Ground based X-band radar backscatter measurements of wheat, barley and oats 1975-1981

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CABO-Verslag nr. 119
1989

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Contents

Abstract

Radar data of wheat, barley and oats are analysed in relation to canopy structure and the growth and development of the crop. The data set consists of ground based, X-band scatterometer measurements made by the Dutch ROVE team (Radar Observation on VEgetation) in the growing seasons of 1975-1981.

For each crop the temporal curve of the radar backscatter at both vertical (VV) and horizontal (HH) like polarization, and at angles of incidence between 10° and 80°, is described in relation to the morphological development of the crop. The influence of row spacing, row direction, crop variety and weather is investigated and quantified. Row spacing and crop variety influence the radar backscatter of wheat and barley notably at low angles of incidence. Wind can have a large impact on the backscatter of especially barley at high angles of incidence through its effect on the structure of the canopy (azimuthal orientation of ears, lodging). The above mentioned factors cause a large spread around the mean radar backscatter of a crop per development stage.

The possibilities of deriving quantitative information on the development and growth of the crop from temporal signatures of the radar backscatter are investigated. The number of crop development classes which can be distinguished from such a signature at a medium angle of incidence is three, four and five for respectively barley, wheat and oats. For wheat and barley, the appearance of the ears has no significant effect on the radar backscatter. For oats, on the contrary, the appearance of the panicles sharply increases the backscatter at high angles of incidence. For all cereals, the backscatter is in general similar just before and just after harvesting.

The canopy biomass and the height of wheat and barley can be estimated from radar data at a medium angle of incidence during the period from emergence to grain filling. The standard errors of estimate are about 220 g/m and 19 cm respectively. For oats, a direct estimation of crop growth parameters is generally not feasible.

A more precise monitoring of crop growth and development is hampered by 1) the fluctuations in, and the spread between the curves of the radar backscatter in time, and 2) the relative low contrast between the radar backscatter of a bare soil and that of an optically thick crop canopy. The use of radar data from a number of incidence angles and at both VV and HH polarization does not increase the monitoring possibilities. This is caused by the high correlation between the backscatter at different angles of incidence and between the states of polarization. It is stressed that the conclusions from this report derive from ground-based scatterometer data only.

Finally, a semi-empirical 'Height model' is derived from the Cloud model for wheat and barley. It describes the radar backscatter of the crop with soil moisture content and the height of the canopy as parameters.

Preface

This report on the X-band radar backscatter of cereals is a follow-up on a similar report on the radar backscatter of beets, peas and potatoes (CABO report 71). Both reports are written in the framework of the MONISAR project initiated in 1987 by the Dutch ROVE team (Radar Observation on VEgetation). Together they present an evaluation of the sensitivity of X-band radar backscatter to the growth and development of agricultural crops, and to other agronomic (e.g. canopy morphology) and non-agronomic (e.g. wind, rain) factors. The purpose of the study is to investigate the possibilities of X-band radar data for monitoring growth and development of crops. The interpretation of the data is from an agronomic point of view. It does not adress technical aspects and does not include any comparison with other techniques of remote sensing.

The data used for this study is the X-band scatterometer data set collected by the ROVE team during 1975-1981. On the one hand this set is very suitable for such a study because of the high frequency of observation (about 2-7 days) and the ground truth information available for the test fields. On the other hand, the experiments were a first introduction with radar remote sensing. They were initially designed for the purpose of crop(stage) discrimination. As insight developed, different experiments were conducted which related to specific research questions. Therefore, the analysis can be more thorough on certain aspects while others, though perhaps equally important, are treated in less detail. Nevertheless, the authors believe that conclusions can be drawn on the general usefulness of X-band radar for monitoring crop growth and development, from an agronomic point of view.

The conclusions of this report apply to the specific data set under consideration. Care should be taken with any extrapolation to air- or spaceborne radar observations, be it from scatterometers or from imaging systems. However, so far similar phenomena as described in this report have been observed in imagery of the Dutch Side Looking Airborne Radar (SLAR).

The authors thank the members of the ROVE team who participated in the experiments during 1975-1981. The following institutes contributed to the measurements:

- The department of Microwaves from the Technical University of Delft, which was responsible for the instrumentation and calibration of the radar, and
- The Physics and Electronics Laboratory FEL-TNO, who processed the radar data.

Finally, the authors thank the Netherlands Remote Sensing Board (BCRS) for the financial support for this study, and the assistance and comments on the work by dr. H. Breman (CABO), dr. J. Goudriaan (Agricultural University) and dr. G.P. de Loor (FEL-TNO).

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1 Introduction

During the years 1975-1981 the Dutch ROVE team (Radar Observation on Vegetation) collected an extensive series of measurements on the radar backscatter of agricultural crops during the growing season. All the data were taken in the X-band (≈ 10 GHz) and some, in 1980 and 1981, also in the Ka band (≈ 35 GHz). This report only deals with the X-band data. These ground based measurements were performed on bare soils and on crops at different research farms in the Netherlands. The objective of this research was mainly to gain insight in the interactions between radar backscatter and crop-soil systems (de Loor, G.P. et al, 1982). In 1987 the project MONISAR was initiated to re-evaluate this data set to assess the potentials of X-band radar for the monitoring and yield prediction of agricultural crops. A first selection was made for the relatively broad leaf crops beet, pea and potato and the results of this study were presented by Bouman (1987; 1988). A second study included the cereals wheat, barley and oats of which the results are presented in this report. The attention is focussed on three aspects:

1: the effect of management practices, canopy structure and external conditions on the X-band radar backscatter of cereals,
2: the possibilities of estimating crop development, and
3: the possibilities of quantitatively estimating crop growth.

In total 18 plots of wheat, eight plots of barley and three plots of oats were measured during the growing season (table 1.1). Between 1975 and 1977 the experiments were done on the test farm 'Droevendaal' at Wageningen, between 1978 and 1980 on 'De Bouwing' at Randwijk and in 1980 and 1981 on 'De Schreef' near Dronten. These farms are located in different environments and comprise sandy soil (Droevendaal), alluvial clay (De Bouwing) and marine clay (De Schreef). In some cases, differences between the plots were introduced with respect to row spacing, row direction and crop variety. Visual observations and quantitative measurements were made of the soil surface and of the crops. In general quantitative measurements were made of the following variables: soil moisture content of five cm topsoil (percentage by weight), fresh and dry weight of the above ground biomass (g/m^2), crop height (cm), crop cover (%), row spacing, number of stems/m^2 and for some crops the dimensions and number of leaves per plant. Visual observations were made of the crops and the soil surface: structure, morphology, phenological stage, cover, slaking, anomalies etc.

The radar backscatter was measured with a Frequency Modulated-Continuous Wave (FM-CW) scatterometer mounted on a trailer. This trailer could be moved along the test field to measure different plots. The central frequency of the scatterometer was 9.5 GHz (corresponding to a wavelength of about 3 cm) with a frequency sweep of about 0.4 GHz. The scatterometer was calibrated by directing the radar beam on a corner reflector of known radar cross-section. The radar backscatter parameter obtained was γ: radar cross-section of target per unit projected area of the cross-section of the radar beam (m^2/m^2). The relationship between γ and $\sigma°$ (the Normalised Radar Cross Section NRCS, which is the radar cross-section per unit area illuminated by the antenna) is:

$$\gamma = \sigma° / \cos\theta \quad \text{with } \theta = \text{angle of incidence}$$

Table 1.1: cereal plots 1975-1981.

crop	year	specifications
Wheat		
	1975	-, 1 plot
	1976	-, 1 plot
	1977	Melchior, 6 plots with varying row spacing
	1979	Arminda, Okapi, Adonis, 1 plot each
	1980	Bastion, 1 plot
	1981	Durin, Adamant, Okapi, 1 plot each
		Arminda, 3 plots with varying row direction
Barley		
	1975	-, 1 plot
	1976	-, 2 plots with varying row direction
	1977	Aramir, 3 plots with varying row spacing
	1979	Aramir, 1 plot
	1980	Havila, 1 plot
Oats		
	1975	-, 1 plot
	1979	Leanda, 1 plot
	1980	Dula, 1 plot

Measurements could be performed at different angles of incidence and at both like- (VV and HH) and cross-polarization (HV and VH). The scatterometer was mounted in such a way that the distance along the axis of the beam to the target could remain 10 m at all angles of incidence. The antenna beamwidth was 4° (at the half power or 3 dB points), so the cross-section of the antenna beam at the place of the target was 0.6 m^2. More information on the measurement configuration is given by van Kasteren (1977) and by de Loor (1982).

For this study, measurements of the cereals were selected at both vertical (VV) and horizontal (HH) like-polarization, and at angles of incidence ranging from 10° to 80°. These measurements were made at each individual day of observation. The number of observation days varied from some 20 in the growing season of 1975 to some 36 in the growing season of 1980. The total number of measurements was about 5214 for wheat, 3006 for barley and 1464 for oats.

For the ease of writing, three general classes of incidence angle are distinguished:

low : 10°-30° incidence angle
medium : 30°-60° incidence angle
high : 60°-80° incidence angle

The incidence angle is defined as the angle between the look direction and the vertical.

This report is divided in three sections. After a general description of the radar backscatter of cereals (chapter 2), part I deals with the influences of management practice and canopy structure on the radar backscatter of cereals (chapters 3-7). Part II investigates the possibilities of X-band radar backscatter for the monitoring of the growth and development (chapters 8-10). Specific attention is given to model considerations for wheat and barley, with emphasis on the applicability for the estimation of crop growth parameters (chapter 11). In both part I and part II side-steps are made in qualitative descriptions of the interaction of microwaves with vegetation. Finally part III summarizes and discusses the results of parts I and II for the possibilities of X-band radar for the monitoring of crop growth of cereals.

2 The radar backscatter of cereals

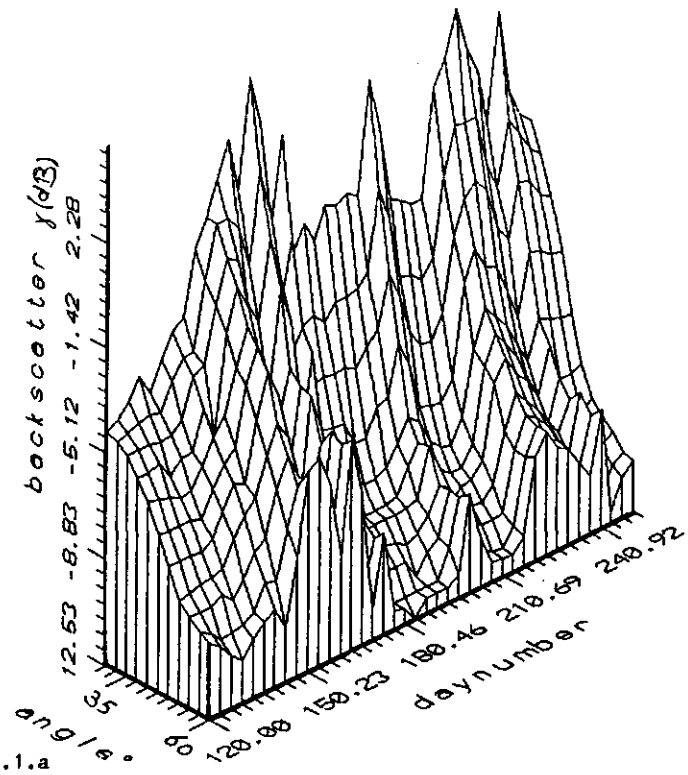
Contrary to more broad-leaf crops like beet, potato and pea (Bouman, 1987), the X-band radar backscatter of wheat, barley and, to some extent, oats is generally a decreasing function of crop growth. Due to the open structure of the canopy and the small dimensions of the canopy elements with regard to the wavelength, microwaves can penetrate relatively deeply into the canopy. Extinction takes place through scattering and absorption by the canopy elements (stems, leaves, heads). During the vegetative phase, the backscatter decreases with increasing crop growth and drops well below the level of the bare soil. With increasing crop development heading takes place and ears or panicles are formed. The ears of wheat and barley have a strong capacity for scattering and absorption. In this stage, the backscatter is dominated by the layer of ears in the top of the canopy and penetration of the microwaves may become limited. The backscatter is then very sensitive to the orientation of the ears. Especially for barley with its large ear needles fluctuations in the backscatter of 5 to 10 dB may occur due to changes in the orientation of the ears. In the generative phase, the backscatter of oats differs considerably from that of wheat and barley. At high angles of incidence the panicle of oats acts as a structure of strong backscatter instead of absorption. With the emergence and development of the panicle the backscatter at high angles of incidence increases above the level of that of the soil background.

At the stage of ear filling, cereals may be sensitive to lodging when they are heavy with ears and adverse wheather conditions occur. The lodging of the crop may result in increases in the radar backscatter of up to 5 to 10 dB at vertical polarization and at all angles of incidence. When the cereals ripen at the end of the growing season the backscatter increases again because of the decrease in soil cover and the loss of plant water. At harvest, the level of backscatter has returned to that of the bare soil. Considerable differences in backscatter may be caused by differences in length and orientation of the straw that remains on the field.

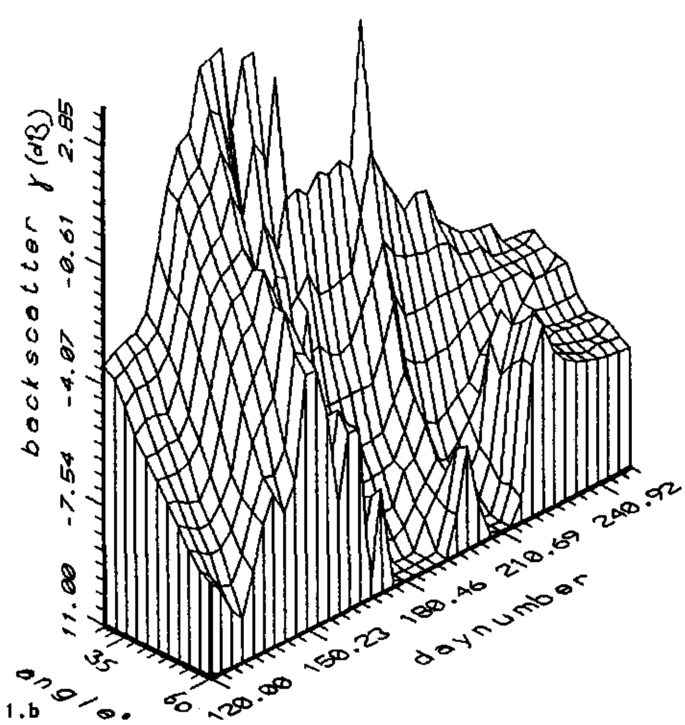
A general impression of the radar backscatter of a crop during the growing season is obtained by 3-dimensional plots. The backscatter is plotted on the z-axis with time on the x- and the angle of incidence on the y-axis. Time is expressed in Julian day which starts with number 1 on the first of Januari.

The wheat variety Adonis in 1979 serves as an illustration of the relation between radar backscatter and the growth and development of summer wheat (figs. 2.2.a/b). The backscatter of a bare soil is given for comparison (figs. 2.1.a/b). This plot was harrowed at the beginning of the growing season to get a relatively smooth, fine-grained surface structure. The plots for VV and HH polarization are both smoothed in time for a good impression of general trends.

For the X-band, now under consideration, the backscatter of wheat generally decreases in time at all angles of incidence until the beginning of the period of grain filling, when compared to a bare soil. After emergence the backscatter initially increases until the soil cover reaches about 45 % on day 147. At low angles of incidence the same pattern is observed for bare soil but at high angles of incidence this pattern is a typical characteristic of cereals. With further growth the backscatter decreases while the soil cover increases and tillering, flowering and ear formation takes places. The backscatter reaches a minimum level on about day 200 only

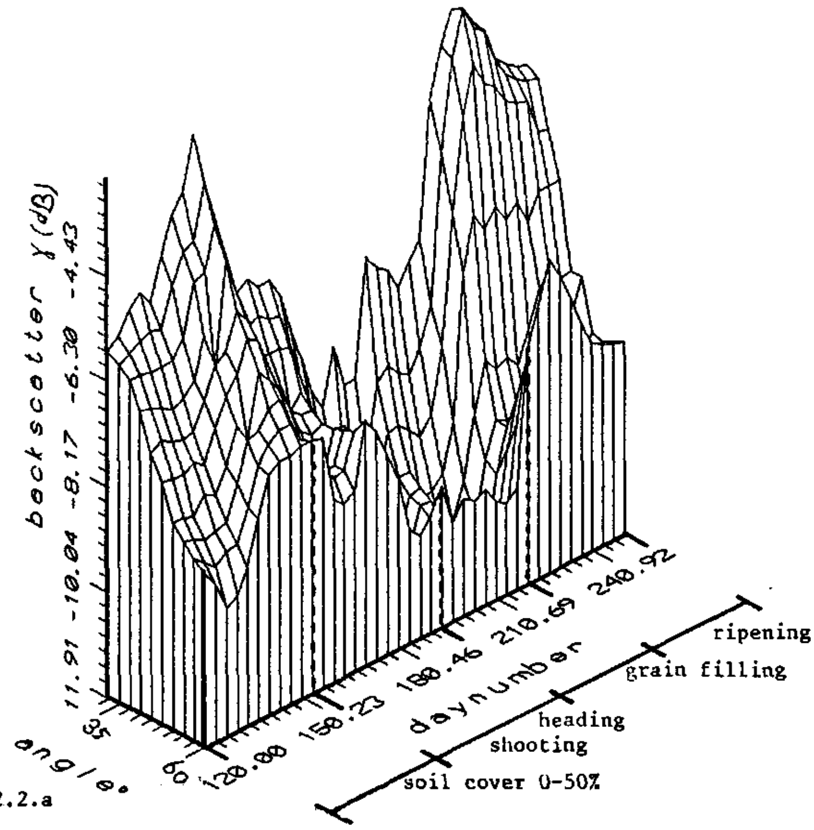


2.1.a

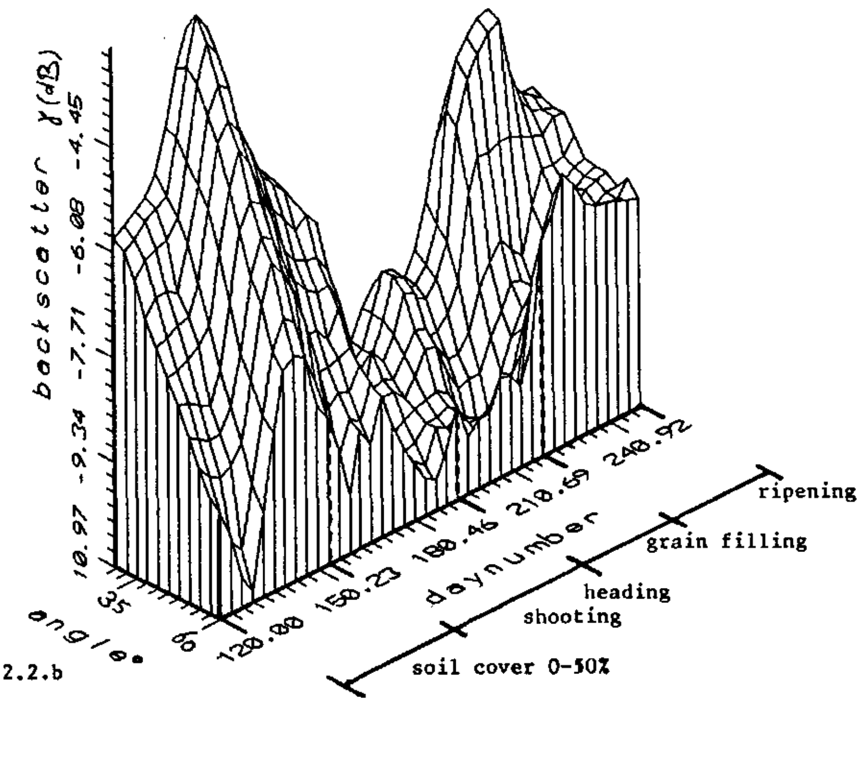


2.1.b

Figure 2.1: three dimensional plot of the radar backscatter (in γ dB) in time at VV (2.1.a) and at HH (2.1.b) polarization at different angles of incidence. Bare, harrowed soil, 1979.



2.2.a



2.2.b

Figure 2.2: three dimensional plot of the radar backscatter (in γ dB) in time at VV (2.2.a) and at HH (2.2.b) polarization at different angles of incidence. Summer wheat Adonis, 1979.

when the crop enters the phase of grain filling and no more growth in height occurs.

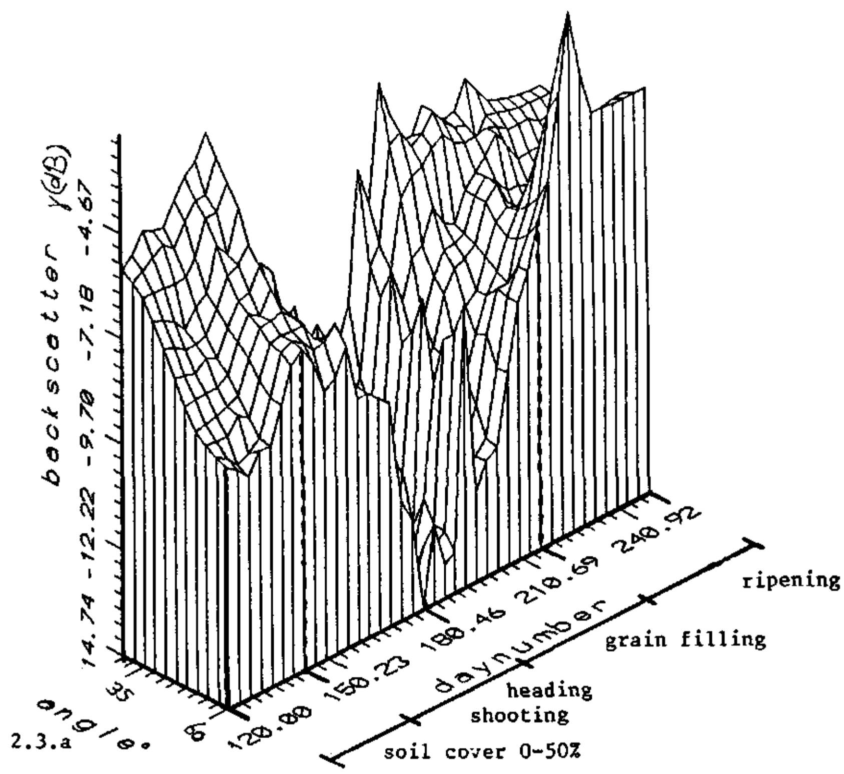
At VV polarization, the angular dependency of the backscatter changes with the formation of the ears. Before ear formation, the backscatter continuously decreases with incidence angle, while after ear formation the backscatter at high incidence angles increases with respect to the medium incidence angles; it is said that the angular dependency curve becomes hollow. The angular curve remains hollow until harvest and this hollowness is characteristic for wheat and barley. This phenomenon occurs to a lesser extent also at HH polarization and in the present example only in the midst of the grain filling period.

