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Significance of radar remote sensed imagery for agricultural applications

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Abstract

Remotely sensed optical image data acquired by airborne or satellite sensors provide useful information about crop discrimination as well as infield crop variability. It has been demonstrated that optical remote sensing data is applicable to estimate crop biomass variability for developing management strategies. Due to the weather dependency of this technique, data availability is not guaranteed when it is needed. A solution to this problem might be radar technology which can be acquired at any time, which means at all relevant growth stages.

Synthetic aperture radar (SAR) backscattering provides information about canopy structure and water content. The insufficient understanding of SAR backscatter mechanisms according to agricultural soil and plant conditions is the biggest gap of SAR data usage in agriculture at present time.

The objective of the presented study was to improve the understanding of radar backscattering of agricultural crops and to show the potential and restrictions of radar remote sensing in agriculture. Research was performed during the vegetation periods of 2001 and 2002 in an agricultural dominated area of Mecklenburg-Western Pomerania in northern Germany (13.4° E; 53.9° N). Multi-dimensional airborne X- and L-band SAR-data were acquired by the German E-SAR (DLR) with 1 m ground resolution.

The results indicate that different crops can be discriminated and infield variability can be located clearly by radar imagery. Further single radar bands and several different band combinations were tested for determining infield biomass variability in winter wheat. Therefore a correlation analytical and a discriminant analytical approach were chosen. It turned out, that backscatter of horizontal polarized X-band (X-HH) is most suitable, but relationships were improved by using band combinations. Likewise the generalized discriminant analysis revealed better relationships than the correlation analysis.

Despite the difficulties of understanding radar backscattering, radar imagery provides valuable information about infield spatial crop variability, even if the acquisition of optical data is limited by unfavorable weather conditions.

Keywords: SAR, radar, remote sensing, wheat, spatial variability, precision agriculture

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Zusammenfassung

Bedeutung von Radar-Bilddaten für die landwirtschaftliche Praxis

Optische Fernerkundungsdaten können Informationen über die Biomassevariabilität liefern, auf deren Grundlage Managementstrategien entwickelt werden können. Aufgrund der Witterungsabhängigkeit dieser Aufnahmetechnik ist eine ausreichende Datenverfügbarkeit nicht gewährleistet. Eine Lösung kann die Radarfernerkundung darstellen, welche witterungsunabhängig ist und zu nahezu jedem relevanten Termin Daten bereitstellen kann.

Das *Synthetic Aperture Radar* (SAR) reagiert sensitiv auf Struktur und Wassergehalt der Vegetationsdecke. Das noch schlechte Verständnis der Zusammenhänge zwischen Radarrückstreuung und Boden- bzw. Vegetationseigenschaften schränkt die Anwendung der Radarfernerkundung in der landwirtschaftlichen Praxis derzeit noch stark ein.

Ziel dieser Arbeit war es, das Verständnis der Radarrückstreuung landwirtschaftlicher Kulturen zu verbessern und das Potenzial als auch die Grenzen für landwirtschaftliche Anwendungen aufzuzeigen. Die Untersuchungen wurden in den Jahren 2001 und 2002 in Mecklenburg-Vorpommern, Norddeutschland (13.4° E, 53.9° N) durchgeführt. Multidimensionale SAR-Daten wurden mit dem E-SAR Sensor (DLR) in X- und L-Band Konfiguration mit 1 m geometrischer Auflösung aufgezeichnet.

Die Ergebnisse zeigten, dass sowohl unterschiedliche Fruchtarten eindeutig differenziert, als auch schlaginterne Variabilitäten in den Radarbilddaten erkannt werden können. Neben den Einzelkanälen wurden auch verschiedene Kanalkombinationen auf ihren Informationsgehalt hinsichtlich Biomassevariabilität von Winterweizen analysiert. Hierfür wurden korrelations- und diskriminanzanalytische Methoden verwendet. Es zeigte sich, dass die Rückstreuung des horizontalen X-Bandes (X-HH) für die Erfassung der räumlichen Variabilität am besten geeignet war und die Verwendung von Kanalkombinationen stärkere Zusammenhänge lieferte. Der generalisierte diskriminanzanalytische Ansatz führte ebenfalls zu besseren Ergebnissen.

Trotz vorhandener Schwierigkeiten mit der Interpretation der Radarrückstreuung bieten Radardaten wertvolle Informationen über die räumliche Variabilität der Pflanzenentwicklung, insbesondere dann, wenn aufgrund ungünstiger Witterung keine Information durch optische Aufnahmesysteme bereitgestellt werden kann.

Schlüsselworte: SAR, Radar, Fernerkundung, Winterweizen, Bestandesvariabilität, Precision Agriculture

1 Introduction

Precise geocoded information of inherent spatial variability of soil and crop characteristics is essential for efficient and sustainable farm management, in order to develop optimized management strategies (Panten et al., 2003). Remote sensing techniques have a great potential to provide such information (Moran et al., 1997; Dixon and McCann, 1997; Brisco et al., 1998; Kühbauch, 2002). Remotely sensed data acquired by optical airborne and satellite sensors provides information about crop types as well as infield crop variability. It has been demonstrated that the red and near-infrared reflection of plant canopy is generally applicable to estimate variability of crop growth and plant status (Tucker et al., 1979; Wanjura and Hatfield, 1987; Wiegand et al., 1992; Blackmer et al., 1996; Flowers et al., 2001).

Based on such information management strategies were developed and applied successfully in the case of fertilizer and pesticide application (Bjerre, 1999; Taylor et al., 2000; Miller et al., 2002). The application of chemical inputs according to recent crop variability is an important contribution to sustainable agricultural production and its economic optimization. It was shown that disease control can be optimized with variable treatment (Secher, 1997; Bjerre and Secher, 1998) and that for example fungicide doses to winter wheat can be safely reduced by up to 40 % if timing and dose are optimized (IACR, 2002).

