscattering has been obtained by averaging large areas of same crops, and for example in Finland parcels are so small that backscattering time series cannot be calculated for small parcels using Envisat SAR images.

3.4 Summary of the suitability of Radarsat-1 and Envisat SAR systems for agricultural monitoring in Finland

Table 2 summarizes our experiences in agricultural monitoring using satellite SAR images. The statements in Table 2 are based on our experiences of Radarsat-1 and Envisat SAR images in 2001 and 2003.

Table 2. Summary of the experiences of Radarsat-1 and Envisat SAR images in agricultural monitoring in Finland.

Application area	**Radarsat-1 (HH)**	**Envisat (VV/VH)**
Cultivation practises	Detection of sowed fields is very good, which could be used to trigger the yield prediction model	VV polarization might be used for detecting sowing date.
Yield damages	Flooding in the fields can be detected very reliably. Damages caused by lodging could not be detected.	There were no flooding in 2003 season, but presumably HH polarization is better for flooding detection. Lodging could not be detected. 30 meters spatial resolution hinders the usability of the Envisat SAR images.
Yield estimation	Not adequate for individual parcels, but seems to be usable when large areas of same crops are averaged	Not adequate for individual parcels, but when large areas are averaged crop growth can be seen. Cross-polarization VH is probably best for the crop biomass estimation, but noise equivalent σ^0 of Envisat SAR is too high to see low vegetation.

4. CONCLUSIONS

Agricultural applications, such as the monitoring of cultivation practises, estimation of crop yield and mapping of yield damages, are among the most promising civilian application areas of SAR images in the future. However, considerable amount of research needs to be done to retrieve information from SAR images. It is evident that several SAR images are needed to cover the whole growing season from the sowing to the harvesting. These multitemporal SAR images then provide a time series of SAR backscattering for agricultural fields. Multitemporal changes in SAR backscattering correspond to the variations in physical parameters of the agricultural fields, such as soil moisture, soil surface roughness, vegetation biomass and vegetation moisture. According to our experience, an approximate sowing date for individual parcel can be detected reliable, because there is a big change in the soil surface roughness from ploughed to sowed field. Crop growth or the increase of the vegetation biomass can be seen in the backscattering time series, but large areas of same crops must be averaged because of the SAR speckle and poor spatial resolution of satellite SAR systems. The change in the backscattering is in order of 2 to 4 dB in C-band in all polarizations. Crop yield damages caused by lodging were detected only in very few cases and in this case the spatial resolution must be in order of few meters before variations within parcel can be seen.

Envisat SAR backscattering time series from 2003 will be analysed in more detail. The agricultural research using the

SAR images continues in summer 2004 using Envisat satellite SAR images. In 2004, the goal is to additionally measure the vegetation biomass during the growing season. A great potential still waits in the future, when very-high-resolution satellite SAR images with few meters spatial resolution will become available.

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