During the period of grain filling and the beginning of ripening the backscatter is quite stable at a low level, especially at the medium angles of incidence. At low angles of incidence, the backscatter increases around day 201 which corresponds with a similar pattern in the bare soil plots. In this stage, the crop is somewhat transparant for microwaves in the frequency band now under discussion (X-band) at low angles of incidence. On day 222 the crop lodges which results in an increase in backscatter at all angles of incidence and at both states of polarization. The effect is most dramatic at low and high angles of incidence at VV polarization and may be enhanced by an increase in soil moisture of the top soil. After harvetsing the backscatter returns to the level of the bare soil. Finally it is noticed that despite the fact that both the plots of VV and HH polarization are smoothed in time, the plot of HH polarization is smoother in appearance than that of VV. The backscatter at VV polarization is more sensitive to momentaneous changes in canopy structure.

The variety Aramir in 1979 illustrates the radar backscatter of barley in the course of the growing season (fig. 2.3.a/b). The backscatter pattern is generally comparable to that of wheat with some specific differences. After an initial increase in radar backscatter in the beginning of the growing season, the backscatter sharply decreases at all angles of incidence. This decrease is faster and the minimum that is reached is lower than for wheat, especially at high angles of incidence.

In the present example, the angular backscatter curve does not become hollow with the formation of the ears. The absense of a hollow angular dependency is, however, not a typical characteristic of barley.

With the heading completed and no more growth in crop height taking place, the minimum level of backscatter is reached on about day 180. This minimum occurs earlier in the growing season than for wheat. The crop lodges already in an early phase of the period of grain filling. This lodging results in an increase in the radar backscatter on day 194 at all angles of incidence and in both states of polarization. The crop remains lodged during all further stages of development and the backscatter develops differently at the various angles of incidence. At low angles of incidence the backscatter remains high and only increases slightly until the end of the growing season. At medium angles of incidence the backscatter steadily increases during ripening and at high angles of incidence the backscatter increases even more. Contrary to the backscatter of wheat no influence of the soil background is present, not even at the steepest angles of incidence. The layer of ears in the top of the crop effectively shield the canopy for penetration of the microwaves. At the end of the growing season a hollowness in the angular backscatter curve is introduced.



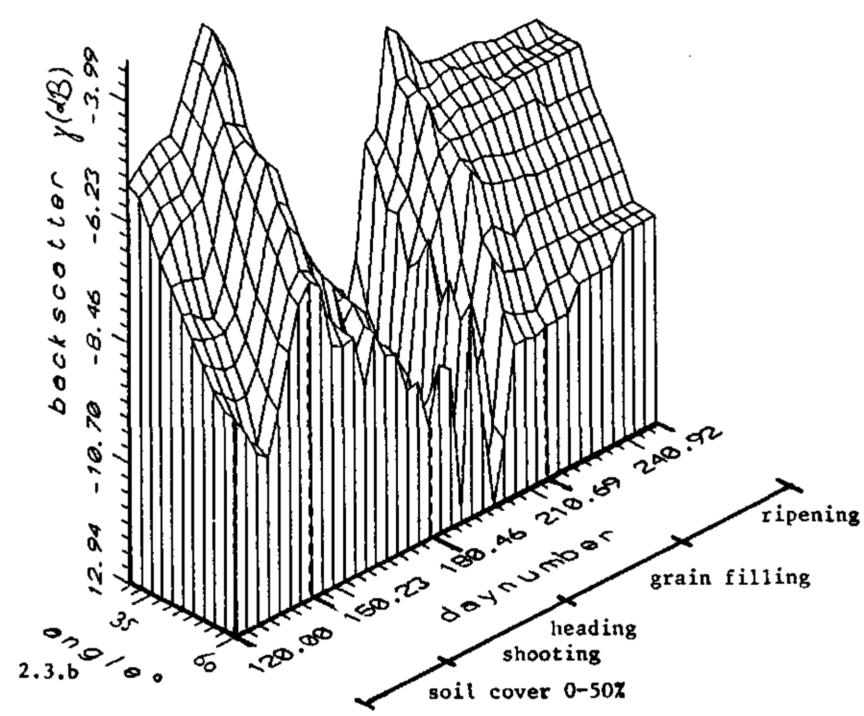


Figure 2.3: three dimensional plot of the radar backscatter (in γ dB) in time at VV (2.3.a) and at HH (2.3.b) polarization at different angles of incidence. Barley Aramir, 1979.

The pattern of the backscatter during grain filling and ripening described here is not truly typical for all barley crops. The backscatter during these phases is very sensitive to the orientation of the ears and stems in the top of the canopy. When the ears are bent towards the antenae of the radar, a different pattern of backscatter is observed than when the ears are bent away from the radar. Strong wind thus has a momentaneous impact on the backscatter through its effect on the orientation of the canopy elements.

Finally, as with wheat, the plot of HH polarization is smoother in appearance than that of VV.

A typical pattern of backscatter of oats is given by the variety Leanda in 1979 (figs. 2.4.a/b). The plots differ from those of wheat and barley. After a similar initial increase in backscatter at all angles of incidence the backscatter also decreases after about 45 % soil cover of the crop. The decrease stops for medium and high angles of incidence at both VV and HH polarization on about day 180. At the first appearance of the panicles, the backscatter starts to increase again. Contrary to the ears of wheat and barley the panicle of oats is a structure of strong backscatter. The increase at VV polarization continues until the stage of grain filling while at HH polarization it stops already after the panicle has appeared in the top of the canopy. The increase is also more pronounced at VV than at HH polarization. During the stages of grain-filling and ripening, the backscatter is more or less stable and no influence of the underlying soil is present.

At the low angles of incidence the backscatter remains a decreasing function of crop development until the stage of dying. The total decrease is smaller (about 3 dB) than the comparable decrease at steep incidence angles for wheat and barley (respectively about 5 and 7 dB). With the lodging of the crop on day 222 the backscatter increases at low and medium angles of incidence but is hardly affected at high angles of incidence. After harvesting the backscatter returns to the level of that of the bare soil.

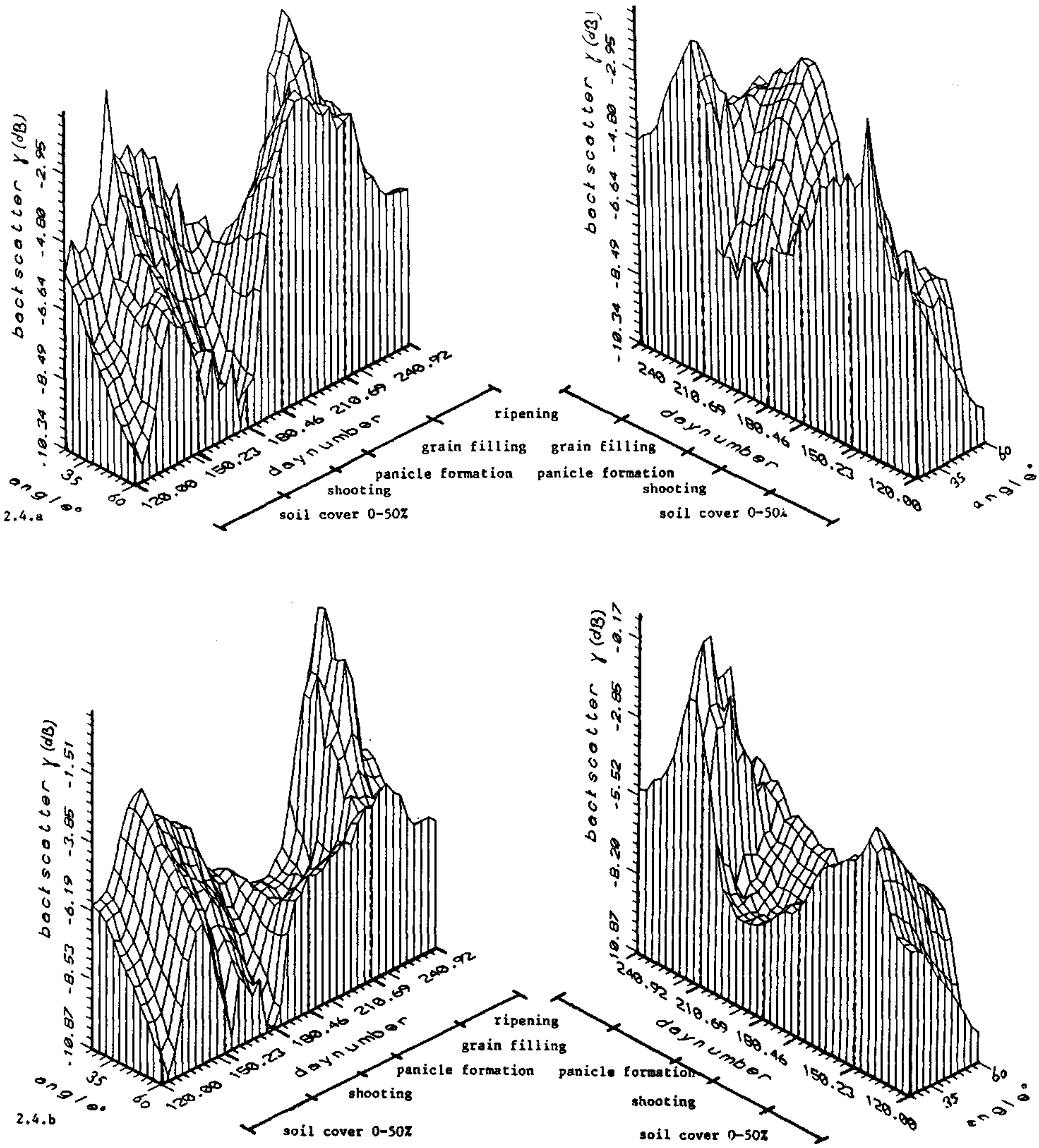


Figure 2.4: three dimensional plot of the radar backscatter (in γ dB) in time at VV (2.4.a) and at HH (2.4.b) polarization at different angles of incidence. Oats Leanda, 1979.

Part 1.

The influence of management practice and canopy structure

3 Row spacing

The effect of row distance on the backscatter of wheat and barley is investigated in an experiment in 1977. The summer wheat Melchior and the barley Aramir were sown at row distances of 12.5, 25 and 37.5 cm. The experiment with wheat was repeated once so that a total of nine fields was present. The fields are labeled a, b and c with increasing row distance and the suffixes 1 and 2 are used to distinguish between the first and the second series of the wheat fields.

3.1 Wheat

3.1.1 Crop growth and radar backscatter

Despite the differences in row spacing, the growth of the crops within a series is comparable. The growth in dry biomass, plant water and plant height are similar so that no differentiation is made between these parameters for the fields a, b and c within one series. The effect of row spacing is only notable on soil cover (fig. 3.1). The fields a have the highest soil cover throughout the growing season and the fields c have the lowest.

Some differences, however, exist in the growth and development of the crops between the two series (figs. 3.2 and 3.3). The soil cover of the fields a2, b2 and c2 is some 5% larger during the first half of the growing season and some 15% in the phase of ripening than that of a1, b1 and c1. The crops in the first series wither sooner at the end of the growing season, thereby decreasing the soil cover sooner. Consequently, the average dry biomass of the crops of the second series attains a higher end value than the average of the crops of the first series, respectively 1.2 and 1.0 kg/m2.

The crops of the second series stand closer in the rows than the crops of the first series. The number of stems/m2 varies from 360 to 380 (for c1 and a1 respectively) for the first serie and from 460 to 510 (for c2 and a2 respectively) for the second. This difference of about 100 stems/m2 may account for the difference in soil cover. For both series, the growth in crop height is similar and no differentiation is made between the series. Some curves of the radar backscatter in time for the crops with different row spacing are given in figs. 3.4.a/c. In these figures the radar backscatter is given at three angles of incidence which are representative for the general classes of incidence: 20° for low incidence, 50° for medium incidence and 70° for high incidence. The backscatter at VV polarization is plotted because it is (a little bit) more sensitive to differences in the canopy (structure) than the backscatter at HH polarization.

The general pattern of the radar backscatter is that as described in chapter 2 for wheat. Especially noteworthy here is the influence of the soil background on the total radar backscatter of the crop. In the phase of grain filling the influence of the soil background becomes notable at both medium and low angles of incidence from day 195 onwards. The rise in backscatter between day 195 and 220 is caused by increases in the moisture content of the topsoil. This rise is also present in the backscatter pattern of bare soil. The influence of the soil background is more notable at low angles of incidence than at medium angles. This agrees with the smaller path of extinction of the microwaves at lower angles of incidence. Furthermore, the influence of the soil background is also more notable in the backscatter pattern of the first series than in that of the second.

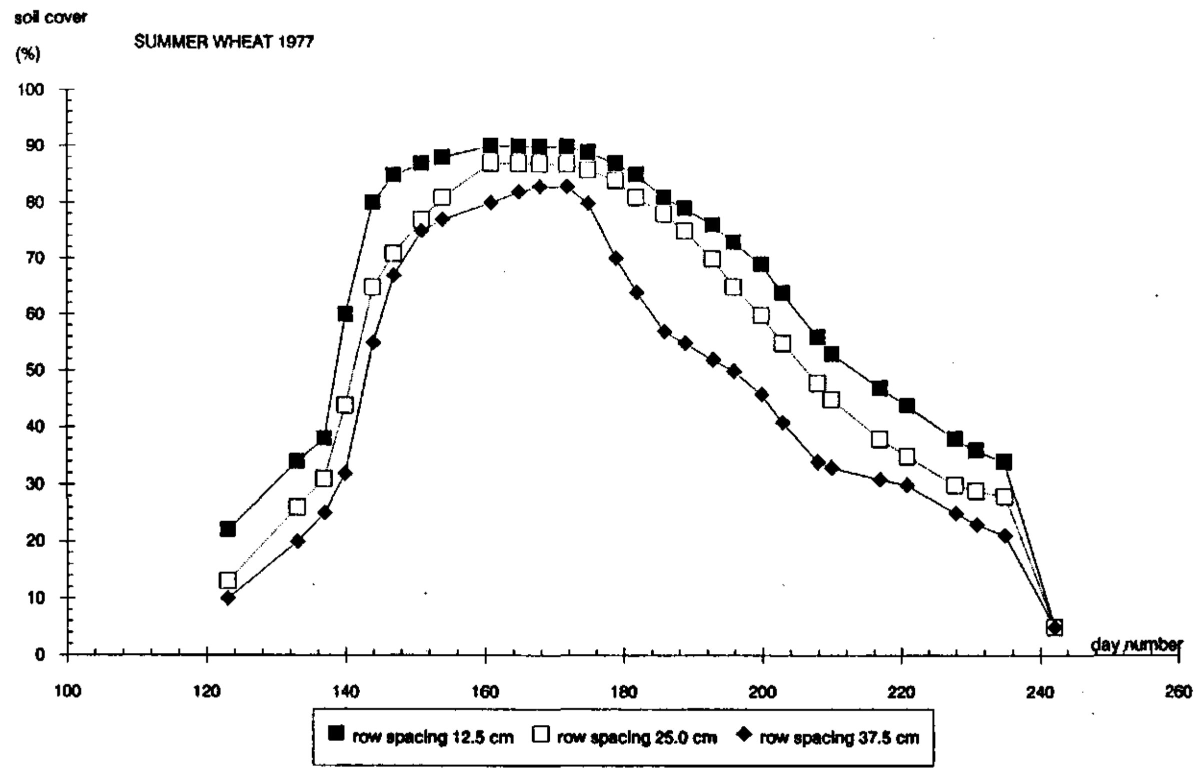


Figure 3.1: soil cover versus daynumber of three wheat crops in 1977; series 1: 12.5, 25.0 and 37.5 cm row spacing.

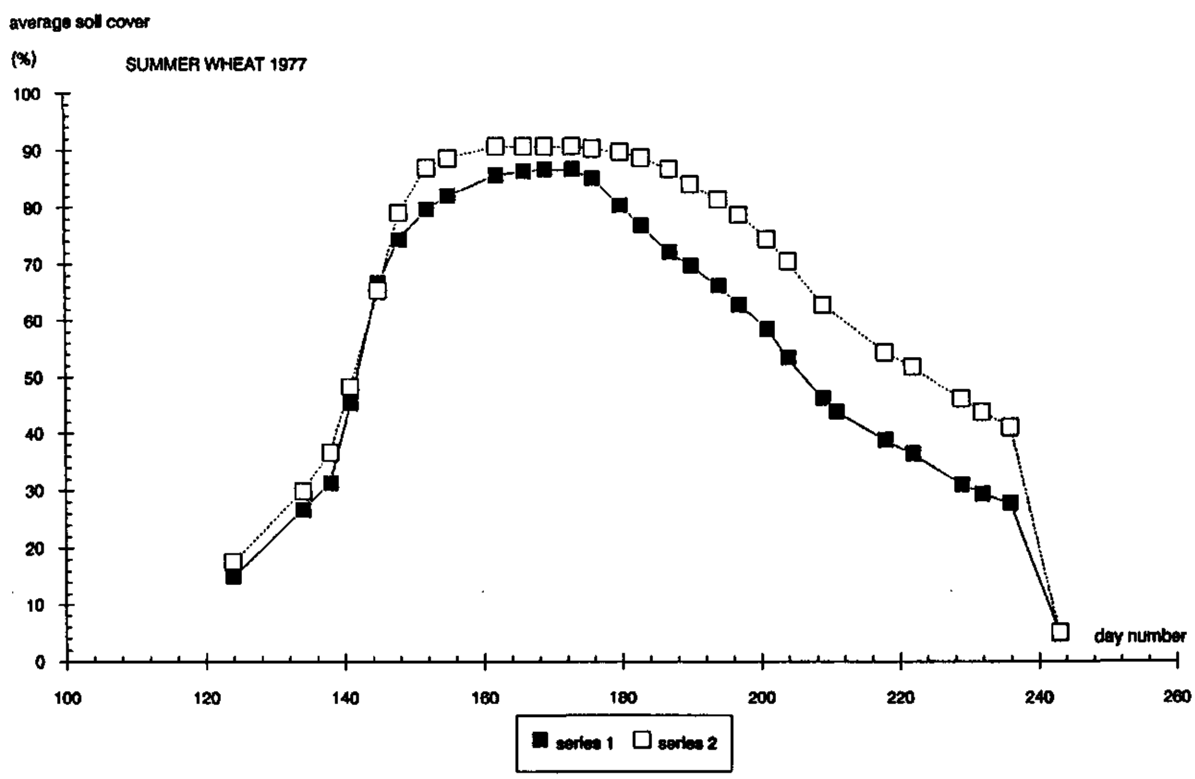


Figure 3.2: average soil cover versus time of the three wheat crops in series 1 and series 2, summer wheat 1977.

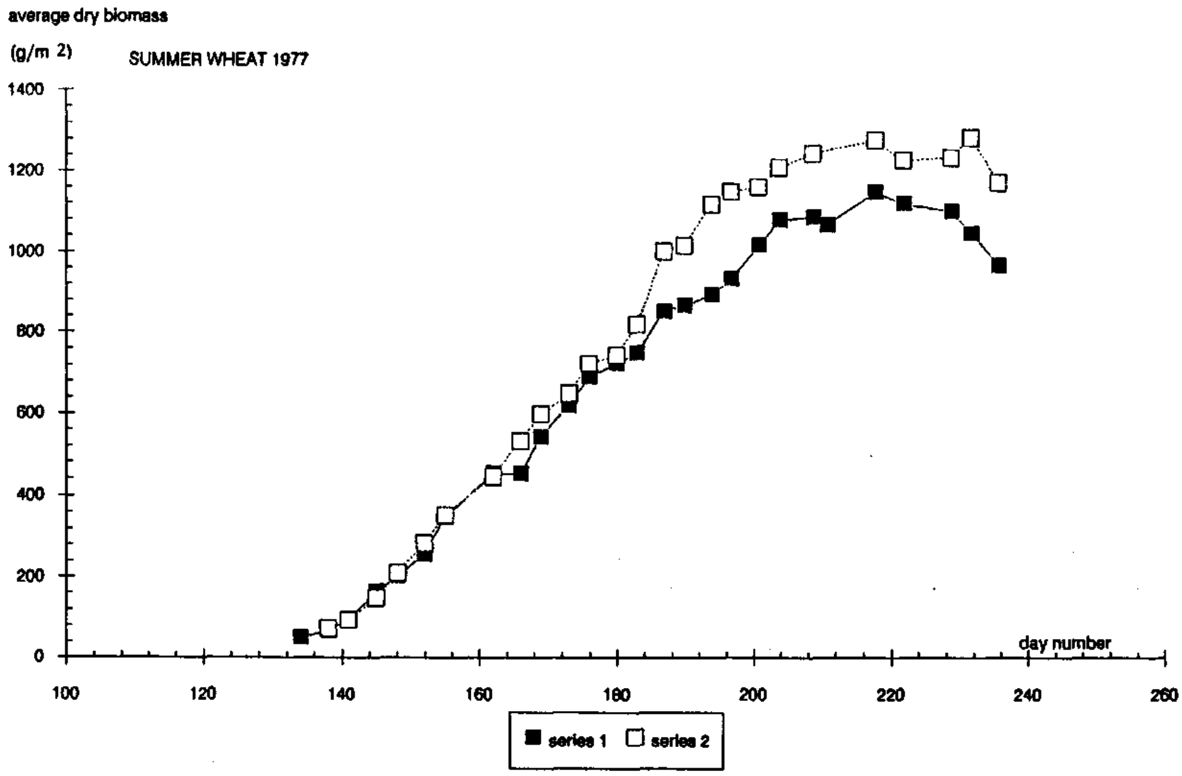


Figure 3.3: average dry biomass versus daynumber of the three wheat crops in series 1 and series 2, summer wheat 1977.