Although optical remote sensing seems to be a powerful farm management tool, there are some serious limitations that restrict farm management applications. For instance regular data availability is restricted due to the weather dependency (Moran et al., 1997; Lilienthal, 2003). Far less attention has been given to the use of radar backscattering data obtained from *Synthetic Aperture Radar* (SAR) sensors at this time. These systems measure the surface reflectivity in the microwave portion of the electromagnetic spectrum (1 mm – 1 m). Unlike optical sensors, SAR systems bear the advantages of cloud penetration, day/night acquisitions and signal independence of solar illumination angle. These properties allow SAR images to provide data frequently and meet the requirements involved with agricultural management decisions.

So far SAR data is mainly used in agriculture for crop type classification (Bouman and Uenk, 1992; Baronti et al., 1995; McNairn et al., 2000). The insufficient understanding of SAR backscatter mechanisms according to agricultural soil and plant conditions is the biggest gap of SAR data usage in agricultural management practice at present time (Moran et al., 1999). In the microwave region it is generally assumed, that backscatter is directly related to surface roughness, soil moisture and vegetation density. SAR backscattering from vegetation canopies is mainly influenced by canopy water content and geometrical structure of the plants (Schmullius and Evans, 1997).

Microwave penetration into the cereal canopy varies in dependence of incidence angle, frequency and polarization of the transmitted electromagnetic wave (EM). In general higher frequencies such as X-band (wavelength $\lambda \sim 2.4 - 3.75$ cm) are dominated by surface scattering, while lower frequencies such as L-band ($\lambda \sim 15 - 30$ cm) penetrate deeper into the vegetation canopy and therefore the soil contributes a significant backscatter amount of the measured signal (Brisco and Brown, 1998).

Close correlations between radar backscatter and plant parameters like leaf area index (LAI), biomass and plant water content (PWC) have been determined (LeToan et al., 1984; Bouman, 1991; Baronti et al., 1995; Pampaloni et al., 1997; Paloscia, 1998; Macelloni et al., 2001). However, particular parameters identified by various researchers as well as the strength of their relationships are inconsistent (Brisco and Brown, 1998). By knowing these relationships radar backscatter may be suitable to determine infield variability of crop development, but it has not been tested yet.

Before SAR backscatter becomes a suitable tool in farm management, the response of backscatter in relation to soil and plant conditions must be better understood. Quantitative relationships between radar backscattering and agronomical relevant crop data are required for using this technique in agricultural practice. Due to the specific sensitivity of microwaves to the geometrical vegetation properties (Brisco and Brown, 1998) the scope of this study was to analyze the spatial variability of winter wheat biomass and stand density.

1.1 Radar remote sensing

In opposite to optical sensors, radar is an active system which transmits a pulse and then measures the time delay and intensity of the reflected echo. The intensity measurement is called radar backscatter. *Synthetic Aperture Radar* (SAR) transmits coherent electromagnetic waves in vertical direction (range) to the flight line (azimuth) of the sensor (Fig. 1). For more information about the radar technique the reader is referred to Henderson and Lewis (1998).

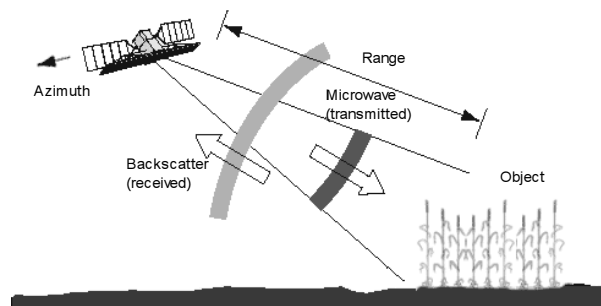


Fig. 1: The radar principle of electromagnetic wave transmission and echo reception

Due to the side-looking measurement various radiometric distortions occur in radar imagery. Effects like foreshortening, layover and radar shadow could not be corrected by methods of image processing (Lewis et al., 1998). The dominating radiometric distortion is caused by the so called “speckle-effect”. Speckle is caused by the interaction of radar waves and the terrain objects, which produce interferences. The resulting grainy texture of the images complicates the detection and identification of features. This speckle is a multiplicative random process whose variance and spatial correlation could be modeled. With multi-look processing and different existing adaptive filter algorithms these effect can be minimized during image processing and image enhancement (Lee et al., 1994).

The incidence angle varies in SAR scenes from near-range to far-range (Fig. 2a). In dependence with the incidence angle the radar backscatter intensity varies likewise within the radar swath (Fig. 2b). Following the calibration of radar data intensity values are converted in scattering coefficients so that a quantitative comparison of different terrain objects within the scene becomes possible. With absolute calibration on basis of the local incidence angle, the near-far-range effect as well as other topographic effects due to terrain relief are corrected.

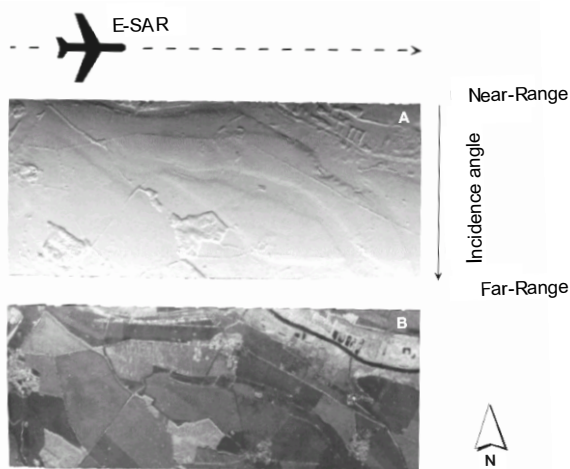


Fig. 2: Influence of incidence angle on backscatter intensity. a: Geocoded Incidence Angle Map (IAM), b: uncalibrated ground-range intensity image

Radar backscatter is a result of complex interrelations of various system- and target specific parameters (Fig. 3). Especially the system parameters wavelength and polarization are important in the interaction process with the plant canopy. As wavelength increases the signal penetration into crop canopy increases likewise. In general the smaller wavelengths like X-band are dominated by canopy scattering, while the longer wavelengths like L-band have a significant soil backscatter contribution to the total measured signal.

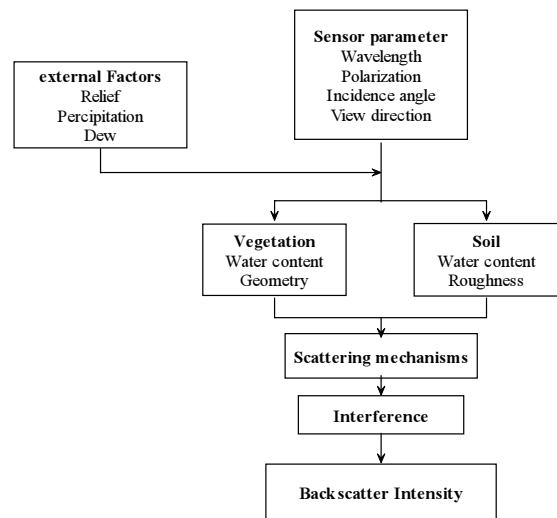


Fig. 3: Radar backscatter affecting system- and target specific parameters

Multi-dimensional radar systems are able to transmit and receive microwave radiation in different wavelengths and polarizations at same time. Polarization is given by the direction of the electric vector in an EM wave. For radar applications the linear horizontal (H) and vertical (V) polarization states are usually used. This means that signals can be measured in four different polarization combinations: Two co-polarizations HH and VV and two cross-polarizations HV and VH (with transmit denoted first). Each radar channel is a combination of wavelength and polarization and provides different information about the target. This is comparable to the different spectral channels of optical systems.

1.2 Microwave interaction with agricultural targets

Various parameters influence the interaction of microwaves with agricultural targets and thus determine the radar backscatter measured by the sensor. Due to complex interrelations of these parameters, it is not possible to estimate the individual scatterer contribution and to attribute backscatter variations to only one parameter. By a given system configuration the backscatter of agricultural fields is dependent upon geometrical structure and water content of vegetation and soil (Ulaby and Bush, 1976; Brisco and Brown, 1998). The interaction between the microwave and the scattering elements of the vegetation canopy is determined by the dimension and orientation of each scatterer (leaf, stem, ear) in relation to wavelength and polarization of the radiation (Bouman and van Kasteren, 1990; Brown et al., 1992; Baronti et al., 1995; Brisco and Brown, 1998; Macelloni et al., 2001).

During the dynamic growing process of agricultural crops geometry of plant canopies changes. Depending upon morphological plant structure and as a function of wavelength and polarization, the backscattering signal is

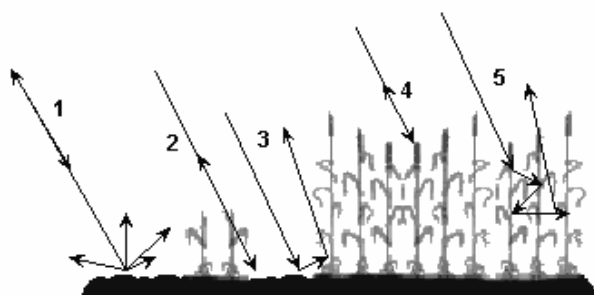


Fig. 4: Backscatter mechanisms in cereal crops: 1. Diffuse soil scattering; 2. Soil backscatter (with double attenuation by canopy); 3. Double-bounce-scattering; 4. Canopy surface scattering; 5. Multiple-scattering

composed by different scattering mechanisms and absorption processes (Hoekman et al., 1992; Lewis et al., 1998). The various scattering mechanisms are illustrated schematically in figure Fig. 4.

Early during the growth cycle of cereals the backscatter signal is dominated by bare soils, which produce mainly surface scattering (Baronti et al., 1995; McNairn et al., 2002a). In this case the soil surface roughness and moisture content are important factors governing the backscatter signal (Ulaby et al., 1996). Longer wavelengths are dominated mainly by mirrored reflection and show low backscatter intensities. For shorter wavelengths the soil appears more rough and leads to increased backscatter to the sensor (Weimann, 1996; Lewis et al., 1998). The same effect is produced by tillering cereals. The vertical polarizations show usually higher backscattering values than the horizontal polarizations (Baronti et al., 1993).

In the further development of the crop, volume scattering within the plant canopy increases and becomes the dominating scattering mechanism. This leads to a continuous increase of backscatter values in the cross-polarization due to depolarization of the microwaves at the coincidentally oriented vegetation components (Ulaby and Elachi, 1990; Baronti et al., 1993). During stem elongation the crop canopy changes from horizontal structure to a stalk-dominated vertical structure. The vertical oriented components of grain plants couple much more effectively with vertical polarized waves resulting in increased absorption and lower backscatter (Le Toan et al., 1984; Ulaby and Wilson, 1985). This effect behaves inversely to the wavelength (Ulaby and Wilson, 1985). The backscatter intensity of the vertical polarized channel is now lower than in horizontal polarization. The backscatter of shorter wavelengths like X-band is predominant from direct scattering at the leaf surface and volume scattering within the first leaf layer (Bouman and van Kasteren, 1990; Brown et al., 1992; Morrison et al., 2000). Longer wavelengths like L-band penetrate the canopy up to the soil and direct soil backscatter as well as multiple scattering between soil and canopy becomes more important (Brisco and Brown, 1998).

The shape, dimension and orientation of a scattering element is important for scattering contribution, if it meets approximately the size of wavelength and polarization. Is the dimension of the scatterer much smaller than the wavelength, the scatterer shape is unimportant. There is no favor radar channel for agricultural radar signatures cause different channels contribute independent information (Brisco and Brown, 1998). To maximize the crop information content, radar operating in shorter wavelengths may be preferred.