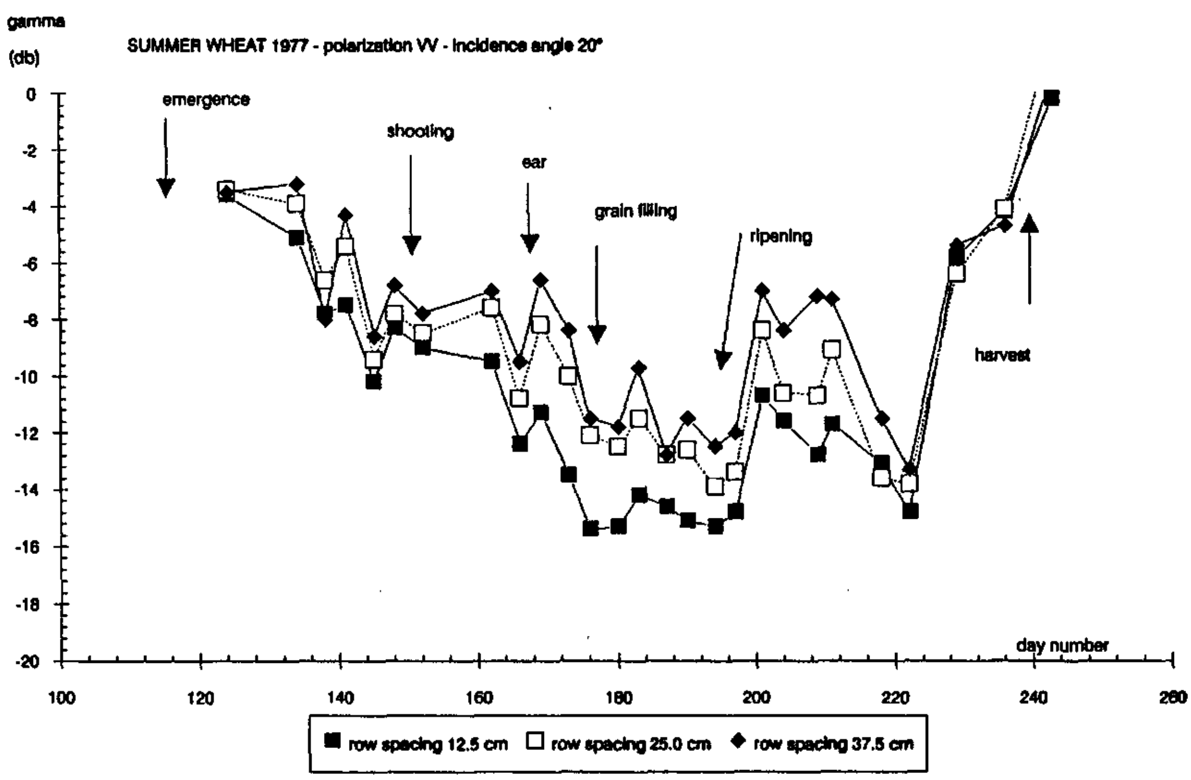
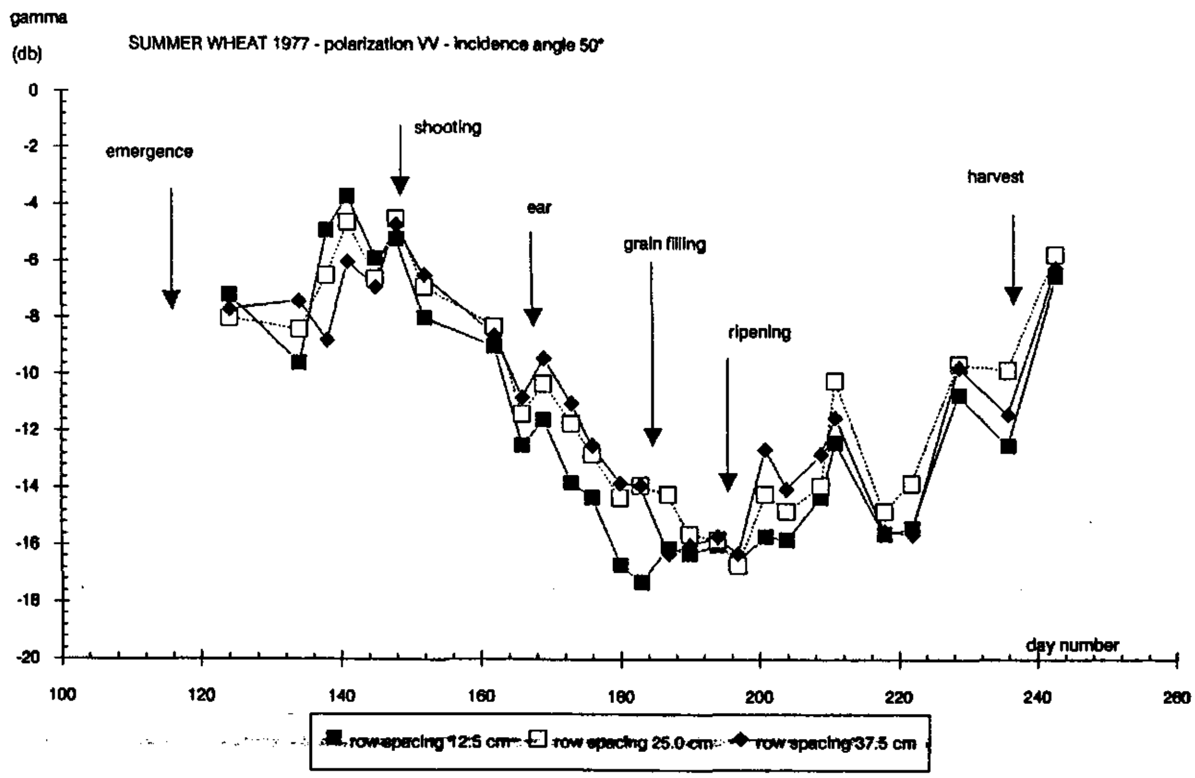


Figure 3.4.a: VV radar backscatter at 20° incidence angle versus daynumber of three wheat crops, summer wheat 1977, series 1.



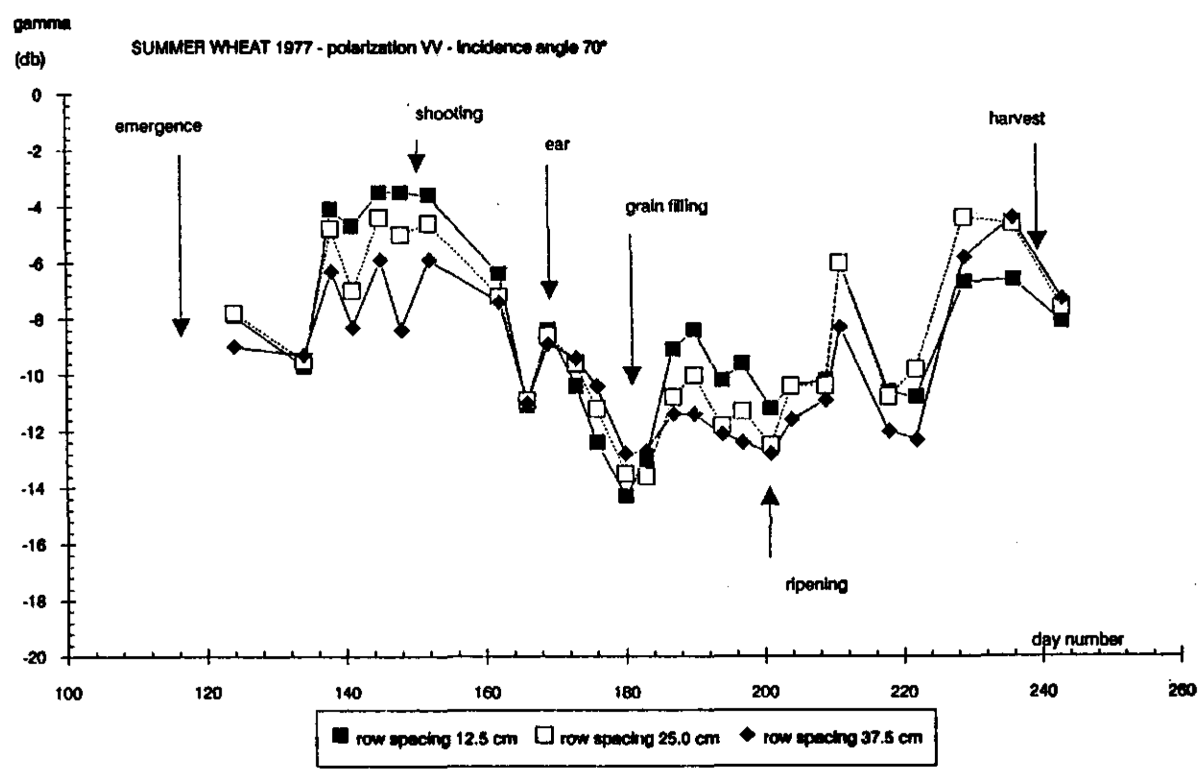


Figure 3.4: VV radar backscatter at 50° (3.4.b) and 70° (3.4.c) incidence angle versus daynumber of three wheat crops, summer wheat 1977, series 1.

This agrees with the lower soil cover of the fields in the first series which renders the canopy more transparant for microwaves. At the end of the growing season, during the phase of ripening, the pattern of radar backscatter at medium and low angles of incidence is completely comparable to that of the bare soil. The backscatter increases and it reaches the same level at harvest as that of the bare soil. For the fields in the first series, the backscatter increases faster at low angles of incidenec than for those in the second series because of their higher transparancy for microwaves.

The effect of row spacing on the radar backscatter depends on the angle of incidence. In general, the typical wheat features in the radar backscatter curve are largest for the fields with the small row spacing, 12.5 cm. Table 3.1 summarizes some average backscatter values during the periods of the most pronounced features in the backscatter curves of wheat; i.e. the period of the relative high radar backscatter at high angles of incidence during early growth, and the period of low backscatter at medium to low angles of incidence during the stage of grain filling.

At low angles of incidence, the effect of row spacing is most pronounced and consistent. The backscatter is continuously lower from the start of the growing season with a small row spacing than with a large row spacing. The backscatter of field a is smaller than that of field b, which is smaller than that of field c. The difference in backscatter between field a and field c varies between 1.5 and 4 dB.

Table 3.1: average (VV) radar backscatter over two periods with the most pronounced features of the radar backscatter of wheat, days 140-150 and days 180-200, 1977.

		vegetative phase days 140-150			generative phase days 180-200		
angle:		20	50	70	20	50	70
field	a1	-9.2	-6.4	-3.5	-14.1	-16.3	-10.8
	b1	-8.6	-6.0	-4.7	-12.1	-15.1	-11.6
	c1	-7.7	-6.0	-6.7	-10.9	-15.1	-12.0
	a2	-9.7	-6.1	-4.1	-13.4	-15.8	-11.4
	b2	-9.1	-7.4	-4.7	-12.8	-14.3	-10.8
	c2	-7.9	-6.1	-6.5	-12.2	-14.3	-9.2

At medium angles of incidence, the differences in radar backscatter are relatively small and only consistent between the 1000 series in the generative period of growth. In the vegetative period of growth the radar backscatter is, with the exception of b2, comparable between all fields in both series.

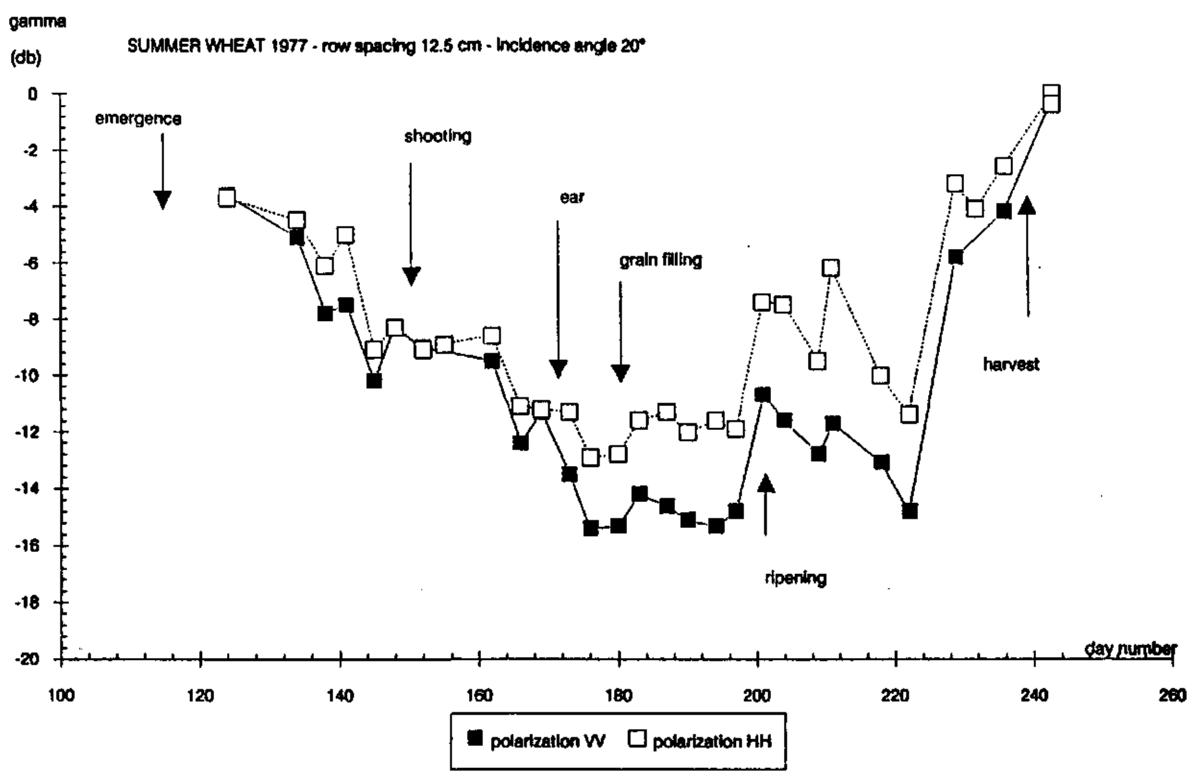
In the generative period of growth, the radar backscatter is in the first series continuously some 0.5 to 2 dB lower for field a than for field c. In the second series, field a is only smaller than field c with about 1.5 dB.

At high angles of incidence, there is only consistency between the two series during the vegetative period of growth. Between days 140-160 the backscatter is higher for the fields with a small row spacing than for the fields with a large row spacing. The difference between fields a and c amounts to 2.5-3 dB. During the period of generative growth the radar backscatter is largely influenced by other factors than the spacing between the rows (see the next paragraph on barley). The backscatter in the first series is highest for field a and lowest for field c, while in the second series this pattern is the reverse.

The level of backscatter of the three plots with different row spacing does not relate to differences in canopy biomass (fresh or dry) nor to differences in crop height. The differences in backscatter are caused by differences in canopy structure induced by the different row spacings. This effect of canopy structure on the radar backscatter is twofold. First it changes the attenuation and backscatter properties of the canopy itself, and secondly, it thereby changes the contribution of the underlying soil to the total backscatter. This latter effect is more easily recognised. With the small row spacing of field a the row structure of the crop gradually disappears with the development of the crop. At full development the soil cover is about 90-95% and the row structure has almost disappeared in the top of the canopy. With the large row spacing of field c the row structure of the crop is discernable throughout the growing season. The soil cover is relatively low and the soil between the rows is visible. Therefore the attenuation of the microwaves is relatively small and the influence of the underlying soil relatively large. This partly explains why the backscatter of field c is higher than that of b, and that of b higher than that of a at low angles of incidence. The backscatter from bare soil at medium and low angles of incidence is larger than that from the crop. The relationship between soil cover and radar backscatter is however not a straight one. The fields with the same row distance do not have the same soil cover in the two series, n.b. the soil cover in the first series is always lower than that in the second. The backscatter from the fields with the same row distance, however, is not higher for the fields in the first series. At low angles of incidence the backscatter of both fields c and both fields b are comparable while that of a1 is even lower than that of a2. (This furthermore implies that the number of stems within the rows does not affect the radar backscatter. This number is about by $100/m^2$ larger for the fields in the second series than for those in the first series.) Only when the influence of the soil background becomes dominating between day 195 and 220 does the sequence of backscatter-level inversely match the sequence of soil cover for all six fields. Differences in the structure of the canopy caused by the different row spacings not only change the contribution of the underlying soil, they also change the backscatter properties of the canopy itself.

3.1.2 The backscatter at VV and HH polarization

The relation between the backscatter at VV and HH polarization depends on the angle of incidence and the stage of growth of the crop (figs. 3.5.a/c). At <u>low angles of incidence</u> the backscatter at VV is about the same to 1 dB lower than at HH polarization during the first stages of growth. With the formation of ears and ear stems the backscatter at VV drops some 2-5 dB below that at HH for the rest of the season. At <u>medium angles of incidence</u> the backscatter is some 2 dB higher at VV than at HH during the period before heading. With the formation of the ears this pattern inverses and the backscatter at VV is about 2-5 dB lower for the rest of the season. <u>At high angles of incidence</u>, the backscatter is some 3 dB higher at VV polarization than at HH before heading (40-90% soil cover). During the period of grain filling and ripening this difference is reduced to about 0.5-1 dB. (The specified differences between the backscatter at VV and HH apply to the fields a1 and a2 with the small row spacing.)



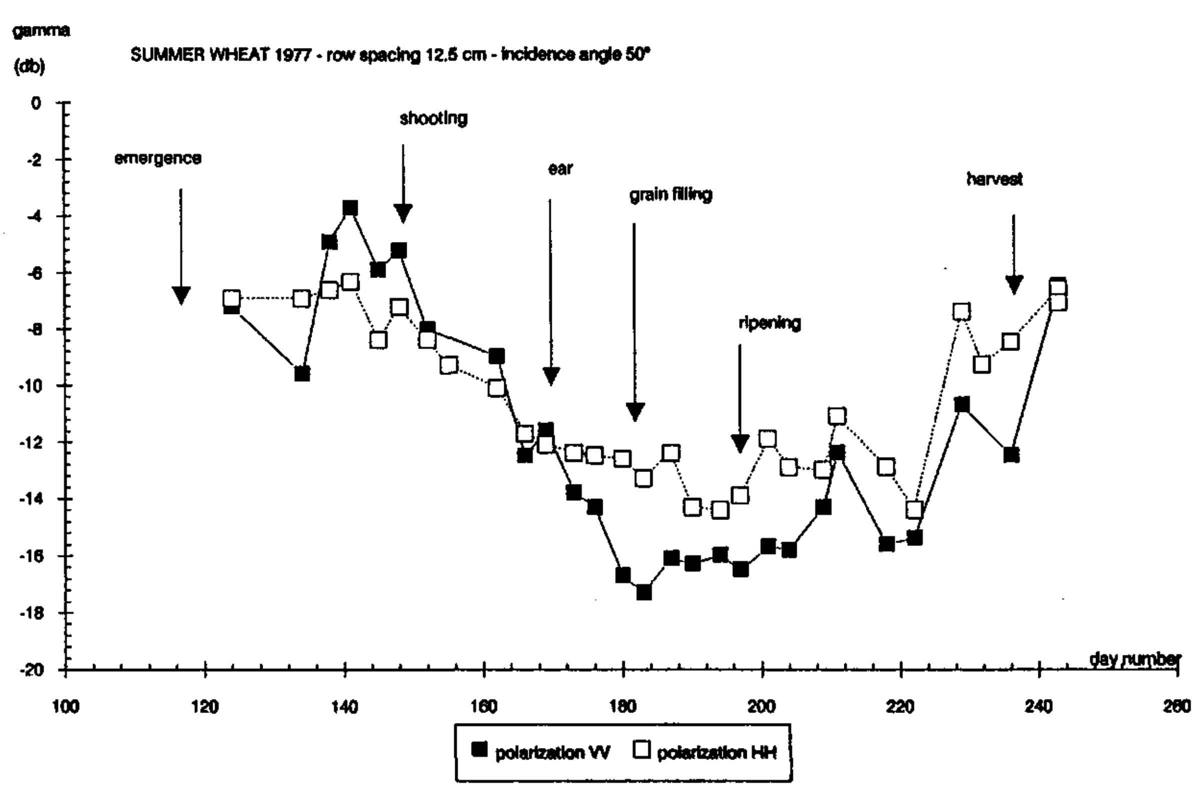


Figure 3.5: VV and HH radar backscatter at 20° (3.5.a) and 50° (3.5.b) incidence angle versus daynumber of wheat with row spacing 12.5 cm, summer wheat 1977, series 1.

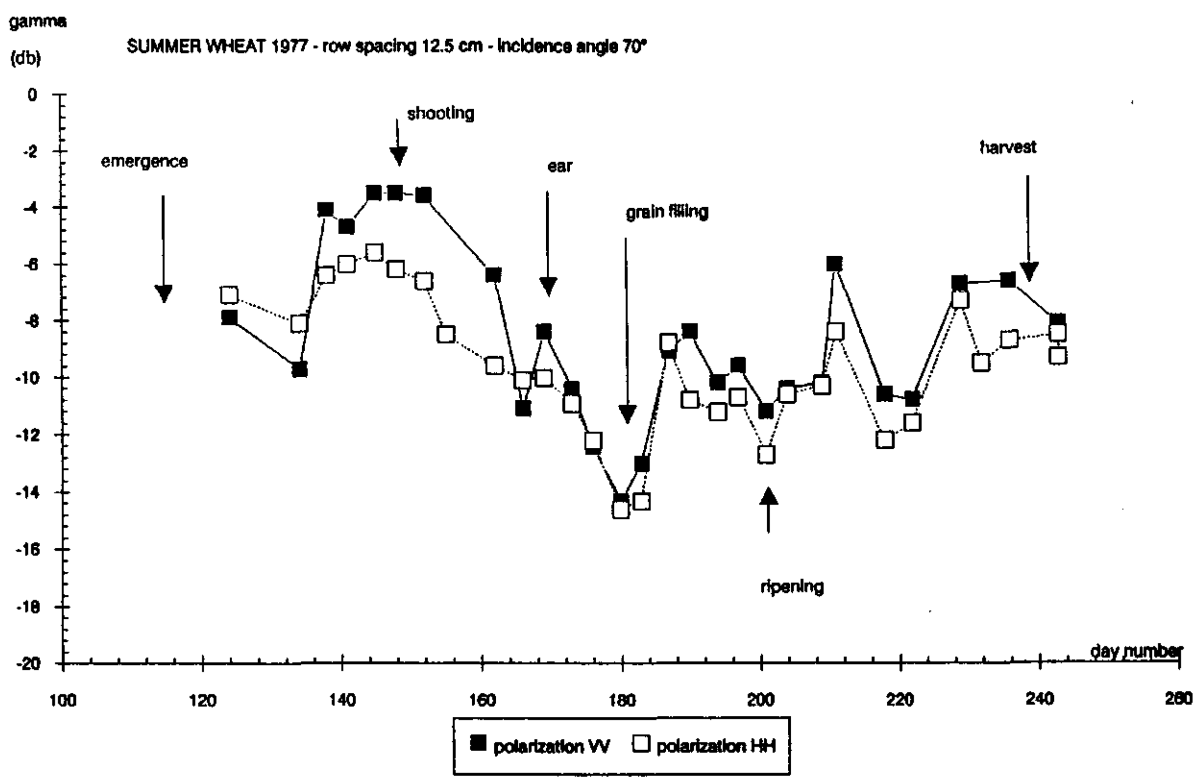


Figure 3.5.c: VV and HH radar backscatter at 70° incidence angle versus daynumber of wheat with row spacing 12.5 cm, summer wheat 1977, series 1.

These observations agree largely with the findings in literature. Allen and Ulaby (1984) reported the polarization dependency of the attenuation of microwaves by the stalks and heads of wheat. The attenuation was found to be larger at vertical than at horizontal polarization and this behaviour was more dynamic for wheat stalks than for wheat heads. They also concluded that the mechanism of attenuation is dominated by absorption and that scattering from the canopy elements plays a less important role. Lopez and Le-Toan (1985) also found that the attenuation was larger at VV than at HH polarization but at low angles of incidence the difference was larger for the heads of wheat than for the stalks. This agrees with our own observations in the example of field a. At medium and low angles of incidence the (negative) difference between the backscatter at VV and HH polarization is larger in the phase of generative growth than in the phase of vegetative growth. (The differences between the radar backscatter properties of the ears and those of the vegetative material are further elaborated in a special experiment described in chapter 6.) Lopez and Le-Toan also measured an increasing difference in the attenuation with increasing angle of incidence. This is contrary to our measurements where the (negative) difference in backscatter in the generative phase of the growing season decreases with increasing angle of incidence. At high angles of incidence the difference in backscatter even inverses, i.e. the backscatter at VV becomes higher than that at HH. A similar observation is made during the phase of vegetatitve growth before heading. The backscatter at VV polarization is about the same as that at HH at low angles of incidence. At medium and high angles of incidence the backscatter is higher at VV than at HH. These differences in results are attributed to the fact that the measurements of Le-Toan and Ulaby concerned the attenuation of microwaves in a crop canopy, while our own concerned the backscatter from

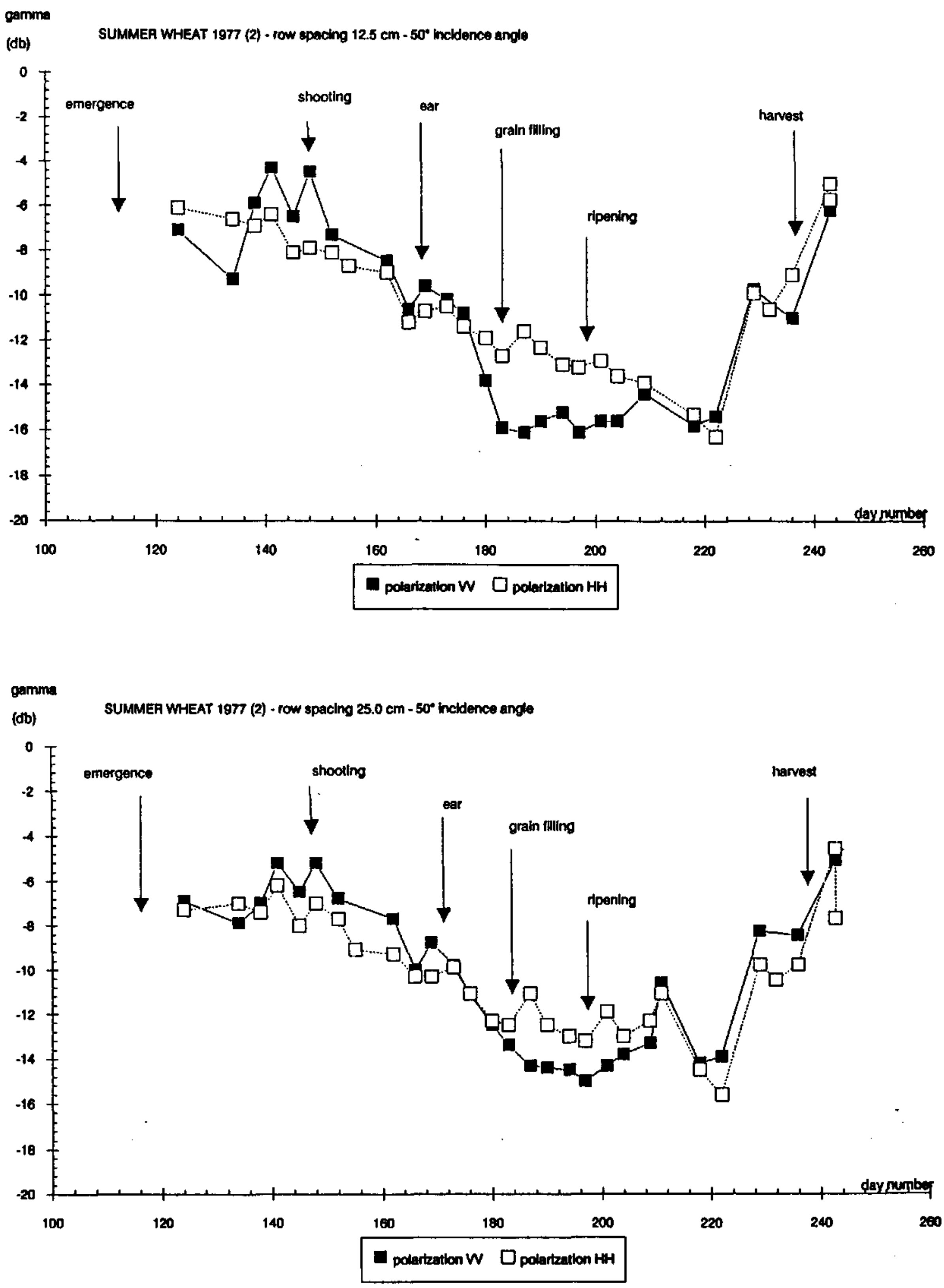


Figure 3.6: VV and HH radar backscatter at 50° incidence angle versus daynumber of wheat with row spacing 12.5 cm (3.6.a) and row spacing 25 cm (3.6.b), summer wheat 1977, series 2.

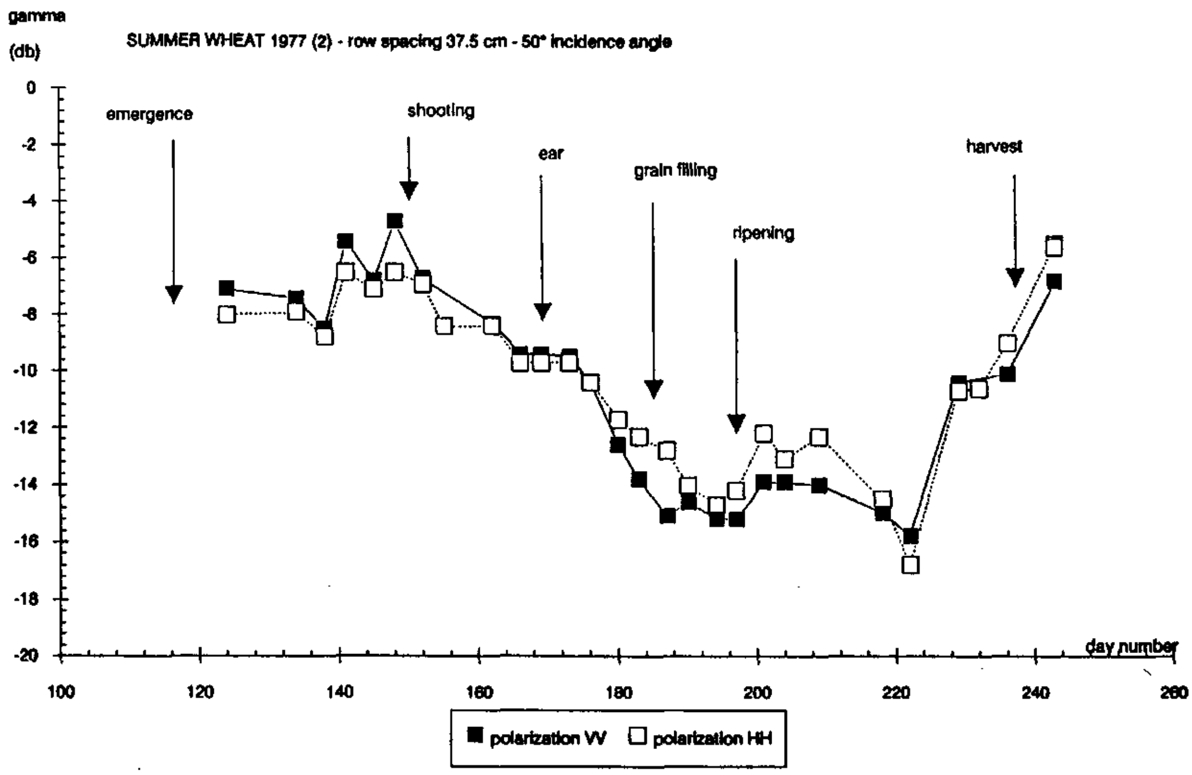


Figure 3.6.c: VV and HH radar backscatter at 50° incidence angle versus daynumber of wheat with row spacing 37.5 cm, summer wheat 1977, series 2.

canopies. It is suggested here that besides absorption, directed scattering from the canopy elements plays a considerable role in the attenuation of microwaves. An increase of extinction in the canopy with increasing angle of incidence can thus coincide with an increase in the radar scatter in backward direction. If the dominant mechanism of attenuation were only to be absorption, than an increase in extinction would always result in a decrease in the backscatter.

The typical features of the radar backscatter described above diminish in dynamics at low and medium angles of incidence when the row spacing becomes larger (figs. 3.6.a/c). The difference between the backscatter at VV and at HH is largest for field a and smallest for field c. At low angles of incidence, there is practically no difference between the backscatter at VV and HH during the vegetative phase for all fields. For field a there is a tendency for the backscatter at VV to be smaller by about 0.5 dB. During the phase of grain filling the difference becomes more prominent and it averages -2.2 dB for the fields a, -1.2 dB for the fields b and -0.7 dB for the fields c. At medium angles of incidence, the difference in both the vegetative and the generative phase (positive and negative respectively) is largest for field a and smallest for field c. The variation in the difference between the fields, however, is only small in the order of 1 dB and less. At high angles of incidence the differences in backscatter are unaffected by different row spacings. At 70° incidence angle the average difference between the backscatter at VV and at HH is in the order of +1 dB for all fields regardless of the row spacing.

The changes in backscatter at the two states of polarization, that occur at medium and low angles of incidence with changes in row spacing are the result of changes in the backscatter properties of the canopy. With small row spacing the ears and top leaves are relatively homogeneously distributed. Especially at low angles of incidence these elements form a closed layer in the top of the canopy. They impose thereby their characteristics on the backscatter properties of the canopy as a whole. At low angles of incidence these are the low level of backscatter and the negative difference between VV and HH polarization in the phase of generative growth. At medium angles of incidence the characteristics are the increase in backscatter at VV in the early stage of growth, the low level of backscatter during the generative phase, and the positive and negative difference between VV and HH during vegetative and generative growth respectively. When the row spacing gets larger the ears and top leaves are more clustered and they no longer form a closed layer in the top of the canopy. Between the rows, the microwaves penetrate deeper into the canopy and the characteristic backscatter properties of the ears and top leaves can be attenuated through multiple scattering within the canopy (volume scattering). Also, the contribution of the soil background to the total backscatter can increase. This effect is largest at low incidence angles and decreases with increasing angle of incidence. The effect of clustering of heads on the attenuation properties of wheat is also reported by Allen and Ulaby (1984). They found that the attenuation of microwaves in a wheat canopy was about twice as high at the places of clustering of the heads within the rows than at the places between the rows (60° incidence angle). When the angle of incidence becomes high, the field of view is dominated by the top elements in the canopy. The distribution of the elements no longer matters much and the differences between the fields with different row spacing disappears. The backscatter characteristics of the canopy at 70° incidence angle are the same for the fields a, b and c.

The explanation of 'clustering of the canopy elements' is largely hypothetical. This hypothesis is not tested with specific measurements and no supporting theoretical calculations are performed.

3.2 Barley

3.2.1 Crop growth and radar backscatter

Like for wheat, the growth of the crops with different row spacings is quite comparable. The differences in crop height and canopy biomass are negligeable. A maximum crop height of 105 cm is reached at the end of June (days 172-179) and a maximum canopy biomass of 1200 g/m^2 at the end of July (days 205-215). Again, the effect of row spacing is only notable to some extent on soil cover. In June (days 150-180) the cover of field a averages 94 %, that of field b 88 %, and that of field c 83 %.

At low and medium angles of incidence, the general pattern of the backscatter of barley ressembles that of wheat (figs. 3.7.a/c). In these figures the backscatter is plotted for the same state of polarization and angles of incidence as in figures 3.4.a/c. At 20° incidence, the notable differences with the curves of wheat are: the larger spread between the curves, the lower backscatter during the period of grain filling (compare also tables 3.1 and 3.2), and the peak of field a and b between days 180-200. At 50° incidence, they are: the larger spread between the curves, the faster decrease of the curves at stem elongation, the lower backscatter during grain filling, and the increase in the curves between days 180-200. At high angles of incidence, the curves of barley no longer ressemble those of the wheat plots. Striking are: the dip in the backscatter on day 166 during the period of stem elongation and the large increase in the backscatter on day 186. The differences between the backscatter of wheat and barley are, however, not the topic of discussion here (some discussion is presented further on in this paragraph and in paragraph 6.2).

The effect of row spacing on the backscatter is similar to, but more pronounced than that of wheat. Table 3.2 summarizes some average backscatter values during the periods of the most pronounced features in the backscatter curves.

Table 3.2: average (VV) radar backscatter over two periods with the most pronounced features of the radar backscatter of barley, days 140-150 and days 170-180, 1977.

	vegetative phase days 140-150			generative phase days 170-180		
angle:	20	50	70	20	50	70
field a	-9.7	-6.4	-5.4	-16.4	-17.6	-13.8
b	-8.9	-6.6	-5.6	-14.0	-16.9	-14.1
c	-7.8	-6.9	-6.7	-10.1	-14.9	-14.1

At low angles of incidence the radar backscatter is lower for field a than for field c during the whole growing season. In the vegetative period of growth this difference is about 2 dB and in the generative period it amounts to 6.5 dB. The influence of the soil background between days 195-200 is notable for all three fields. At medium angles of incidence the effect of row spacing is only noticed during the vegetative period of growth. The backscatter of field a is about 3 dB lower than that of field c. The influence of the soil background between days 195-220 is only notable for the fields b and c. The canopy of the crop on field a is too closed to allow for a large contribution of the soil background. At high angles of incidence an effect of row spacing is only present during the vegetative period of growth, i.e. the radar backscatter of field a is about 1.5 dB higher than that of field c.

A remarkable feature in the backscatter curves occurs in the grain filling period of growth. Between day 182 and day 186 the backscatter at VV suddenly increases at all angles of incidence for nearly all three fields. In this period the stems of the heads are bent and the heads lie almost horizontally in the top of the canopy. On day 182 the heads are generally directed towards the radar because of the predominant wind direction. On day 186 the direction of the heads is reversed and they generally point away from the radar. The effect of this reversal is an increase in backscatter at VV polarization. This increase is largest at high angles of incidence, i.e. about 7-9 dB. At these angles of incidence, no difference is present between the plots with different row spacing. Again, this could be caused by the fact that at high angles of incidence, the heads dominate the field of view and the spatial distribution of the heads is relatively unimportant. At medium angles of incidence an increase occurs also for the fields a and b with 5-7 dB. The backscatter of field c only rises with about 1 dB which could again be explained by the clustering effect of the heads. The 'headless' space between the rows attenuates the backscatter properties of the heads within the rows. At low angles of incidence the

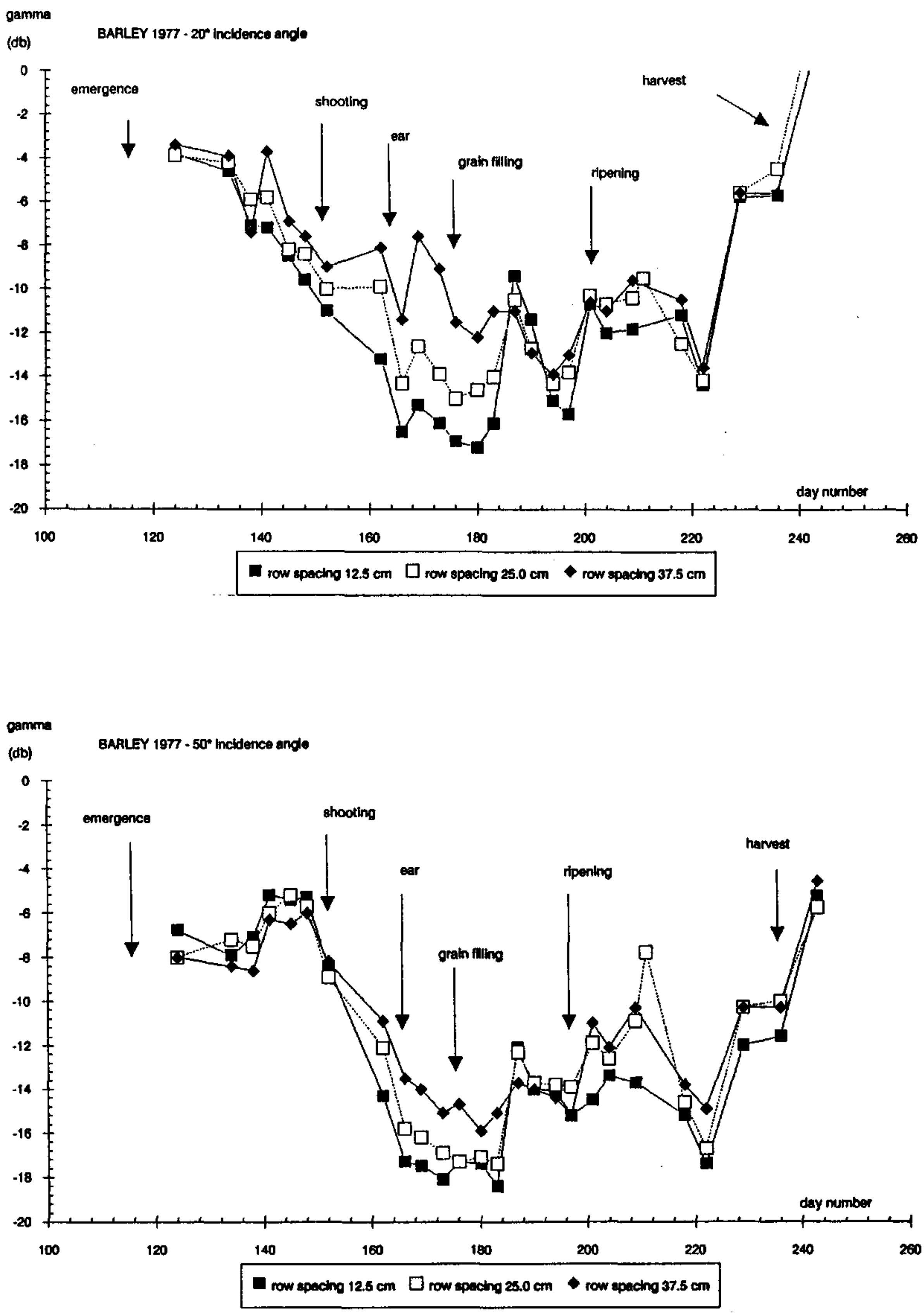


Figure 3.7: VV radar backscatter at 20° (3.7.a) and 50° (3.7.b) incidence angle versus daynumber of three barley crops, 1977.

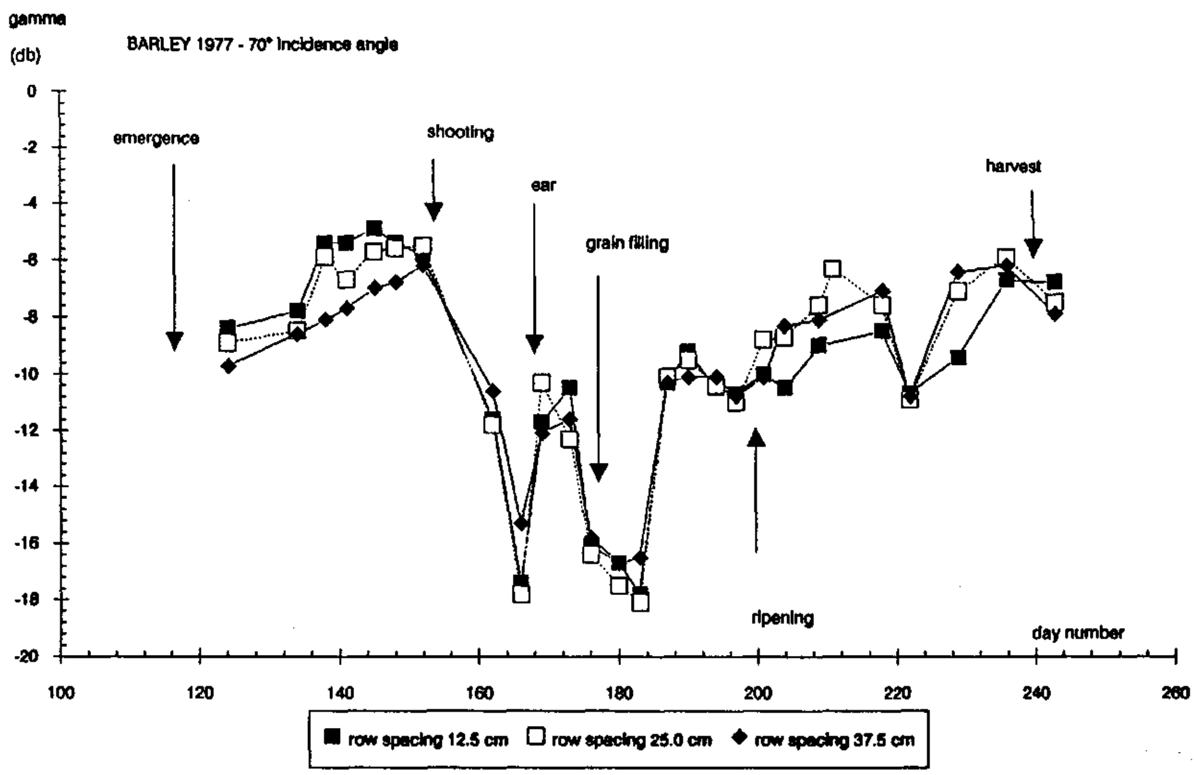


Figure 3.7.c: VV radar backscatter at 70° incidence angle versus daynumber of three barley crops, 1977.

backscatter rises with about 5 dB for field a, with 3 dB for field b and even decreases for field c. The azimuthal direction of the horizontal heads has less influence on the backscatter at low angles of incidence than at high angles of incidence. The impact of the orientation of the heads emphasizes their dominant role on the total backscatter (at VV polarization) of the crop.