2 Material and Methods

The investigation was conducted on three fields (90 – 130 ha) cultivated with winter wheat. The test site is located in the young pleistocene moraine area of Mecklenburg-Western Pomerania (13.4° E; 53.9° N) close to the Baltic Sea. The landscape is characterized by profound differences in geomorphology. During the growing seasons of 2001 and 2002 five campaigns were performed to measure reference data for various growth stages and to acquire radar measurements as well as color infrared aerial photographs (CIR).

2.1 Radar data

The airborne campaign was carried out with the multi-dimensional E-SAR (*Experimental Synthetic Aperture Radar*) operated by the German Aerospace Center (DLR). Technical specifications of the sensor can be found by Horn (1997). Radar-data was acquired in two different wavelengths X-band (3 cm) and L-band (23 cm) with vertical (VV) and horizontal (HH) co-polarization. Additional cross-polarization (HV, VH) was only available for the L-band. All in all 6 different radar channels were available for backscattering analysis. The incidence angle in the center swath (scene center) was $\sim 35^\circ$ during the measurements and the geometrical ground resolution was 1 m.

To guarantee accurate geocoding and radiometric calibration, corner-reflectors were placed in the test area. The measured radar data was processed by the DLR and the resulting image products were then pre-processed. The pre-processing included absolute calibration of backscatter values to the backscatter coefficient σ^0 and speckle reduction by using a 5 x 5 frost filter algorithm. The backscatter coefficient σ^0 is a value for the average reflectivity per m^2 on horizontal ground plane and is measured in dB.

The backscatter signatures were extracted from each of the six radar bands by using the ground truth sampling point locations. A buffer zone of 2.5 m was laid around each sampling point in order to compensate geographical inaccuracies. The value of each pixel inside this area was extracted and averaged. Additionally 74 arithmetical channel combinations (*polarization index*) were computed

to analyze multiple radar information (Zillmann, 2004). Some of the indices were used earlier by other researchers (e.g. Pope et al., 1994; Baronti et al., 1993), but new ratios were also implemented.

2.2 Ground truth

In order to show the internal variability as complete as possible through sampling, it was necessary to obtain an impression of the natural in-field heterogeneity before taking the ground truth measurements. The main emphasis was given on the identification of naturally caused variability, e.g. through variability's in the geologic substrate or terrain conditions, which leads to a different development process of the vegetation. Topography is a main reason for variability (Schröder, 1999). Based on available data (DEM, yield maps, soil maps) integrated in a Geographic Information System (GIS) optimal sample site locations were determined and different sampling strategies were developed for 2001 and 2002.

In 2001 a stratified sampling was performed according to the zones of similar potential soil water regime (Moore et al., 1993) derived from the digital elevation model (DEM). In 2002 two different sampling approaches were performed on the investigated test-sites. One field was partly sampled in a 50 m grid and the other field with a transect also with a point distance of 50 m. The distance of 50 m is dense enough to describe infield variability of soils adequately (Haneklaus et al., 1997). The position of grid and transect were chosen to cover all characteristic terrain features, because most of the variability in plant growth is caused by terrain induced effects. Geographic position of all sample points was measured by differential GPS (2.5 m accuracy).

During field campaigns, between 12 and 26 samples of radar backscattering relevant vegetation and soil parameter were taken per field (Tab. 1). The gravimetric and volumetric soil moisture content, plant biomass, canopy characteristics such as tramline exposure, row-distance, plant height, plant water content (PWC), stem density and

Table 1:
Number of samples

Field	08. May 2001	09. June 2001	07. April 2002	08. May 2002	05. June 2002
3.2	n.a.	n.a.	12	18	18
10.3	18	19	26	26	25
10.2	14	14	n.a.	n.a.	n.a.

n.a. = not available

ground coverage were measured and phenological growth stages were determined according to the BBCH decimal code (Tottman and Broad, 1987). Vegetation parameter were measured for an area of ¼ square meter by cutting the crops. For detailed information about ground truth measurements the reader is referred to Zillmann (2004).

Furthermore aerial color-infrared images were obtained coincident with the SAR imagery. The spectral reflectivity information was used to compute the NDVI - *Normalized Difference Vegetation Index* - (Rouse et al., 1974) of winter wheat. Based on the relationship between NDVI and plant biomass (Tucker, 1979; Wanjura and Hatfield, 1987; Taylor et al., 2000; Flowers et al., 2001) the vegetation index was used as a reference for the spatial variability of plant biomass at measuring date for verification purposes.

2.3 Statistical analysis

Different statistical analysis approaches were conducted to determine the potential of multi-dimensional radar data to determine crop variability. Linear correlation and discriminant analysis were performed. Three groups of stem density isolated by previous hierarchical cluster analysis were subjected to discriminant analysis. In this model the discriminating variable was the mean radar backscatter value and the NDVI value respectively.

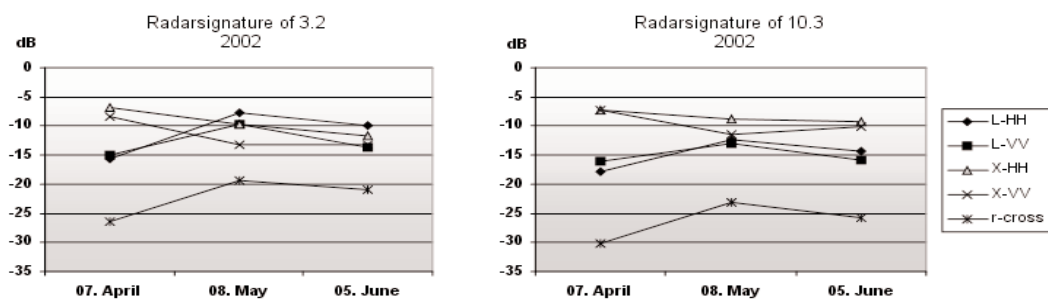


Fig. 5: Radar backscatter signatures of winter wheat on two test fields in Neetzow derived from mean backscatter intensities at different sample locations in dependence on the growth stage

3 Results and Discussion

The scattering signatures of winter wheat over the growing season demonstrated the sensitivity of radar measurements on plant development (Fig. 5). In general the change of backscatter intensity of each radar channel was comparable on the two different test fields, but there were clear differences in the absolute intensities and the relative proportions of the radar channels.

It has to be mentioned that the backscatter signature of winter wheat in 2001 was not comparable due to divergent crop growth stages in June (ear emergence / begin of flowering) and different weather and soil moisture conditions. Changing plant canopy structure due to developing flag leaves or ears and various external environmental factors (wind, dew, rain) have a significant influence on the backscatter signal (Gillespie et al., 1990; Hobbs et al., 1998). This leads to highly variable backscattering signals and to missing consistence of daily and annually radar

measurements (Bouman and van Kasteren, 1990; Brisco et al., 1990).

Nevertheless all six single channel radar images show clearly different backscatter values within the winter wheat at one sampling date (Fig. 6).

The different backscatter intensity (light grey = high backscatter, dark grey = low backscatter) and structure within the field of each single channel is related to different sensitivity on structural canopy properties and confirms the assumption of independent information (Brisco and Brown, 1998). It is also obviously, that the backscatter response of winter wheat is opposite in both wavelengths. Areas with low backscatter intensity in both polarizations of the X-band show high values in all polarizations of the L-band, especially the co-polarizations. The variations of backscatter intensity within the cross-polarized images indicate different vegetation development, because multiple-scattering needed for depolarization is dependent on the number of scattering elements.

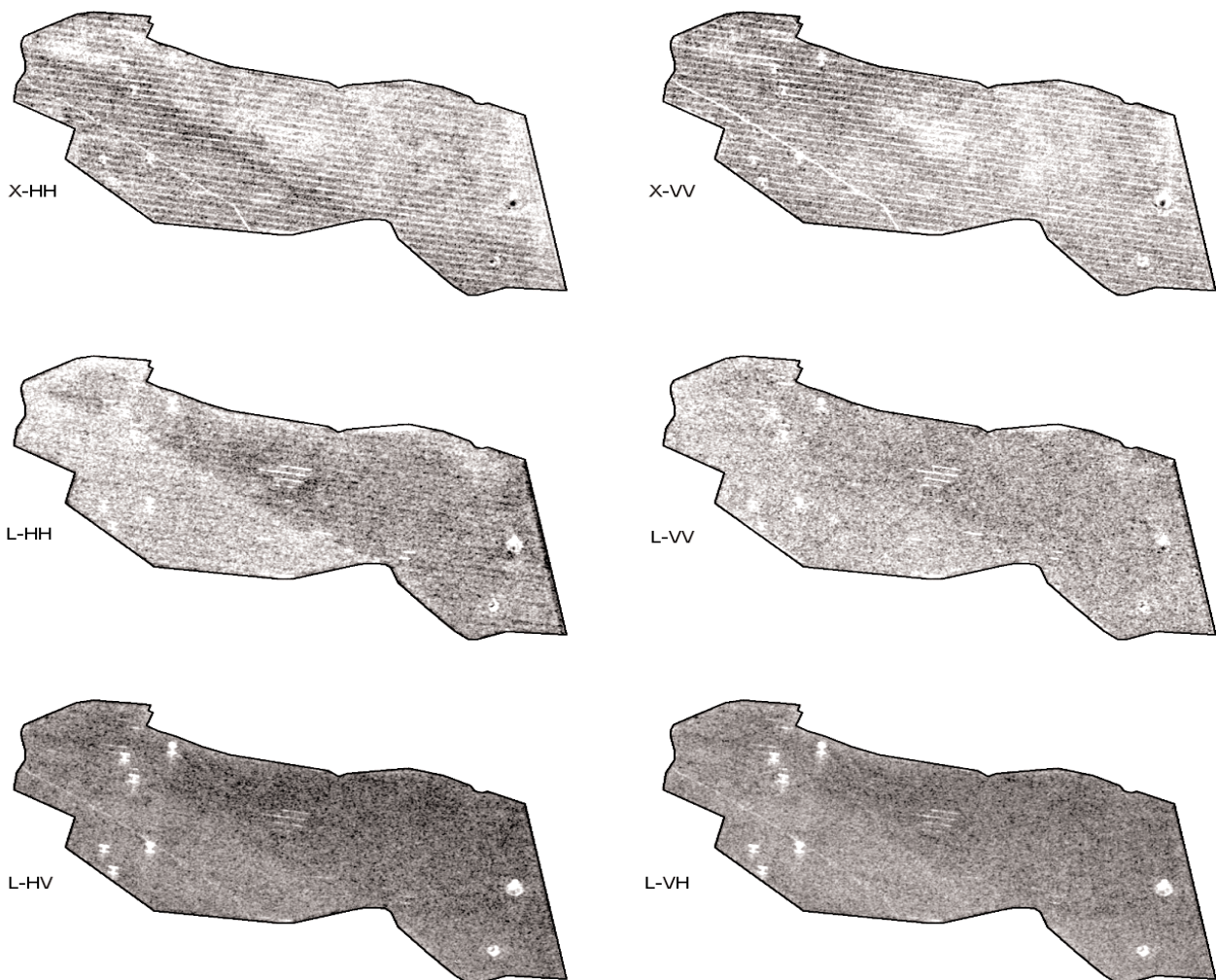


Fig. 6: Calibrated single radar channel backscatter of winter wheat of the test field 10.3 in Neetzow during elongation at 08. May 2002 (BBCH-Code 32).