A similar, though less dynamic effect of the orientation of the ears on the backscatter of wheat is only observed at high angles of incidence. No effect is present at medium and low angles. Contrary to the change in backscatter of barley, the change for wheat varies already at high angles of incidence with the row spacing of the crop: +3.1, +2.2 and +0.9 dB with respectively 12.5, 25 and 37.5 cm row spacing at VV polarization and at 70° incidence angle. The different behaviour between the backscatter of wheat and that of barley might be attributed to the large awns on the ears of barley, and to the larger sensitivity of barley to wind. Awns may have a large impact on the scatter properties of the crop while the smaller sensitivity of wheat to wind renders this crop more rigid.

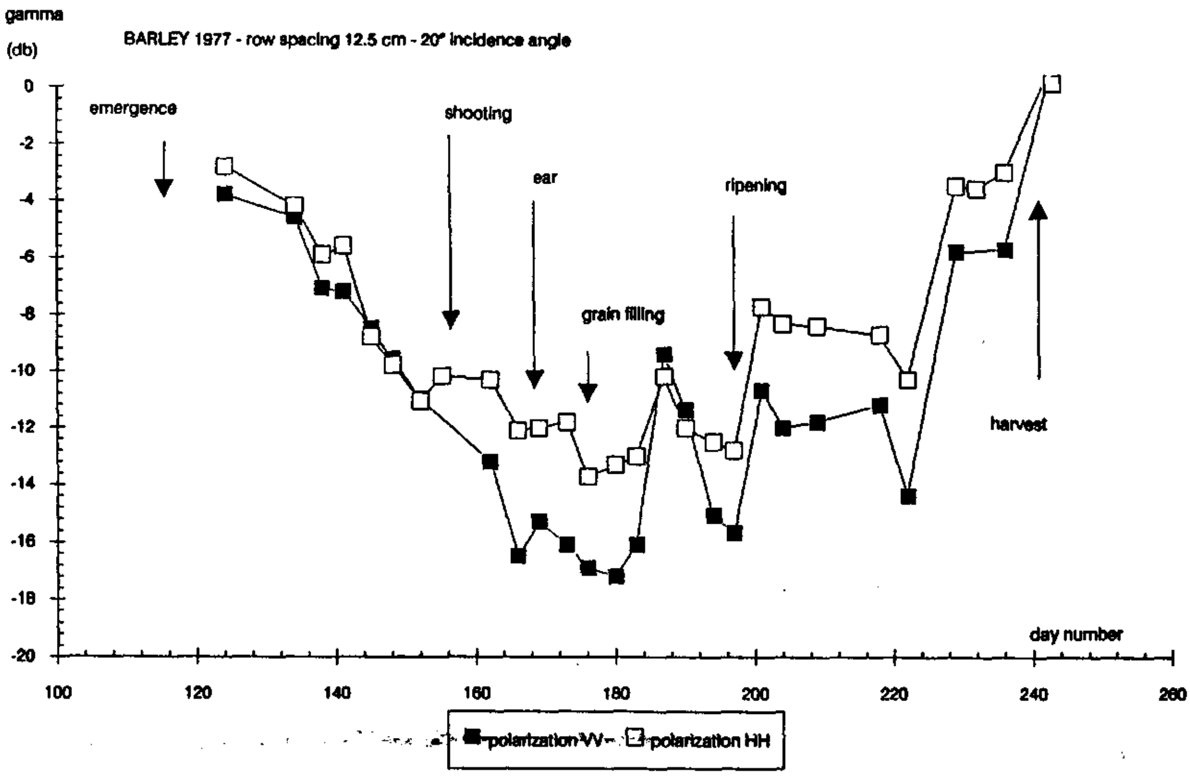
3.2.2 The backscatter at VV and HH polarization

The effect of row spacing on the relation between the backscatter at VV and HH polarization is also similar to that of wheat (figs. 3.8.a/c and 3.9.a/c). In these figures, the backscatter at VV and HH is plotted for field a and field c respectively at all three angles of incidence to complement the figure 3.6 of wheat (which gives the backscatter at VV and HH at only 50° incidence). At <u>low to medium</u> angles of incidence the discrepancy between VV and HH increases with smaller row spacing. At 20°

incidence angle the difference between VV and HH is only about -0.5 dB for field c while for field a this difference is about -3 to -5 dB for the largest part of the growing season. At high angles of incidence the difference in backscatter is comparable for all fields. The backscatter continuously changes in relative magnitude between VV and HH by 0.5 to 3 dB at 70° incidence angle.

The effect of the change in azimuthal orientation of the heads on day 182 on the radar backscatter differs for the two states of polarization. At low angles of incidence the backscatter rises 5 dB at VV and 2 dB at HH for field a, while no significant change occurs at either state of polarization for field c. At medium angles of incidence the backscatter rises with 6 dB at VV and with 3.5 dB at HH for field a, and with 1 dB at both states of polarization for field c. At high angles of incidence the backscatter at VV sharply rises while at HH no effect is notable. This pattern is the same for field a and field c, the spatial distribution of the heads being relatively unimportant.

Summarizing, the influence of the orientation of the heads is mostly felt at VV polarization and at high angles of incidence. With a close row spacing (field a) the influence is also present at low angles of incidence. At HH polarization the influence is absent at high angles of incidence and becomes notable at lower angels of incidence with a close row spacing. The difference between the backscatter at VV and HH polarization is also remarkable during the period of ripening in which the moisture content of the underlying soil is high (days 195-220). At 70° incidence angle the backscatter at VV is already high because of the orientation of the heads, while that at HH is still relatively low. With the increase in moisture content of the underlying soil the backscatter at VV remains unaffected while that at HH increases with 6-7 dB. This rise occurs for all three fields. Despite the high angle of incidence, and for field a despite the close row spacing, the influence of the soil background is still large at HH polarization! At medium angles of incidence the effect depends on the row spacing of the field. For field c with the open canopy structure, the backscatter increases similarly at both states of polarization. For field a with the closed canopy structure, the backscatter increases again only at HH (5 dB) while it remains practically unaffected at VV (0.5-1 dB). These observations point again to the conclusion that the polarization-dependent attenuation of microwaves is not only caused by the process of absorption but also by directed scattering at the top of the canopy. At medium to high angles of incidence the microwaves are more attenuated in the canopy at VV than at HH polarization (see also Lopez and leToan, 1985). Therefore the influence of the soil background at high moisture contents, days 195-220, is more notable at HH than at VV polarization. With increasing soil moisture content the backscatter at HH increases while that at VV remains unaffected for relatively closed crop canopies. At low moisture contents, before day 195, the backscatter at VV is larger than at HH because of the orientation of the heads. Since the attenuation of microwaves at VV is also larger, this means that the attenuation is not only caused by selective absorption but also by directed scattering from the heads.



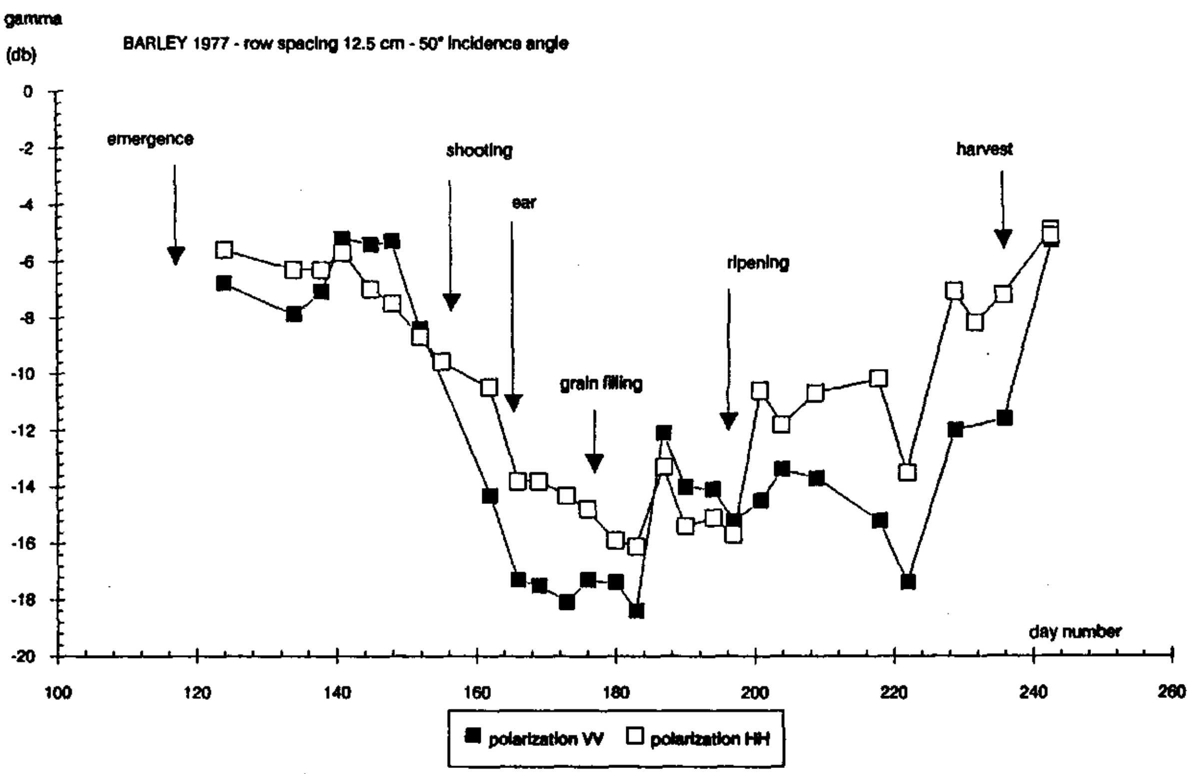


Figure 3.8: VV and HH radar backscatter at 20° (3.8.a) and 50° (3.8.b) incidence angle versus daynumber of barley with 12.5 cm row spacing, 1977.

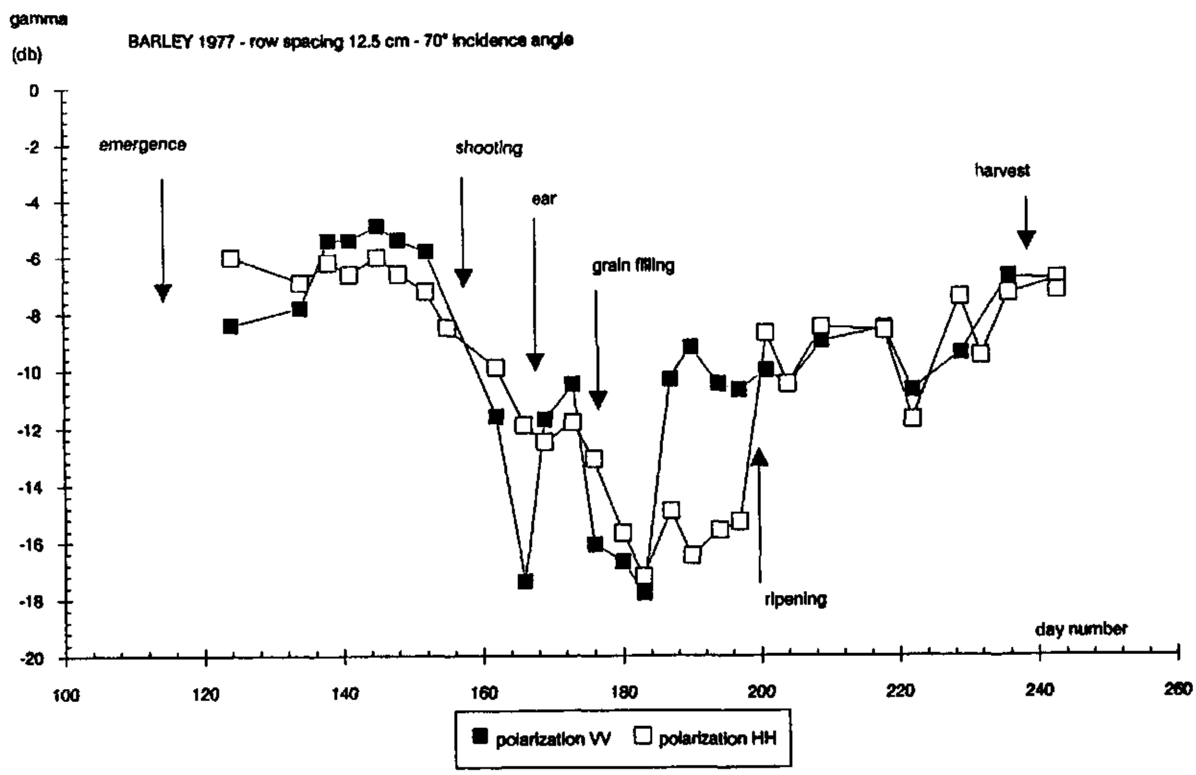


Figure 3.8.c: VV and HH radar backscatter at 70° incidence angle versus daynumber of barley with 12.5 cm row spacing, 1977.

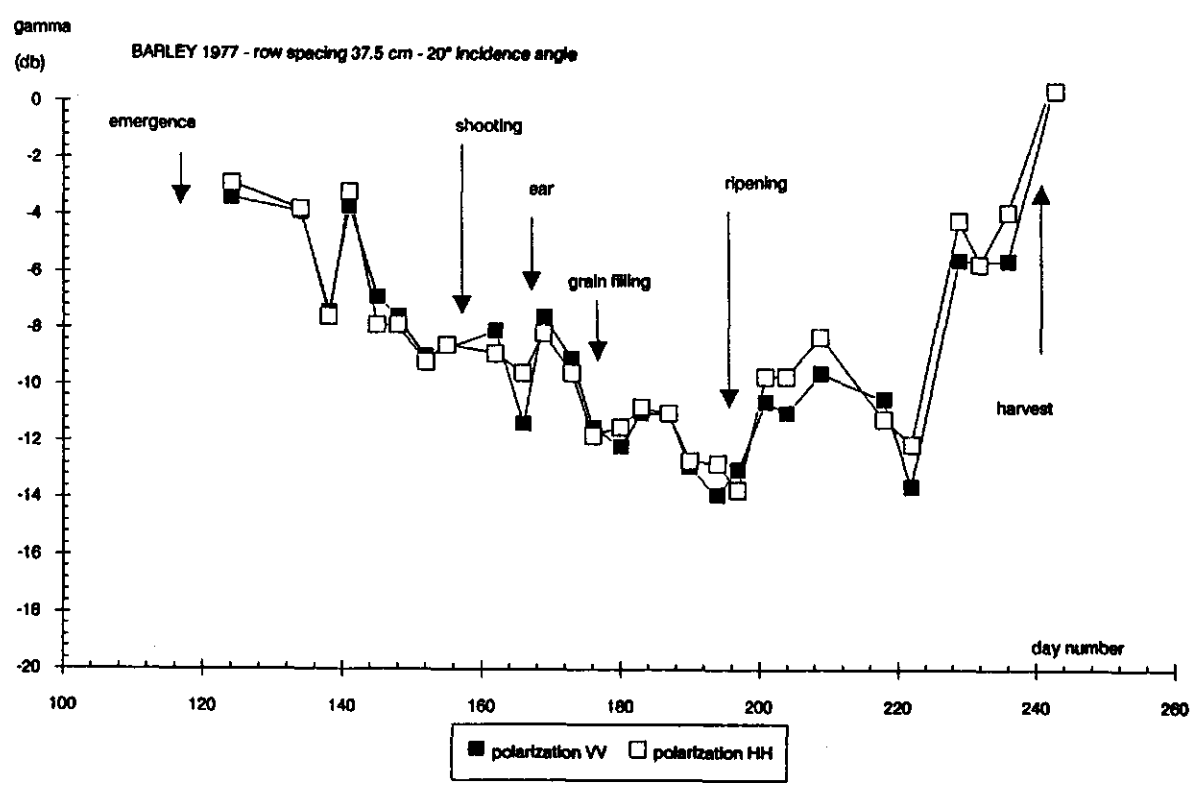
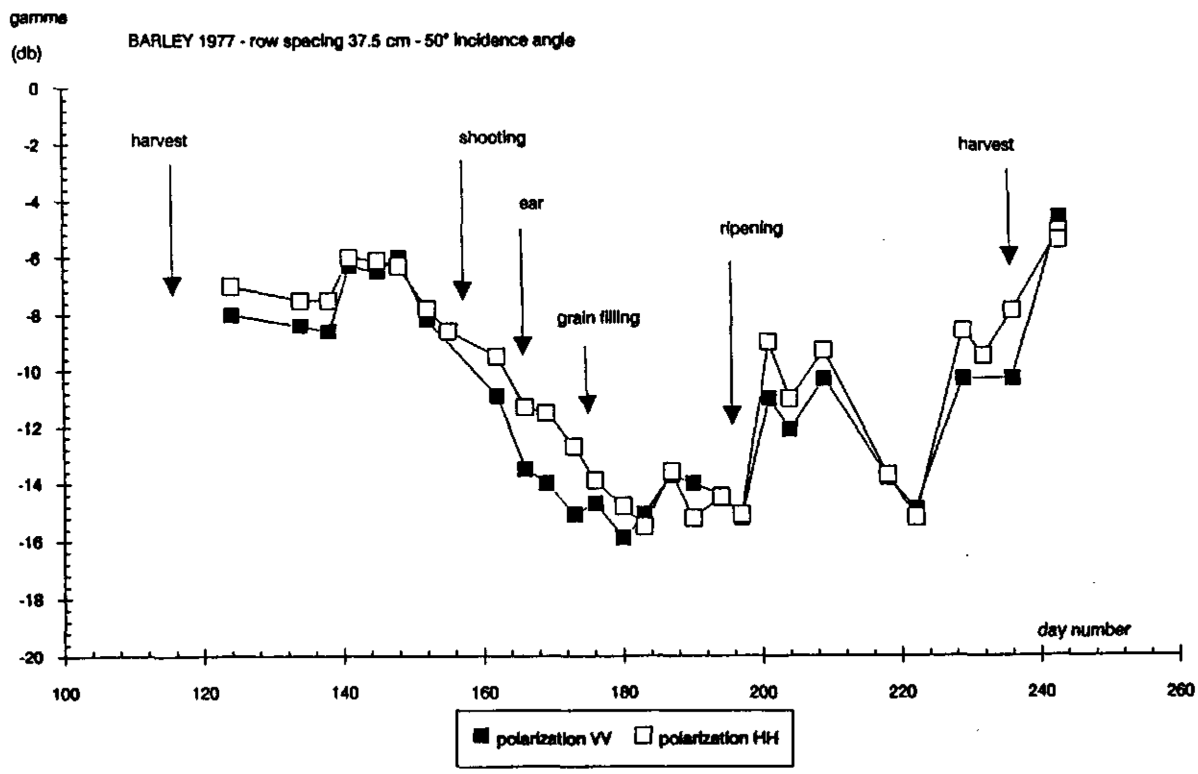


Figure 3.9.a: VV and HH radar backscatter at 20° incidence angle versus daynumber of barley with 37.5 cm row spacing, 1977.



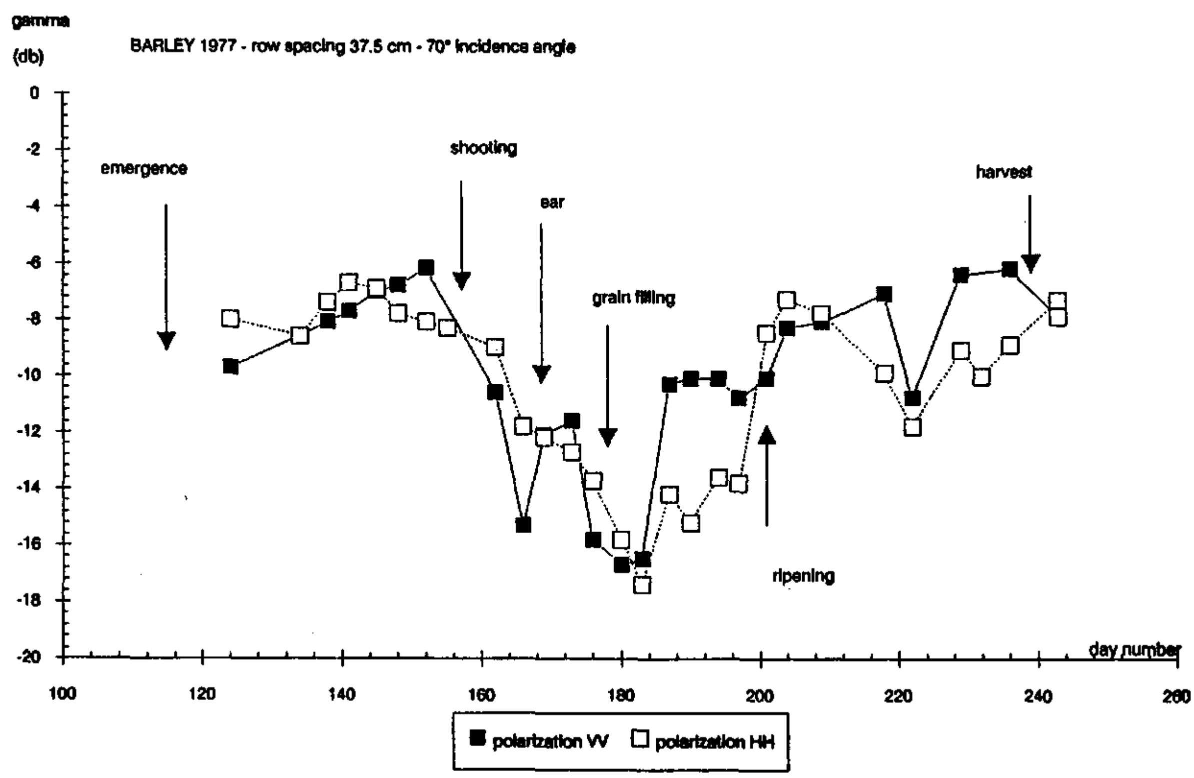


Figure 3.9: VV and HH radar backscatter at 50° (3.9.b) and 70° (3.9.c) incidence angle versus daynumber of barley with 37.5 cm row spacing, 1977.

3.3 Summary

The effect of row spacing on the radar backscatter from wheat and barley depends on the angle of incidence. The effects are the result of changes in the attenuation and scatter properties of the canopy, and of the consequent changes in contribution from the soil background. In general, a close row spacing results in an enhancement of the typical features of the backscatter curve. For example, at low and medium angles of incidence, the backscatter is lower during the phases of grain filling and ripening. At high angles of incidence, the backscatter is generally higher during the vegetative period of growth. These effects are larger for barley than for wheat. For barley, the difference between the radar backscatter (VV) at 20° incidence angle from a crop with 12.5 cm row spacing and from a crop with 37.5 cm row spacing varies between 1 and 6 dB. For wheat, this difference varies between 1 and 4 dB. At medium and high angles of incidence, the differences are generally no more than 2-3 dB.