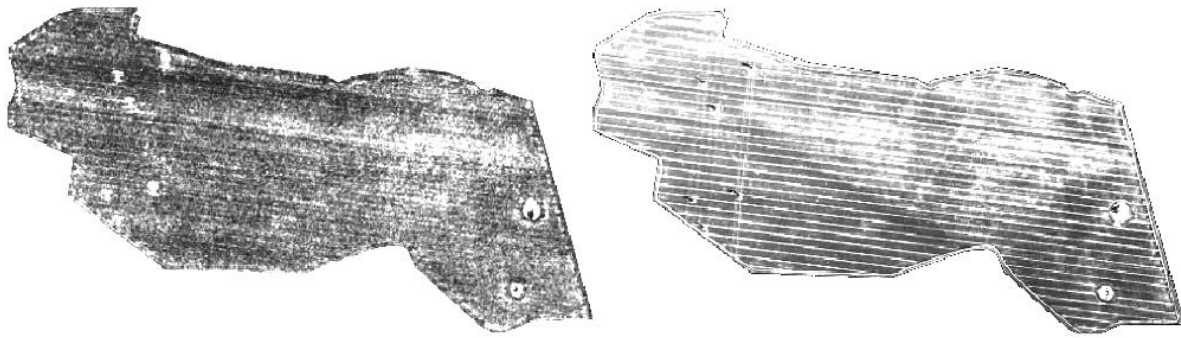


Fig. 7: Spatial variability of winter wheat on the test field 10.3 in Neetzow during elongation of winter wheat at 08. May 2002 (BBCH-Code 32). Left: Black and white imagery generated by combining the three radar channels L-VV, X-VV and L-HV, right: Black and white imagery of the false color aerial photograph (CIR).

Cross-polarized backscatter is usually lower than backscatter of co-polarized measurements.

The radar backscatter of winter wheat shows spatial variability within the field. Especially the horizontal polarizations of both wavelengths are suitable for the differentiation of areas with miscellaneous scattering properties. It is remarkable, that the spatial patterns in the radar imagery are almost identical in size and location with the mapped spatial variability of winter wheat in the aerial photographs (Fig. 7). The reflection variability in the CIR-

images is directly related to different plant development. The higher the intensity of infrared reflection, the higher is the amount of biomass or the vegetation cover. In figure 6 areas with increasing vegetation development are represented in darker grey shades. Since reflection measurements of vegetation correspond with plant development, it is obviously that the shown spatial variability of radar measurements is also associated with it. These relationships reveal the potential of radar imagery for the detection of spatial variability of plant development.

Table 2:

Coefficients of correlation (r) between σ^0 of the single radar channels and the crop features biomass and stem density of winter wheat on the three test fields in Neetzow during different growth stages (2001/2002)

		Fresh weight [g m ⁻²]									
		08. May 2001		09. June 2001		07. April 2002		08. May 2002		05. June 2002	
Test field/ radar channel		10.2 (n=11)	10.3 (n=16)	10.2 (n=13)	10.3 (n=18)	3.2 (n=12)	10.3 (n=26)	3.2 (n=17)	10.3 (n=26)	3.2 (n=15)	10.3 (n=24)
σ^0 L-HH		-0.12	0.55*	0.11	0.39	0.39	0.32	0.50*	-0.16	0.02	0.22
σ^0 L-HV		-0.09	0.36	0.08	0.05	0.24	0.50	0.13	-0.06	0.17	0.26
σ^0 L-VV		-0.36	0.21	0.19	0.52*	0.26	0.55**	-0.47	-0.31	0.25	0.15
σ^0 L-VH		0.19	0.21	0.04	0.16	-0.10	0.28	0.18	0.25	0.12	0.30
σ^0 X-HH		-0.20	-0.63**	0.81**	0.27	-0.28	0.27	-0.30	-0.40*	0.07	-0.38
σ^0 X-VV		0.36	-0.50*	0.51	0.56*	-0.37	0.42	-0.56*	-0.17	-0.18	-0.17
σ^0 r-cross		0.07	0.34	0.06	0.10	0.06	0.44	0.17	0.10	0.15	0.28
	[dB]	Stem density [stems m ⁻²]									
σ^0 L-HH		-0.15	-0.56*	0.07	0.37	0.25	-0.14	0.32	0.05	-0.06	0.12
σ^0 L-HV		0.44	0.46	0.00	0.07	0.31	0.15	-0.02	-0.02	0.23	0.20
σ^0 L-VV		-0.02	0.23	0.14	0.51*	0.34	0.05	-0.47	-0.37	0.25	0.14
σ^0 L-VH		0.27	0.23	0.02	0.18	0.12	0.38	-0.17	0.24	0.17	0.28
σ^0 X-HH		-0.05	-0.47	0.77**	0.37	-0.33	-0.12	-0.07	-0.40	-0.10	-0.56**
σ^0 X-VV		0.38	-0.41	0.53	0.55*	-0.20	0.32	-0.41	-0.14	-0.06	-0.40
σ^0 r-cross		0.44	0.41	0.01	0.12	0.22	0.27	-0.10	0.11	0.20	0.24

r-cross: Mean value of both cross-polarisations, *: $\alpha = 0.05$, **: $\alpha = 0.01$
 each highest significant correlation > |0.5| between crop feature and σ^0 is grey marked

Table 3:
Coefficients of correlation (r) between polarization indices and crop features of winter wheat on the test fields in Neetzow (2002)

Date	Fresh weight [g m ⁻²]					
	07. April 2002		08. May 2002		05. June 2002	
Test field	3.2 (n=12)	10.3 (n=26)	3.2 (n=17)	10.3 (n=26)	3.2 (n=15)	10.3 (n=24)
PI	LHH - XHH	LHH + LHV + LVV + LVH	LHH - XVV	(LVH + XHH)/ (LVH - XHH)	(XHH + XVV)/ (XHH - XVV)	(r _{-cross} ⁺ XHH)/ (r _{-cross} ⁻ XHH)
r	0.53	0.54**	0.66**	0.46*	-0.36	0.50
Date	Stem density [stems m ⁻²]					
	07. April 2002		08. May 2002		05. June 2002	
PI	(LVV - XHH)/ (LVV + XHH)	XHH - XVV	(LHH + XVV)/ (LHH - XVV)	(LVH + XHH)/ (LVH - XHH)	LHV - XHH	(r _{-cross} ⁺ XHH)/ (r _{-cross} ⁻ XHH)
r	-0.62*	-0.39*	0.55*	0.44*	0.30	0.65**

PI: polarisation index r-cross: Mean value of both cross-polarisations, *: $\alpha = 0.05$, **: $\alpha = 0.01$

Areas with higher amount of biomass lead to decreasing backscatter intensity in the X-Band (Fig. 6), whereas backscatter increases for all L-Band channels. The spatial delimitation of areas with different plant development is a valuable information for further in-situ investigations and optimization of inputs such as fertilizers, fungicides and growth regulators.

3.1 Quantitative analysis of infield crop variability

Relationships between biophysical properties of winter wheat and their backscatter have been studied theoretically by developing radiative transfer models based upon simplified descriptions of crop canopies (Ulaby and Wilson, 1985; Cookmartin et al., 2000), or empirically by relating backscatter to field measurements (Ulaby and Wilson, 1985; Bouman and van Kasteren, 1990; Baronti et al., 1995).

Within the framework of this study the relationship was investigated by empirical measurements. The results of correlation analysis revealed a few significant correlations between radar backscatter of single channels and the crop features biomass (fresh weight) and stem density (Tab. 2). Tendentiously the relationship between crop features and the X-band were stronger than with the L-band. Particularly the horizontal polarization (HH) was most suitable for determining the spatial variability of winter wheat characteristics by means of a pixel based evaluation.

The strength of the relationships between radar backscatter and crop characteristics were improved by using multi-dimensional radar information (*polarization indices*). Particularly a channel combination of both wavelengths lead to stronger correlations. Here, combinations of one co-polarized X-Band with one cross-polarized L-band distinctly improved the correlations. The strongest

correlations of each growth stage in 2002 are shown in table 3. This results demonstrate the importance of availability of different radar channels for the detection of variability in crop development. Single radar bands are less suitable than multi-dimensional data, especially radar observations in one short and one longer wavelength seem to suffice for cereal crops.

The correlation between radar backscatter and crop features were not very strong. These results were caused by the relatively large fluctuations of radar backscatter signal for similar crop development. This is explained by the highly variable canopy structure due to randomly oriented crop elements (stalks, leaves, ears), which especially affected X-band data cause to its dominant interaction with the leaves. In contrast to this L-band data is affected mostly by variation in the soil moisture content. The influence of the plant water content on backscatter variation was negligible. A great influence has to be ascribed to the speckle effect, which occurs in all radar imageries and produces a target independent signal.

To avoid these fluctuations in backscatter signal discriminant analysis was tested to determine the potential for radar imagery to discriminate variations in crop development. Therefore crop data were subjected to hierarchical cluster analysis as a means of grouping the sample sites based upon measured stem density. Later groupings isolated using cluster analysis were subjected to discriminant analysis. In this models the discriminating variables were the mean digital values of each radar channel and polarization index. In the following tables 4 and 5 the best results are presented exemplary for field 10.3 at June 2002.

The results of discriminant analysis revealed that radar backscatter data of winter wheat were useful to discriminate groupings based on stem density differences. The

Table 4:
Results of discriminant analysis using backscatter values of X-HH (June 2002) as discriminating variable (field 10.3 in Neetzow) 66.7 % of the grouped cases were correctly classified (58.3 % after cross-validation)

X-HH		Group	Predicted group membership			
			1	2	3	total
Original	No.	1	3	1	0	4
		2	1	5	2	8
		3	1	3	8	12
	%	1	75.0	25.0	0.0	100
		2	12.5	62.5	25.0	100
		3	8.3	25.0	66.7	100
Cross-validation	No.	1	2	2	0	4
		2	1	5	2	8
		3	1	4	7	12
	%	1	50.0	50.0	0.0	100
		2	12.5	62.5	25.0	100
		3	8.36	33.3	66.7	100

Table 5:
Results of discriminant analysis using digital values of X-HH * L-HV⁻¹ (June 2002) as discriminating variable (field 10.3 in Neetzow) 66.7 % of the grouped cases were correctly classified (66.7 % after cross-validation)

X-HH * L-HV ⁻¹		Group	Predicted group membership			
			1	2	3	total
Original	No.	1	2	1	1	4
		2	1	5	2	8
		3	1	2	9	12
	%	1	50.0	25.0	25.0	100
		2	12.5	62.5	25.0	100
		3	8.3	16.7	75.0	100
Cross-validation	No.	1	2	1	1	4
		2	1	5	2	8
		3	1	2	9	12
	%	1	50.0	25.0	25.0	100
		2	12.5	62.5	25.0	100
		3	8.3	16.7	75.0	100

prediction accuracy of the most useful single channel X-HH and polarization index X-HH * L-HV⁻¹ is similar. The relationship between stem density and radar data improved due to generalization by using discriminant analysis instead of correlation analysis based on single point data.

3.2 Quantitative analysis of infield soil moisture variability

Information about soil moisture variability within fields is valuable for agricultural management practice. The large spatial and temporal variability that soil moisture exhibits in the natural environment makes it difficult to measure. A number of experiments have demonstrated, that soil moisture can be measured with means of radar backscatter (Ulaby et al., 1996). The theoretical basis for measuring soil moisture by microwave technique is based on the large contrast between dielectric properties of wet and dry soil (Engman and Chauhan, 1995). Radar backscatter is sensitive to variations in dielectric properties, which are strongly dependent on variations of moisture content of the soil surface layer. The fundamental problem is that the radar backscatter is also affected by the soil surface roughness and vegetation cover if present.