The effect of the row spacing on the difference between the backscatter at VV and HH polarization is largest at low angles of incidence. With a close row spacing of 12.5 cm, the difference in backscatter between VV and HH from barley in the period of grain filling is relatively large with about -4 dB. With a wide row spacing of 37.5 cm, this difference is reduced to practically 0 dB. For wheat, the differences are smaller and average -2.2 dB with 12.5 cm row spacing and -0.7 dB with 37.5 cm row spacing. At high angles of incidence, the differences in backscatter are unaffected by variations in row spacing. At low to medium angles of incidence, the backscatter at VV polarization is more affected by row spacing than the backscatter at HH.

The azimuthal direction of ears can influence the radar backscatter of barley. At high angles of incidence, the influence is largest (7-9 dB difference with a reversal in orientation of the ears) and independent of the row spacing of the crop. At medium and low angles of incidence, the influence is less and depends on the row spacing of the crop. With a close row spacing of 12.5 cm, the influence is still present (5-7 dB) at low angles of incidence. With a row spacing of 37.5 cm, no effect of a reversal in orientation of the ears is notable at low angles of incidence.

In general, the backscatter of wheat and barley is most sensitive to changes in the orientation of the canopy elements at high angles of incidence.

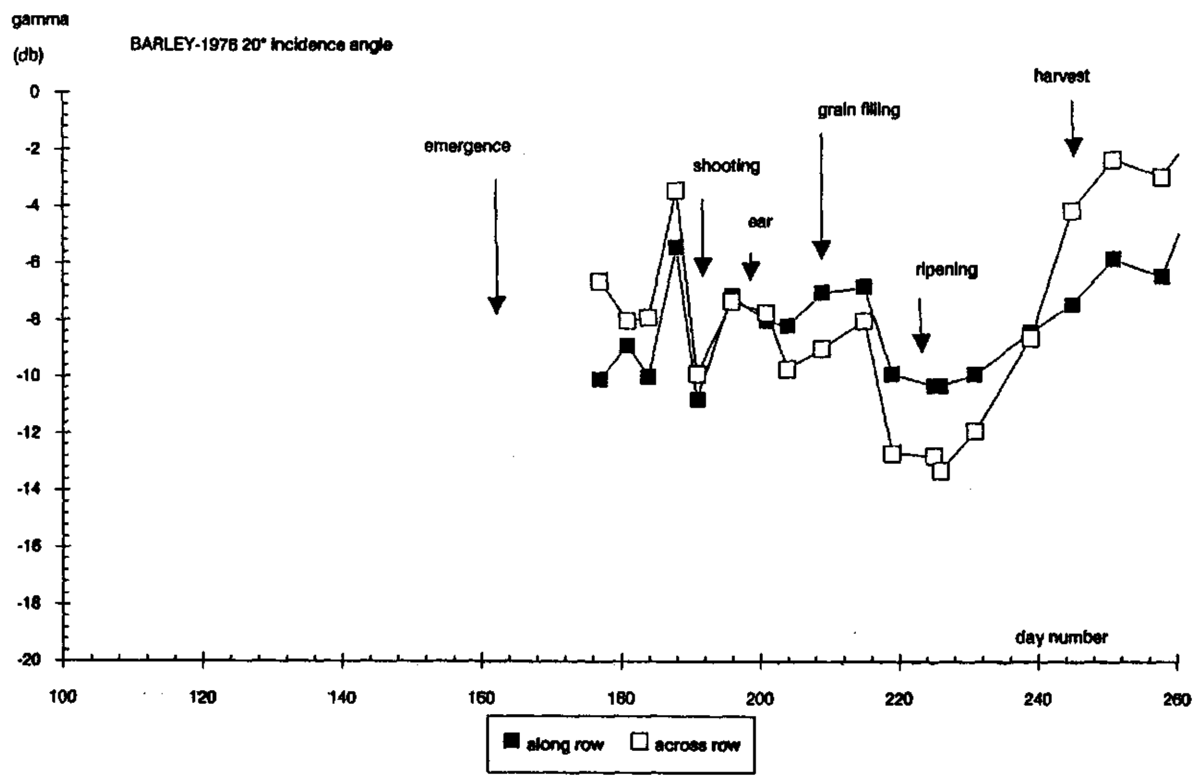
4 Row direction

The effect of row direction on the radar backscatter is studied in an experiment in 1976 and in 1981. In 1976, barley was sown on two neighbouring plots with a row distance of 20 cm. On one plot the radar beam was directed parallel to the row direction (along row) and on the other perpendicular (across row). In ground-truth sampling no differentiation was made between the two plots and they are treated as one. The crops were sown late in the season, in the midst of June, day 165, after a failing oats crop. Therefore leafiness and yield were quite low. The soil cover only reached 60%, the amount of plant water 1200 g/m^2 (versus 2200-2700 g/m^2 in normal years) and the yield 500 g/m^2 (versus 1000-1200 g/m^2 in normal years). The height of the crop remained also relatively low with only 70 cm (versus 105 cm in an average year).

In 1981, the winter wheat Arminda was sown on two neighbouring plots with a row distance of 18.8 cm. On one plot the radar beam was again directed parallel to the row direction and on the other perpendicular. This year the period of radar observation was relatively short. It started at half May, day 138, and ended already at the beginning of July, day 184. Therefore only the first half of the growing season from tillering to ear-filling can be studied. On both plots the soil cover remained quite low, 70%, and the crop height attained 100 cm. During the last measurements in June, differentiation took place between the two crops with regard to fresh weight. The crop with the perpendicular row direction attained a fresh weight of 4224 g/m^2 and the crop with the parallel row direction of 3306 g/m^2.

The backscatter of the barley plots in 1976 is given in figs. 4.1.a/c for VV polarization and for the three angles of incidence 20°, 50° and 70°. Because of the bad crop growth, the typical backscatter features of barley are only present in a limited degree at medium angles of incidence. Here, the backscatter decreases some 5 dB during the phase of shooting and ear formation. During grain filling and ripening the backscatter remains quite stable. Harvest is only recognised at both states of polarization after day 260 when the stubble-field is rotavated. The typical negative VV-HH backscatter difference vanishes and the backscatter becomes the same at both states of polarization.

The general pattern of the radar backscatter is similar for both crops, with some differences at low angles of incidence. At 20° incidence angle the (VV) backscatter of the perpendicular-row crop is initially higher than that of the parallel-row crop. Between shooting and ripening it decreases faster and reaches a minimum that is about 2.5 dB lower (than that of the parallel-row crop). During ripening the backscatter increases again faster and is some 3 dB higher just before harvest. At HH polarization these features are the same, though a little less pronounced. At 50° incidence angle, the differences have nearly disappeared. At both states of polarization, the backscatter of the perpendicular-row crop is on the average 0.7 dB lower than that of the parallel-row crop until the phase of ripening. After ripening the backscatter is about 0.5 dB higher. At 70° incidence there are hardly any differences. At VV polarization, the backscatter of the perpendicular-row crop is 0.5-1 dB higher than that of the parallel-row crop at only four out of the 20 measurements. At HH, the backscatter of the perpendicular-row crop is on the average 0.3 dB lower throughout the growing season.



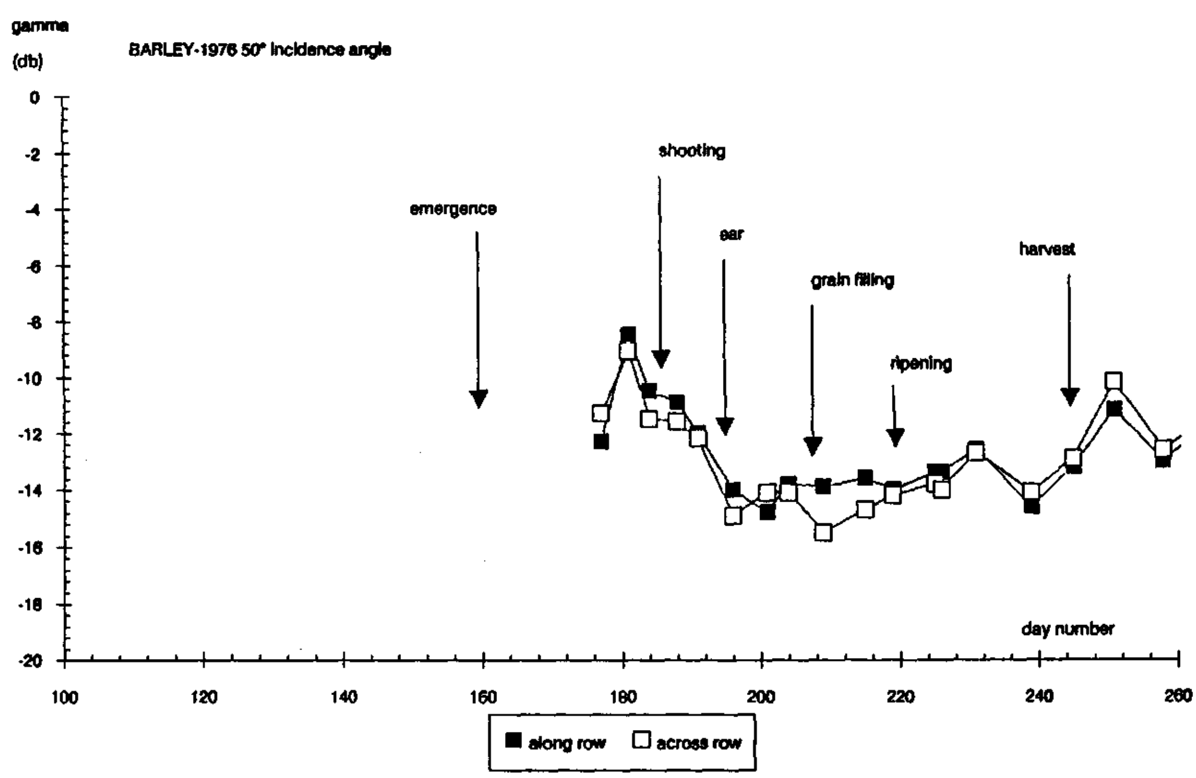


Figure 4.1: VV radar backscatter at 20° (4.1.a) and 50° (4.1.b) incidence angle of barley with row directions along and across the radar beam, 1976.

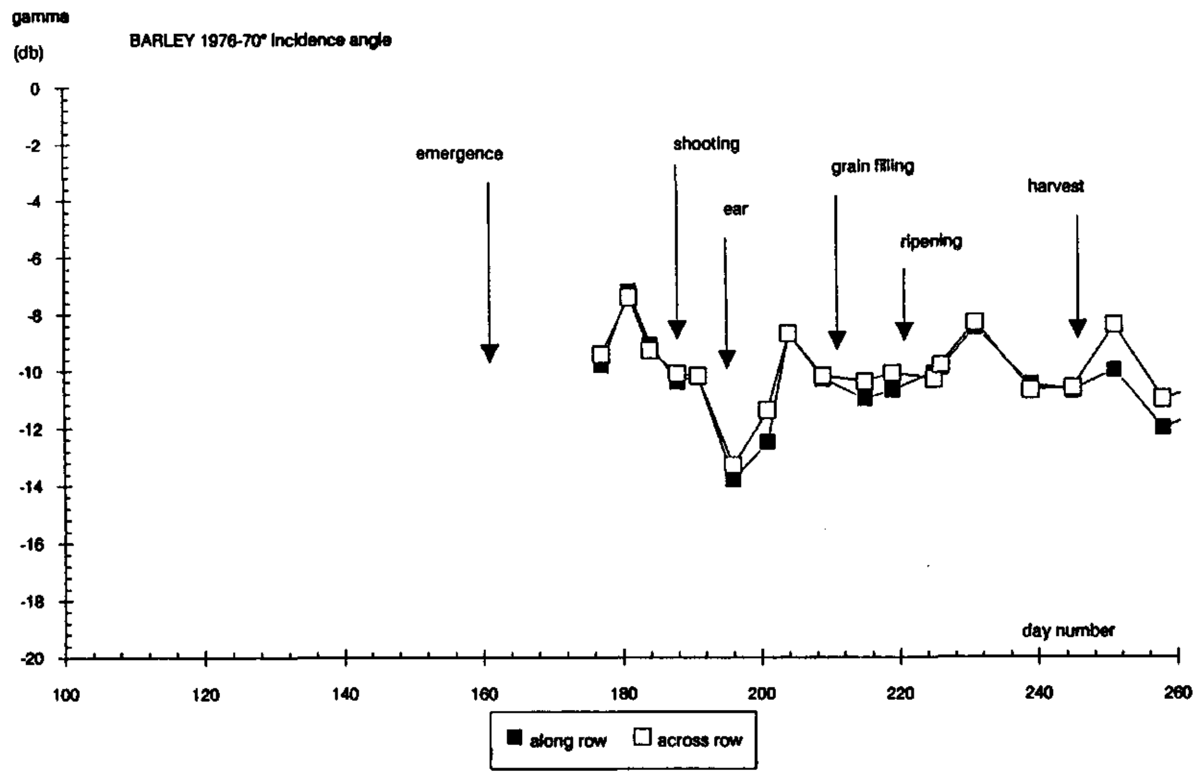


Figure 4.1.c: VV radar backscatter at 70° incidence angle of barley with row directions along and across the radar beam, 1976.

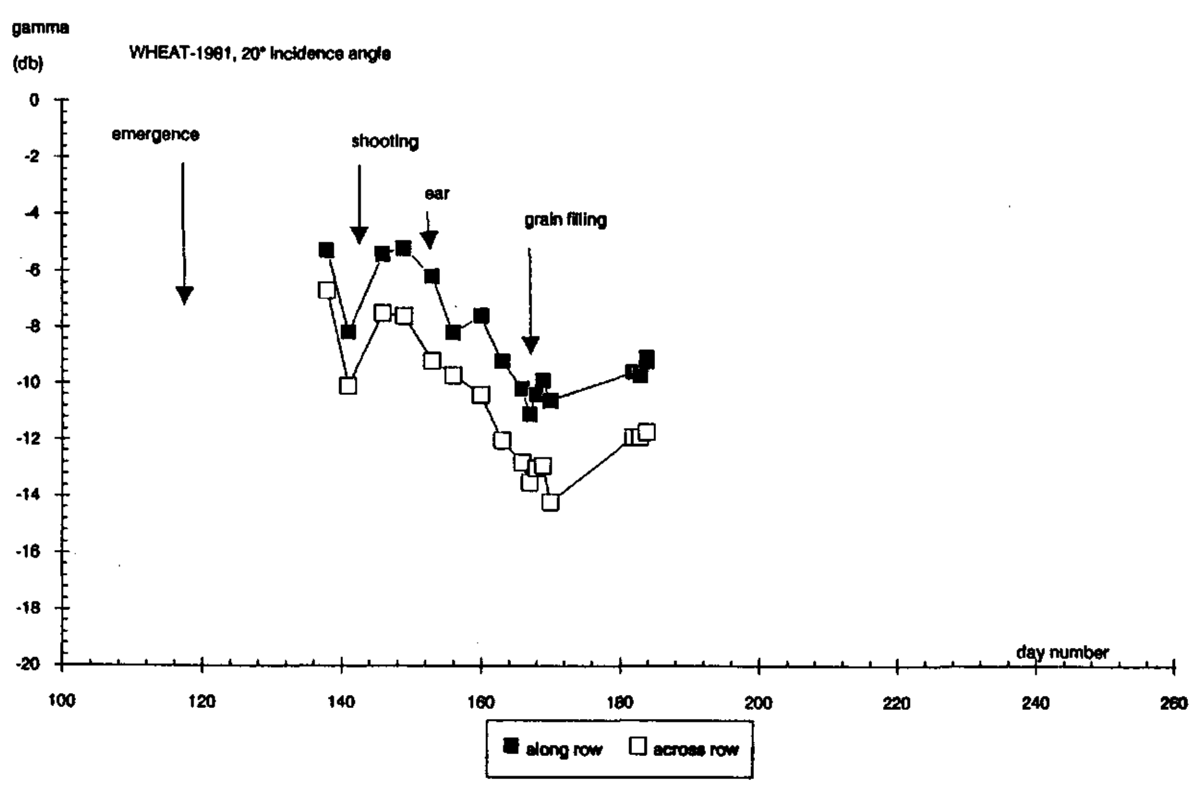
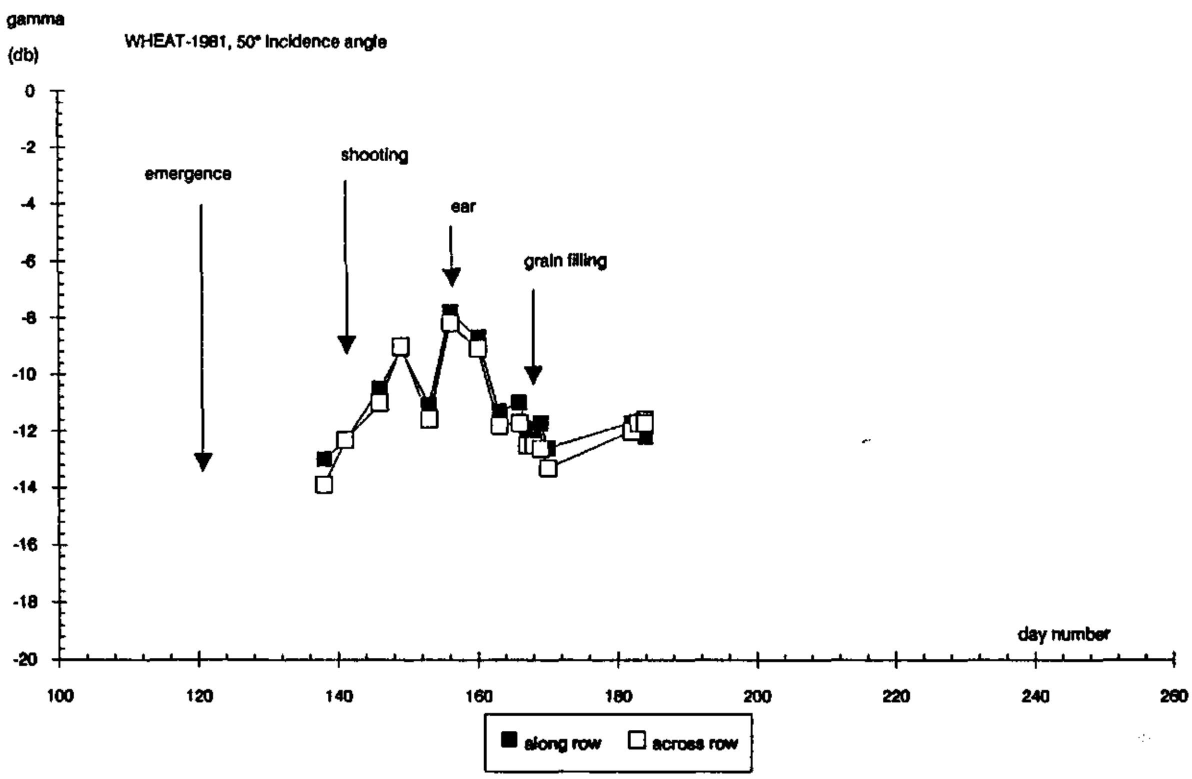


Figure 4.2.a: VV radar backscatter at 20° incidence angle of winter wheat Arminda with row directions along and across the radar beam, 1981.



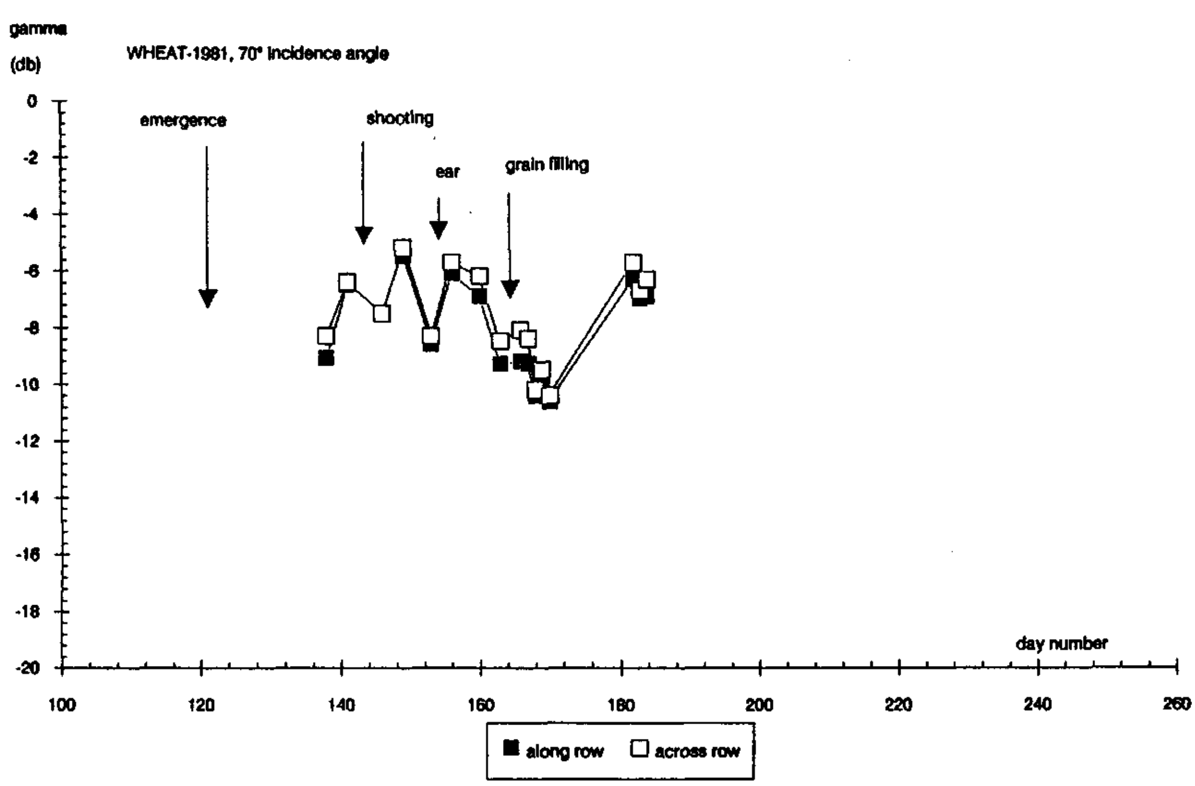


Figure 4.2: VV radar backscatter at 50° (4.2.b) and 70° (4.2.c) incidence angle of winter wheat Arminda with row directions along and across the radar beam, 1981.

The VV backscatter of the wheat crops in 1981 is given in figs. 4.2.a/c for the three angles of incidence. The shape of the curves is nearly identical for both plots al all angles of incidence. Only at low angles of incidence a consistant difference between the backscatter of both plots is observed. The backscatter of the perpendicular-row crop is continuously some 2.5 dB lower than that of the parallel-row crop. At HH polarization the differentiation is less pronounced with only 0.5-1.5 dB. At medium and high angles of incidence there is practically no difference in backscatter. At 50° incidence the (VV) backscatter of the perpendicular-row crop is on the average 0.3 dB lower. On the other hand, at HH polarization it is on the average 0.3 dB higher. At 70° incidence angle the backscatter of the perpendicular-row crop is about 0.3 dB higher at both states of polarization.

Summarizing, the influence of the direction of the rows in these experiments is generally small to non-existent, and inconsistent. At low angles of incidence the differences between the perpendicular-row crops and the parallel-row crops are relatively mosst pronounced. The backscatter from the perpendicular-row crops is about 2.5 dB lower at VV polarization. At HH polarization the differences are a liitle smaller, 1-2.5 dB, and not consistent between the two experiments. Because of the different behaviour of the backscatter at VV and at HH polarization, the VV-HH backscatter difference is more pronounced for the perpendicular-row crops than for the parallel-row crops. At medium and high angles of incidence, there are practically no differences in radar backscatter (on the average 0.3-0.7 dB only).

The absence of a (consistent) influence of the direction of the rows at medium and high angles of incidence is especially striking in the early period of the growing season. The field of view of the radar beam perpendicular to the direction of the rows is in this period dominated by the crop. On the contrary, the field of view parallel to the row direction still includes a large fraction of bare soil. Apparantly, this makes no difference to the radar at high angles of incidence. The backscatter properties of the stems, which protrude above the soil surface, dominate the total radar backscatter without regard to their physical distribution in the field. This observation is to some extent in contradiction with some of the effects of row spacing described in chapter 3. At high angles of incidence, there is a consistent difference between the backscatter from a crop with a close row spacing and that from a crop with a wide row spacing during the early period of vegetative growth. However, these differences already disappear for the rest of the growing season after the phase of stem elongation.

The observed differences at the low angle of incidence are also striking. With lower angles of incidence, the field of view at perpendicular and at parallel beam direction becomes similar and ultimately the same. Therefore, any difference between the radar backscatter from the fields with different row directions, would be expected to decrease with lower angles of incidence instead of to increase. This relative large influence of the direction of the rows agrees with some observations in the row direction experiment (chapter 3). Contrary to the radar backscatter at high angles of incidence, the backscatter at low angles of incidence is affected by the distribution of the stems and ears in the field.

The measurements of the radar backscatter at the two beam directions are not made on the same crop but on neighbouring fields. Therefore, care must be taken with the interpretation of the results. Especially at low angles of incidence, the observed differences in radar backscatter might derive from other differences in the plots than only from the direction of the rows. Because of the low soil cover of the crop in both 1976 and 1981, the influence of the soil background can be considerable. Differences might then be the result of differences in soil surface roughness between the plots. Such differences could be caused by different directions in the sowing of the seed.

5 Crop variety

5.1 Crops in 1979

5.1.1 Crop characteristics

Three different wheat varieties were studied in 1979, i.e. two varieties of winter wheat, Arminda and Okapi, and one summer wheat variety Adonis. The winter wheats were already sown in October 1978, day 293, and the summer wheat was sown in April 1979, day 102. Therefore, at the start of the growing season the winter wheats had a small advance in growth and development over the summer wheat. The soil cover on day 130 was four to eight times larger for respectively Arminda and Okapi than for Adonis; the crop height three to five times and the biomass about 50 times for both winter wheat varieties. In the course of the growing season the growth in dry matter was comparable between Arminda and Okapi. The dry biomass of Adonis was initially smaller than that of the winter wheats, but at the end of the growing season the growth continued longer. At harvest the crops had about the same dry biomass, ≈ 1400 g/m^2. Table 5.1 summarizes some average crop parameters over the period of generative growth from grain filling to ripening.

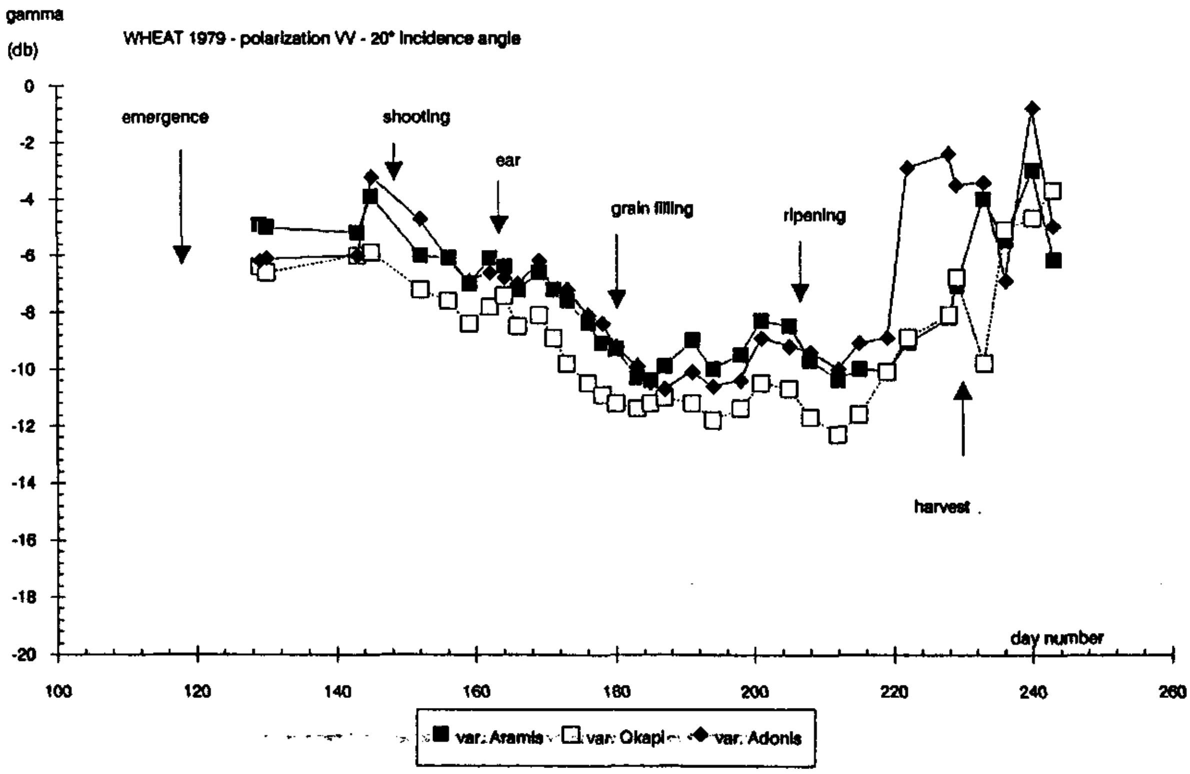
Table 5.1: Average crop parameters over the period of generative growth from grain filling to ripening (day 180-200), wheat 1979.

variety	height (cm)	soil cover (%)	fresh weight (g/m^2)	fresh density (g/m^3)
Arminda	95	80	4061	4275
Okapi	103	95	3759	3650
Adonis	102	92	3837	3762

Arminda was a relatively low, dense crop with a low soil cover. The canopy appeared quite open with a distinct row structure and the presence of some spots of bare field. Since the fresh density was relatively high, this means that the crop was very dense within the rows and open between the rows. Okapi on the other hand was a little bit taller, thin crop with a higher optical soil cover. The structure of the canopy was quite closed and the row structure disappeared during the growing season. The summer wheat Adonis ressembled Okapi in all parameters. The canopy of the crop, however, was relatively open and the structure of the rows remained discernable throughout the growing season.

5.1.2 Radar backscatter

The general trend of the radar backscatter is for all three varieties the same as that described in chapter 2. The differences in radar backscatter of the three varieties are not very large and they generally vary between 0.5 and 2 dB depending on the angle of incidence. Figs. 5.1.a/c give the VV backscatter of the crops at 20°, 50° and 70° incidence angle.



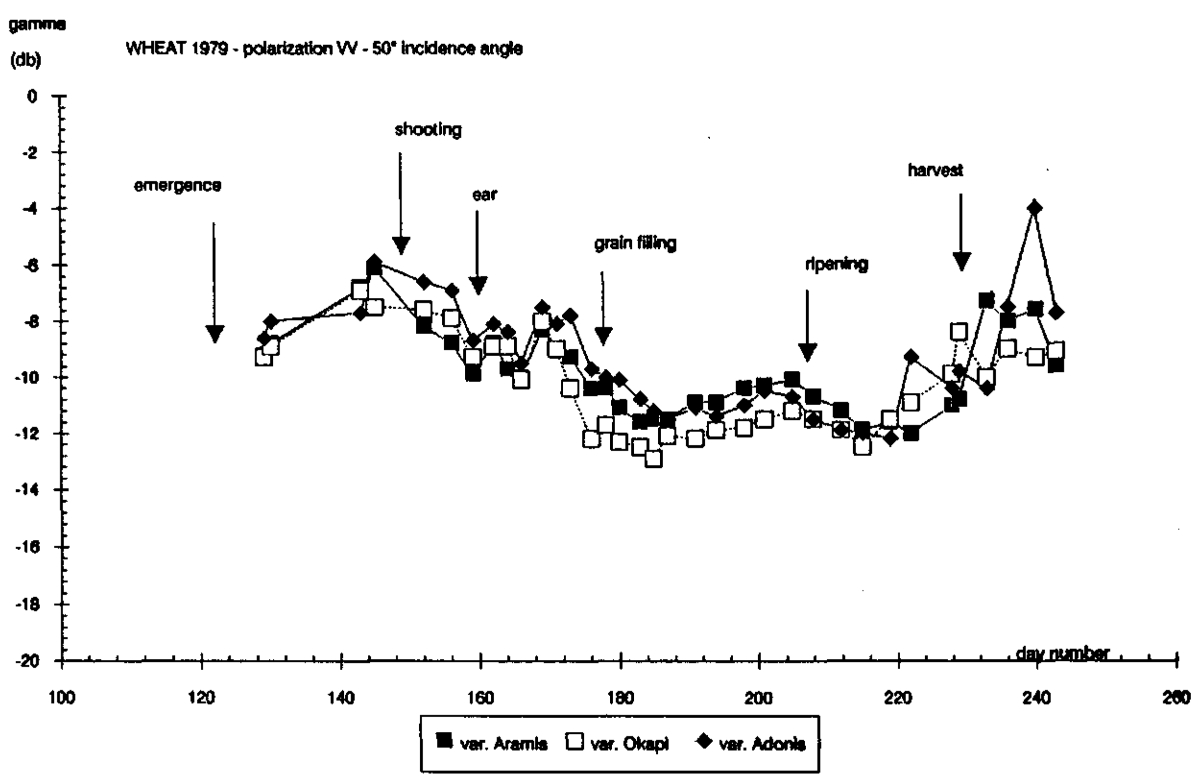


Figure 5.1: VV radar backscatter at 20° (5.1.a) and 50° (5.1.b) incidence angle of three wheat varieties Arminda, Okapi and Adonis, 1979.

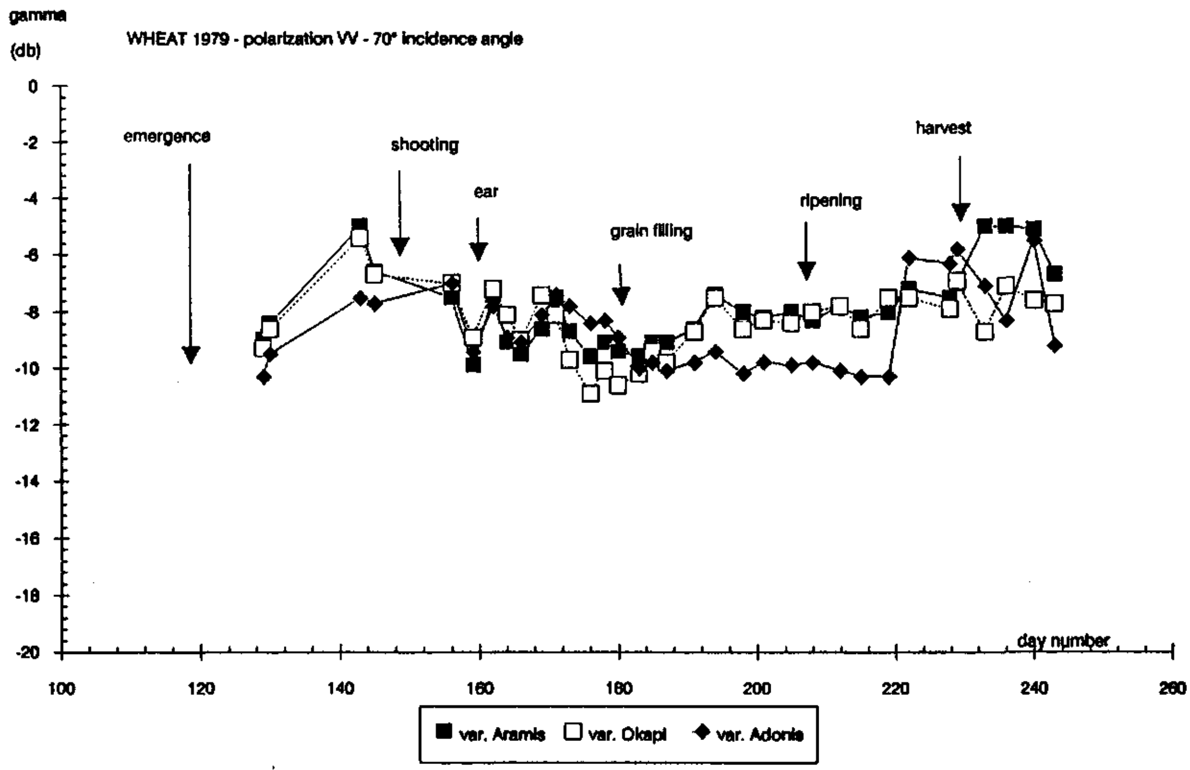


Figure 5.1.c: VV radar backscatter at 70° incidence angle of three wheat varieties Arminda, Okapi and Adonis, 1979.

At 20° incidence angle the differences in backscatter between the two winter wheats are relatively largest. From the start of the growing season until the period of dying the radar backscatter of Okapi is some 2 dB lower than that of Arminda. In the phase of dying the backscatter of both varieties is the same. The backscatter of Adonis is similar to that of Arminda during the vegetative phase until the period of grain filling. During this latter phase it is about 0.5 dB lower while it is higher again during the phases of ripening and dying. This relative increase is partly caused by the lodging of the crop on day 222 which makes the radar backscatter increase by 6 dB.

In the vegetative phase there are only a few small fluctuations present in the order of 0.5 dB. During grain filling the fluctuations increase a little in magnitude to the order of 1 dB. Even from the early growing season on these fluctuations do not compare with those in the backscatter of the bare soil. Only the increase in backscatter for all three crops on days 201-205 might be caused by the contribution of the underlying soil. However, this does not seem very likely because the backscatter of Okapi and Arminda does not react markedly on the increase in soil moisture on day 222 at the end of the growing season. Only the backscatter of Adonis rises because of the lodging of this crop.

At 50° incidence angle the backscatter is similar for both winter wheats from the beginning of the growing season until the formation of the ear stems. With this formation the backscatter of Okapi decreases faster and reaches a lower level than that of Arminda. During the rest of the growing season until ripening the backscatter of Okapi is 1 dB lower. At the end of the growing season the backscatter of both varieties increases and reaches the level of that of the bare soil. The backscatter of Adonis decreases later than that of the winter wheats in the vegetative period of growth (which agrees with the pattern of growth). In the early stage of grain filling the backscatter crosses that of Arminda and in the late stage of ear filling that of Okapi. On day 222 the backscatter increases 2.5 dB because of the lodging of the crop and rises during the period of dying to the level of the bare soil. During the whole growing season the differences in backscatter between the three varieties are never larger than 1.5-2 dB.

The fluctuations in the backscatter during the period of vegetative growth are small, 0.5-1.5 dB for all three varieties. No fluctuations occur in the generative period of growth until the phase of dying. In neither the vegetative nor the generative stage do the fluctuations in the backscatter of bare soil compare with those of the wheat crops. The increase in backscatter of the soil on day 222 in the phase of dying is not even seen for Okapi and Arminda. Only the backscatter of Adonis increases because of the lodging of the crop.

At 70° incidence angle the backscatter of Arminda and Okapi is 1.5 dB higher than that of Adonis in the beginning of the growing season. This agrees with the higher values of biomass and soil cover for the winter wheats. In the phase of shooting and ear formation the backscatter decreases for all three varieties and hardly any differentiation is present. In the phase of grain filling the backscatter of Okapi and Arminda increases again by 2-3 dB while that of Adonis remains unchanged. Therefore, the backscatter of Adonis is about 2 dB lower than that of the winter wheats. At the end of the growing season the canopy of Adonis lodges on day 222 because of heavy rains. This lodging results in an increase in the radar backscatter of 4 dB. A similar increase is present in the backscatter of bare soil, but is not present for Okapi and Arminda. It is therefore concluded that the increase in the radar backscatter of Adonis is the combined result of lodging and increased soil contribution.

For all three crops the curve of the radar backscatter is characterized by fluctuations in the order of 1.5-3 dB during vegetative growth. These fluctuations do not result from variations in radar backscatter from the underlying soil but derive from weather-induced changes in the canopy structure. During the period of generative growth the radar backscatter is relatively stable and only minor fluctuations of 0.5 dB and less occur. For the whole growing period the differences in backscatter between the three varieties average 0.5-2 dB.

The differences in backscatter level between the three crops over the stage of generative growth from grain filling to ripening (days 180-200) are summarized in table 5.2.

Table 5.2: Average backscatter level over the stage of generative growth from grain filling to ripening (day 180-200), wheat 1979.

polarization incidence angle	VV 20	VV 50	VV 70	HH 20	HH 50	HH 70
Arminda	-9.6	-11.0	-8.6	-8.6	-9.9	-9.8
Okapi	-11.2	-12.1	-8.9	-10.0	-10.6	-9.3
Adonis	-10.2	-11.0	-9.2	-9.1	-10.1	-10.1

The differences are very small and vary from 0.5 to 1.5 dB only. When these average values are compared with the average crop parameters given in table

5.1, a tendency might be present between these parameters and the backscatter at low and medium angles of incidence. Arminda, with the short canopy, high density and low soil cover, has generally the highest radar backscatter level. On the other hand, Okapi, with the high canopy, low density and high soil cover, has generally the lowest level of radar backscatter. The differences however are too small to truly relate the backscatter levels to the crop parameters.

The differences between the backscatter at VV and HH polarization are generally the same as described in the previous section for wheat in 1977 (figs. 5.2.a/c). The differences in the VV-HH backscatter-difference are almost negligable between the three varieties, i.e. between 0 and 0.5 dB only.

At low angles of incidence the relation between the backscatter at VV and HH is slightly different for Adonis than for the winter wheats. For all three varieties the backscatter is continuously lower at VV than at HH throughout the growing season. For Okapi and Arminda the difference averages -1.4 dB while for Adonis it averages -0.9 dB. When the latter crop lodges at the end of the growing season the backscatter increases more at VV than at HH and the difference becomes +1.5 dB.

At medium angles of incidence the pattern is slighlty different for Arminda than for Okapi and Adonis. For the latter two varieties the backscatter at VV is about 0.5 dB lower than at HH during the period before ear-stem formation, and about 1.1 dB in the period afterwards. For Arminda the backscatter is continuously lower at VV with about 1 dB throughout the growing season.

At high angles of incidence the backscatter of Okapi and Arminda is about 0.5 dB larger at VV than at HH during the vegetative phase of growth. With the formation of ears this difference disappears. From the stage of grain filling onwards the backscatter is again larger at VV than at HH. The difference is slightly larger for Arminda than for Okapi, respectively +1.2 and +0.7 dB. For Adonis the backscatter at VV is continuously higher at VV than at HH and the difference averages +0.6 dB. At lodging the backscatter increases slightly more at VV than at HH, resulting in a difference of +1 dB.

It is concluded that the differences in radar backscatter from the three different varieties are small. No relationships are found between the radar backscatter and the crop parameters soil cover, fresh weight and crop height. In the next paragraph, four wheat varieties are studied which have more differences in canopy structure than the three crops in 1979.

5.2 Crops in 1981

5.2.1 Crop characteristics

In 1981, four varieties of winter wheat were studied, Arminda, Okapi, Durin and Adamant. The variety Arminda was sown in three repetitions, i.e. two plots with a row direction parallel to the radar beam and one with a row direction perpendicular to the radar beam. The other varieties all had a parallel row direction. Since the influence of the direction of the rows is already discussed in chapter 4, only the plots with a parallel row direction are discussed here.