The linear correlation between backscattering coefficient and volumetric moisture content in the fields has been calculated for all measurement dates (Tab. 6). The only measurement date with almost bare soil condition was the 7th of April 2002, because the effect of vegetation cover with above ground biomass less than 0.5 kg m⁻² on the radar response may be negligible (Ulaby et al., 1996).

The correlation calculations between soil moisture content and radar backscatter revealed only few significant coefficients of correlation. Despite of large variation in volumetric moisture content, no strong correlation appears in the tested radar channels for the measurements in April 2002 on both test fields.

The radar backscattering signals in May and June were strongly influenced by vegetation cover. Astonishingly the strength of the relationship was getting higher and significant correlations appear especially for test field 10.3 in the co-polarised channels of the L-band. The partly good results for the X-band seem to be more likely coincidental, cause radar backscatter in short wavelengths is dominated by scattering of the vegetation canopy. This is also confirmed by inconsistent direction of the correlation for the X-VV (Tab. 6).

These results clearly indicate that radar backscatter cannot be easily converted into moisture estimates at field scale, essentially due to the effect of soil surface roughness and vegetation cover on radar response (Pantén et al., 2003). The influence of both effects on the radar backscatter is greatly dependent on the instrument configuration (Engman and Chauhan, 1995). Especially steep incidence angles minimize this affect. The used incidence angle during the measurements (35°) was optimised for vegetation response (Brown et al., 2000; McNairn et al., 2002) and it was not to assume to reach meaningful information about the soil. Baronti et al. (1995) also found no influence of soil moisture on L-band radar backscatter using an incidence angle of 35° and Taconet et al. (1994) found almost

Table 6:
Coefficients of correlation (r) single radar bands and volumetric soil moisture on the test fields in Neetzow (2002)

		Soil moisture [vol %]									
		08. May 2001		09. June 2001		07. April 2002		08. May 2002		05. June 2002	
		10.2 (n=11)	10.3 (n=16)	10.2 (n=13)	10.3 (n=18)	3.2 (n=12)	10.3 (n=26)	3.2 (n=17)	10.3 (n=26)	3.2 (n=15)	10.3 (n=24)
Variation of Vol %	%	18.4	25.0	33.4	34.5	17.3	26.3	8.1	17.5	9.0	55.9
σ^0 L-HH	[dB]	-0.41	0.72**	0.04	0.70**	-0.04	-0.05	0.26	0.16	0.25	0.32
σ^0 L-HV		0.24	0.50*	-0.01	0.40	-0.12	0.22	0.49*	0.40	0.11	0.46*
σ^0 L-VV		-0.37	0.61*	0.20	0.77**	-0.14	0.12	0.30	0.03	0.32	0.44*
σ^0 L-VH		0.06	0.09	0.0	0.52*	-0.29	0.43*	0.08	0.25	0.05	0.44*
σ^0 X-HH		-0.40	-0.67**	0.59*	0.34	-0.39	-0.17	-0.14	-0.24	-0.04	-0.60
σ^0 X-VV		0.02	-0.50*	0.53	0.81**	0.04	0.18	-0.10	-0.27	-0.18	-0.73**
σ^0 r-cross		0.19	0.34	0.00	0.46	-0.23	0.34	0.33	0.35	0.09	0.46*

r-cross: Mean value of both cross-polarisations, FW_V: biomass fresh weight, *: $\alpha = 0.05$, **: $\alpha = 0.01$
each highest significant correlation > |0.5| between crop feature and σ^0 is grey marked

no soil influence at steeper incidence angles (20°) for the X-band.

4 Conclusion

The results clearly reveal the difficulties related to a practical application of radar remote sensing in agriculture. The radar backscatter variability of winter wheat is affected by complex scattering mechanisms caused by various system- and crop-specific factors, which are highly variable in time. These physically very complex relationships make the interpretation and comparability extremely difficult. So it is right now hardly possible to assign the radar backscatter signature to a specific growth stage of winter wheat. It is obvious, taking into account that a transferability of empirical methods from one vegetation period to another and from one field to a variety of others is not yet feasible. This is due to a set of parameters which are influencing radar backscatter and are not directly related to crops' biophysical parameters.

At the scale of a single field the potential of radar remote sensing for determination of infield crop parameter and soil moisture variability is limited. Imaging radar has the potential to discriminate infield patterns with different plant development, but the reason for the variability can not be determined exactly. The large effect of the canopy structure with its various randomly orientated scattering elements leads to a highly variable backscatter signal of cereals. Additional various environmental effects such as wind, dew and rain as well as the system inherent speckle effect distorts the measured radar signal of the target. Also the row direction of wheat fields in relation to the radar look direction have to be considered as heavily

affecting the radar backscatter and disturbing the backscatter related to biophysical parameters. Furthermore the range of infield variability at one measuring date seems to be to small, that it could be determined adequately by the radiometric resolution of the radar sensor.

Despite these difficulties with the interpretation of radar backscatter the general sensitivity of imaging radar to the spatial variability of crop development is proven. However, the localisation of such variability within the field is a valuable information for agricultural practice. Particularly if no information about infield variability is available and unfavourable weather conditions prevent regular optical data acquisition the information provision by means of radar measurements becomes an important alternative.

Determination of infield variability of plant development from SAR data is feasible. The most important single radar channel for biophysical parameter retrieval is the X-HH. L-band is less sensitive on fresh biomass and stem density than X-band. It turned out that the use of multi-dimensional radar data (multi-polarization and multi-frequency) improves the correlations between radar backscatter and crop parameters of winter wheat. The multi-dimensionality of radar data offers additional information about crop variability and seem to be considerably for agricultural applications of radar. Recently operating SAR-systems using only single radar channels. Future satellites like the planed Terra SAR will fulfil these requirements of multi-dimensionality.

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