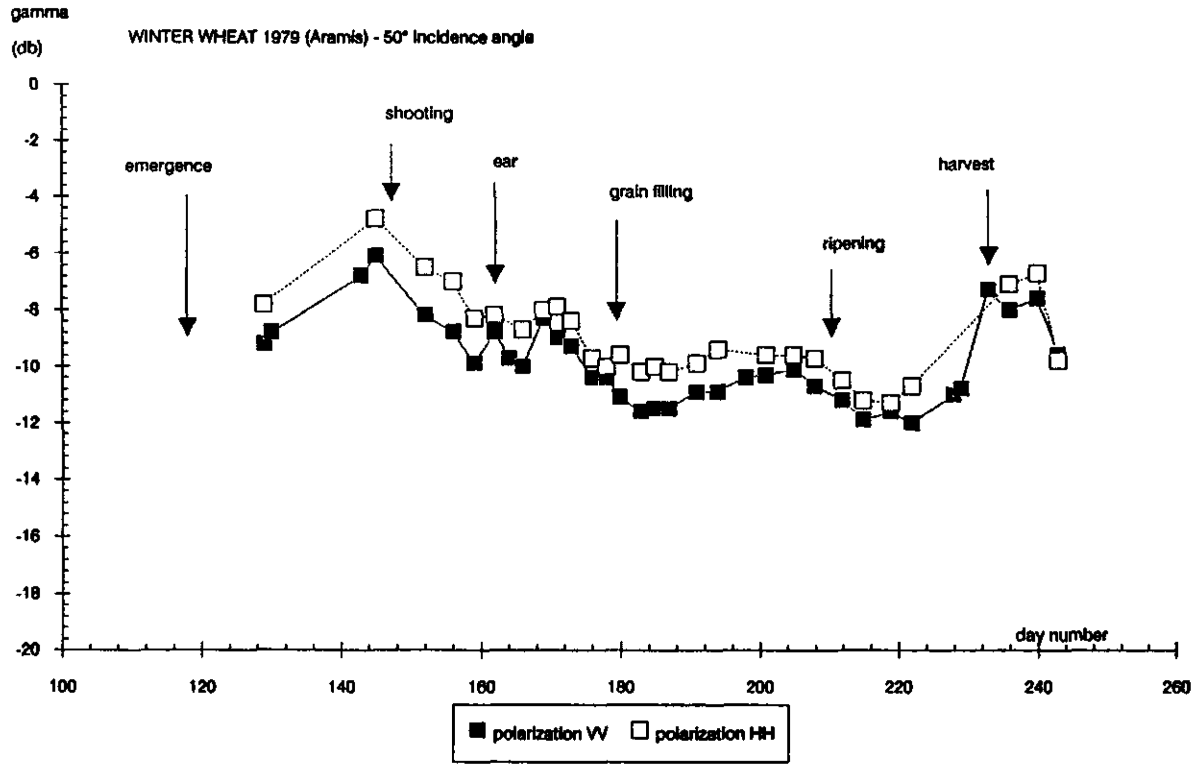


Figure 5.2.a: VV and HH radar backscatter at 50° incidence angle of winter wheat Arminda, 1979

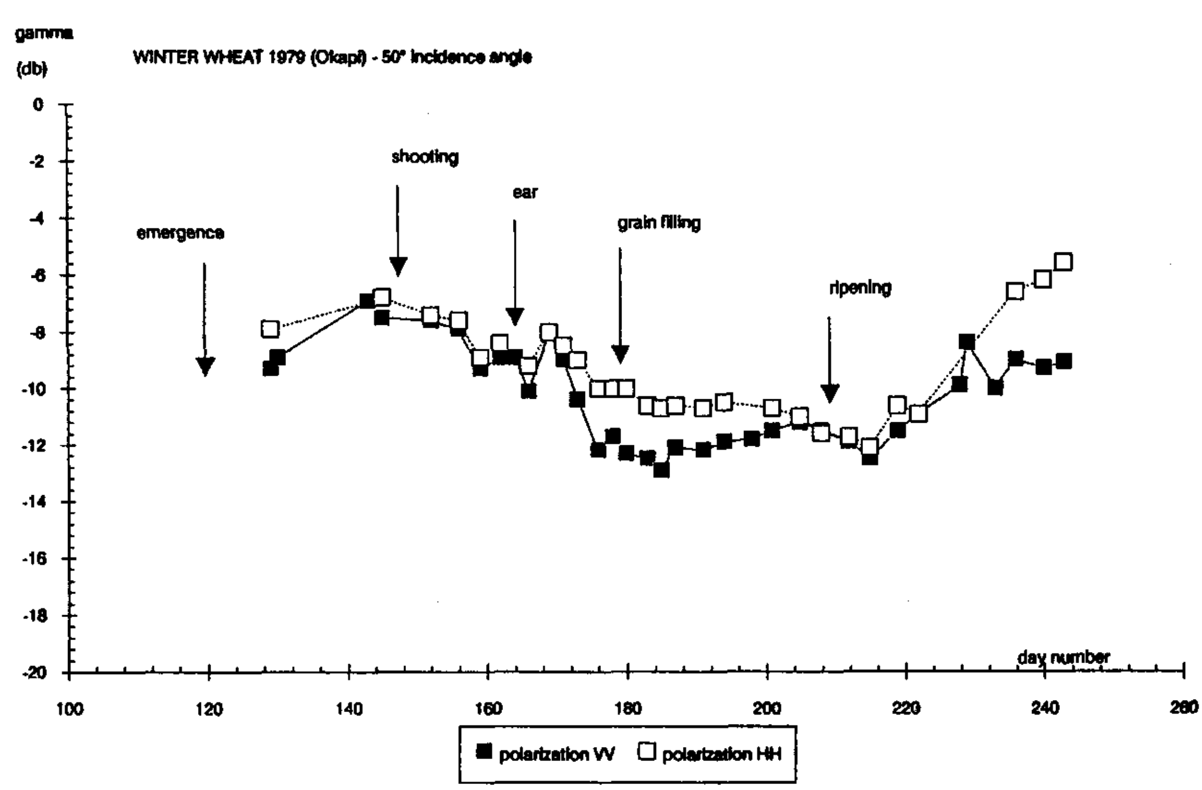


Figure 5.2.b: VV and HH radar backscatter at 50° incidence angle of winter wheat Okapi, 1979

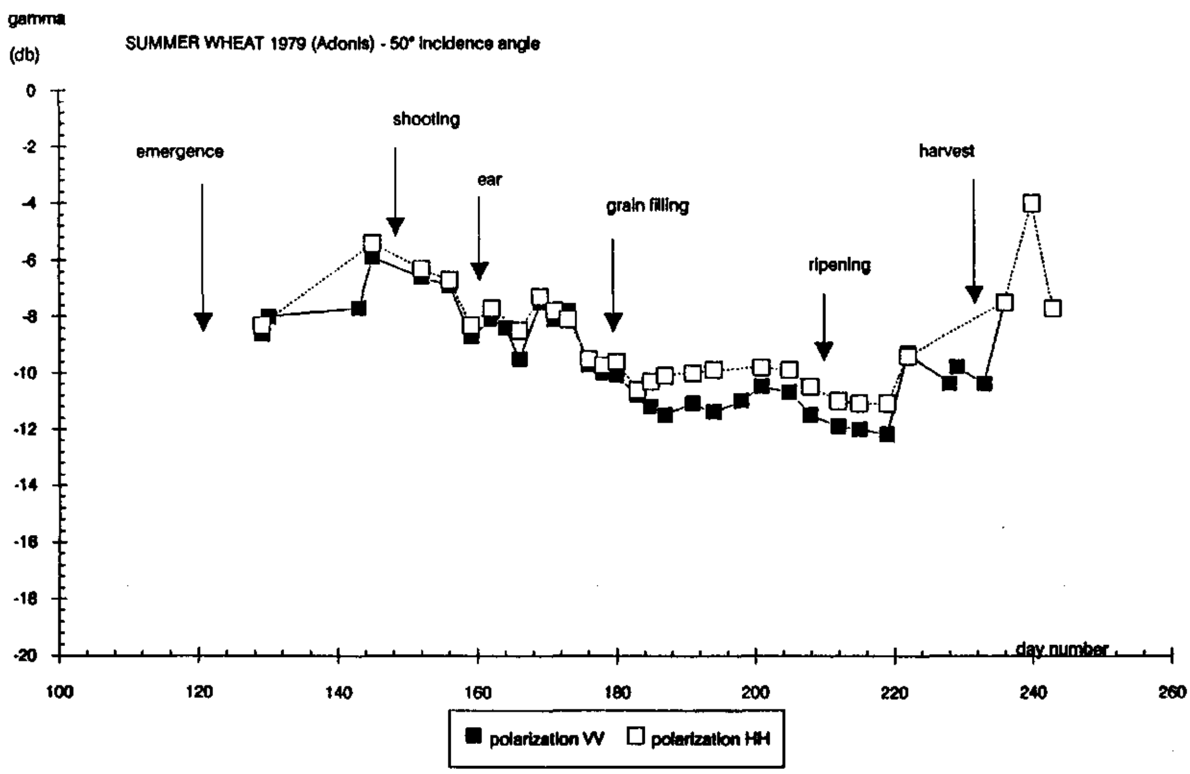


Figure 5.2.c: VV and HH radar backscatter at 50° incidence angle of summer wheat Adonis, 1979

This year, the period of measurement was relatively short. It started at half May (day 138) and already ended at the beginning of July (day 184). Therefore only the first half of the growing season from tillering to grain filling can be studied. However, already from the start of the season, the development of the crops was faster than in other years. At the beginning of the measurements, the crops all had a soil cover of more than 50% and a height of about 40-50 cm. On day 165, the stage of grain filling was reached and the crops had attained their final height. In other years, this stage is only reached on about day 180. Between day 165 and day 184 the crops remained stable in height, cover and fresh weight. For this period, the differences in crop growth and development between the varieties are summarized in table 5.3. In an attempt to characterize the structure of the crop canopies, several physical characteristics were measured on day 169 (table 5.4). Based on these measurements and on visual observations, the following conclusions are drawn on the (relative) structure of the crop canopies in this specific year:

- Durin: a short, dense crop with a relatively high soil cover. The length of the ear stems is small. The top leaves are broad, medium in length and have a large surface area. The Leaf Area Index (LAI) of the top leaves is large. The top leaves generally droop downward so that a large horizontal component is present in the top of the canopy.

Table 5.3: average crop parameters over the period day 164-184 for different wheat varieties in 1981. N.b. the numbers behind the variety name indicate the field numbers.

variety	height (cm)	cover (%)	fresh weight (g/m2)	fresh density (g/m3)	number stems/m2
Arminda 8106	90	70	3363	3737	449
Arminda 8110	90	70	3767	4186	549
Okapi 8107	110	80	3830	3482	450
Adamant 8109	90	80	3538	3931	387
Durin 8108	80	87	3331	4164	472

Table 5.4: some physical characteristics of the wheat crops in 1981, measured on day 169. N.b. the numbers behind the variety name indicate the field numbers.

variety	ear length (cm)	ear stem length (cm)	top leaf length (cm)	top leaf area (cm2)	LAI top leaf (-)
Arminda 8106	7.5	15-16	17-19	20.8	0.98
Arminda 8110	7.0	12-16	15-19	20.8	1.12
Okapi 8107	8.0	15-20	20-23	23.1	1.00
Adamant 8109	8.0	6-12	22-25	28.6	1.04
Durin 8108	8.0	1-10	17-23	28.8	1.32

- Adamant: a dense crop, medium in height with a medium soil cover. The length of the ear stems is small. The top leaves are quite broad, long and have a large surface area. Because the number of stems per square meter is low, the LAI of the top leaves is only small to medium. As with Durin, the top leaves generally droop downward so that a large horizontal component is present in the top of the canopy.

- Okapi: a high, thin crop with a medium soil cover. The length of the ear stems is large. The top leaves are narrow, long and have a small to medium surface area. They are quite erect but may bend at the top. Therefore both vertical and horizontal leaf components are present in the top of the canopy. The LAI of the top leaves is small.

- Arminda: a medium to dense crop, medium in height with a low soil cover. The length of the ear stems is medium. The length of the top leaves is small, the width is medium and the surface area is small. Contrary to the other crops the top leaves are very erect and vertical leaf blades dominate the top of the canopy. Because of this erect structure, the rows and inter-row spaces are clearly visible in the canopy. A difference in canopy density is present between the two plots no 8106 and no 8110. On the latter plot, the number of stems is about $100/m^2$ larger than on the first plot, which results in a denser crop. Also, the LAI of the top leaves is small for the first plot while it is medium for the second plot. However, the optical soil cover is the same for both crops (small) which means that plot no 8180 is specifically denser within the rows and not so much between the rows.

5.2.2 Radar backscatter

The VV radar backscatter of the crops at 20°, 50 and 70° incidence angle is given in respectively figs. 5.3.a, 5.3.b and 5.3.c. First the backscatter of the crops Okapi, Adamant and Durin will be mutually compared, and then the backscatter of Arminda will be discussed.

The general shape of the backscatter curves of Okapi, Adamant and Durin is similar to those in previous years. A notable difference occurs in the generative period of growth. The radar backscatter unexpectedly increases at all angles of incidence around day 183. It is relatively small at low angles of incidence, 1.5-2 dB (1 dB at HH) and large at high angles of incidence, 4-6 dB (4 dB at HH). This increase could be caused by a change in the structure of the canopy on all fields caused by heavy winds. The crops do not stand any longer nicely on rows but are partly bent or lodged between the rows. This results in a rougher appearance of the canopy surface and in the some bare spots.

During the whole period of observation, the level of radar backscatter is highest for Durin, medium for Adamant and lowest for Okapi at all angles of incidence (excluding Arminda). The difference between the curves of Durin and Okapi is largest at low angles of incidence, 1.5-3.5 dB, and smallest at high angles, 1.0-2.5 dB. This agrees with the results from the row spacing and row direction experiment in which the differences are also most pronounced at low angles of incidence.

The differences between the varieties are also illustrated by the average radar backscatter over the beginning of the grain filling stage, days 166-170 (table 5.5). Because of the short period of radar observations, the averaging can not be done over the whole period of grain

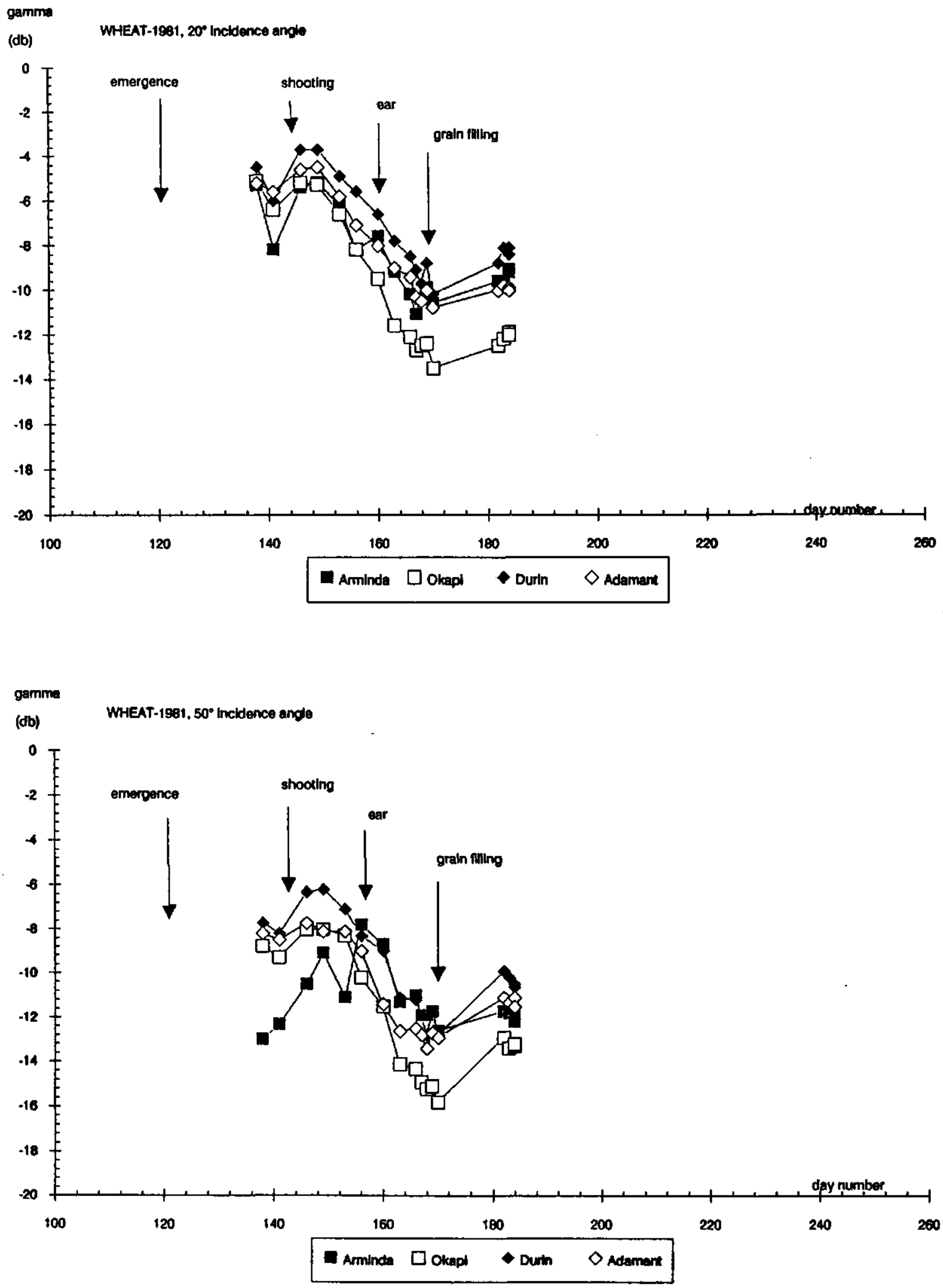


Figure 5.3: VV radar backscatter at 20° (5.3.a) and 50° (5.4.b) incidence angle of four wheat varieties; Arminda, Okapi, Durin and Adamant, 1981

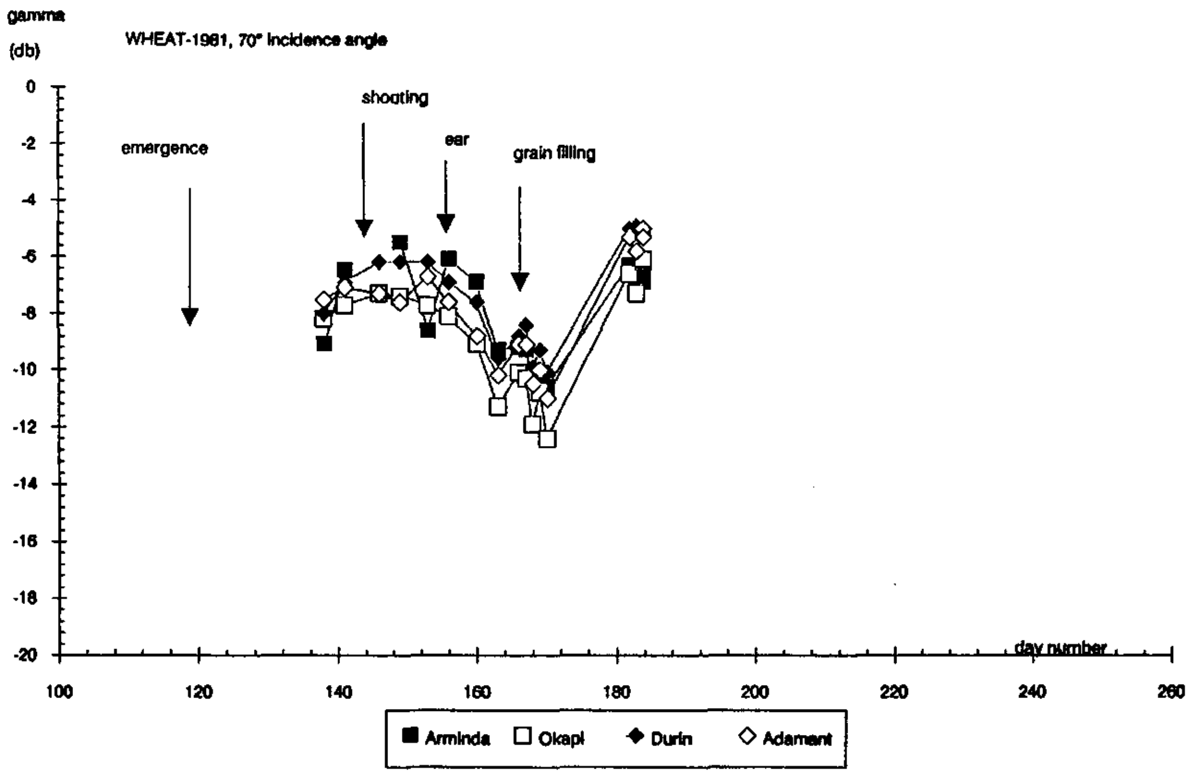


Figure 5.3.c: VV radar backscatter at 70° incidence angle of four wheat varieties; Arminda, Okapi, Durin and Adamant, 1981

filling. Therefore a comparison with the values of table 5.2 for the crops in 1979 is not possible. When these values are compared with the crop parameters in table 5.3, it is clear that no correlation

Table 5.5: Average radar backscatter over the beginning of the grain filling stage, days 166-170, wheat 1981

polarization incidence angle	VV 20	VV 50	VV 70	HH 20	HH 50	HH 70
Arminda 8106	-10.4	-11.8	-9.9	-9.1	-10.0	-9.5
Arminda 8110	-12.2	-12.2	-10.0	-10.8	-10.4	-9.5
Okapi	-12.6	-15.1	-11.1	-10.4	-11.9	-10.4
Adamant	-10.2	-12.9	-9.9	-8.7	-11.1	-11.0
Durin	-9.3	-12.1	-9.3	-7.7	-10.5	-9.8

exists with the number of stems/m^2 or the soil cover. However, the sequence of backscatter level matches the sequence of crop height, fresh weight and crop density. Except for the medium angle of incidence the differences between the crops are similar in magnitude at both states of polarization. At 50° incidence angle the differences are smaller at HH (1.5 dB) than at VV (3 dB). The difference between the backscatter at VV and HH polarization appears related with the absolute level of the backscatter itself. For Durin, with the highest level of backscatter, the VV-HH difference at 50° incidence angle is -1.6 dB. For Adamant, with the medium level of backscatter, it is -1.8 dB, and for Okapi with the lowest backscatter level it is -3.2 dB. These differences are quite small.

The levels of the radar backscatter of Durin, Adamant and Okapi can to some extent be related to the structure of the crop canopies (table 5.4). Durin is characterized by broad top leaves with large surface areas and large horizontal components in the top of the canopy. The ear stems are relatively short which cause the layer of ears to be close to the layer of the top leaves. The top of the canopy has a relatively closed appearance. It is therefore likely that microwaves are (relatively) reflected at the top of the crop and do not enter the canopy very deeply. Consequently, the backscatter from this canopy would be relatively high. The structure of Adamant is comparable to that of Durin but the LAI of the top leaves is smaller. Microwaves can enter a little deeper into the canopy where absorption and extinction takes place. The result would be a lower level of the radar backscatter. Okapi on the other hand has narrow top leaves whith a small surface area. The leaves stand more erect in the canopy and only bend over at the top. The ear stems are quite large which cause the layer of ears to be separated from the leayer of top leaves. The top of the canopy has an open appearance. Microwaves can enter the canopy relatively deeply where they get absorbed and extinct. Therefore, the resulting backscatter would be lower than that of Durin or Adamant. Because of the presence of more vertical leave components, the penetration capability will be larger at low angles of incidence than at high angles of incidence. Together with the narrowness of the leaves, this may explain that the VV-HH backscatter difference is larger for Okapi than it is for Durin and Adamant, and that this is mostly felt at low angles of incidence.

The radar backscatter of Arminda is somewhat special at the beginning of the growing season. At 20° incidence the shape of the curve ressembles those of the other plots. However, at 50° incidence, the backscatter is clearly distinguished from that of the other crops. It increases from about -13 dB on day 140 to -8 dB on day 160. After this day the backscatter settles between that of Okapi and those of Durin and Adamant. At 70° incidence angle, the level of backscatter of Arminda is the same as that of the other crops but more fluctuations are present until day 160. The relative position between the curves of Arminda and Okapi during generative growth is generally the same as in 1979; the curve of Arminda is higher at medium angles of incidence while there is hardly any difference at high angles of incidence.

The deviating pattern of the Arminda plots might be related to the special erect structure of the canopy (table 5.3), but it remains unexplained here. Because no backscatter measurements are made of the bare soil, it is not clear whether the fluctuations derive from fluctuations in the contribution from the underlying soil, or derive from other causes.

The difference between Arminda and the other crops is also interesting to note in the optical wavelength region. A parallel can be drawn between the infrared reflectance and the radar backscatter at medium angles of incidence. This year, (optical) reflectance measurements are made in the green, the red and the infrared bands using the portable CABO-meter (Uenk, 1982). In the two visible bands the reflectance is quite similar for all crops (fig. 5.4.a/b). The reflectance of Arminda only deviates a little from that of the other crops on days 150 and 164 in the green band. In the near infrared band, however, the difference between Arminda and the other

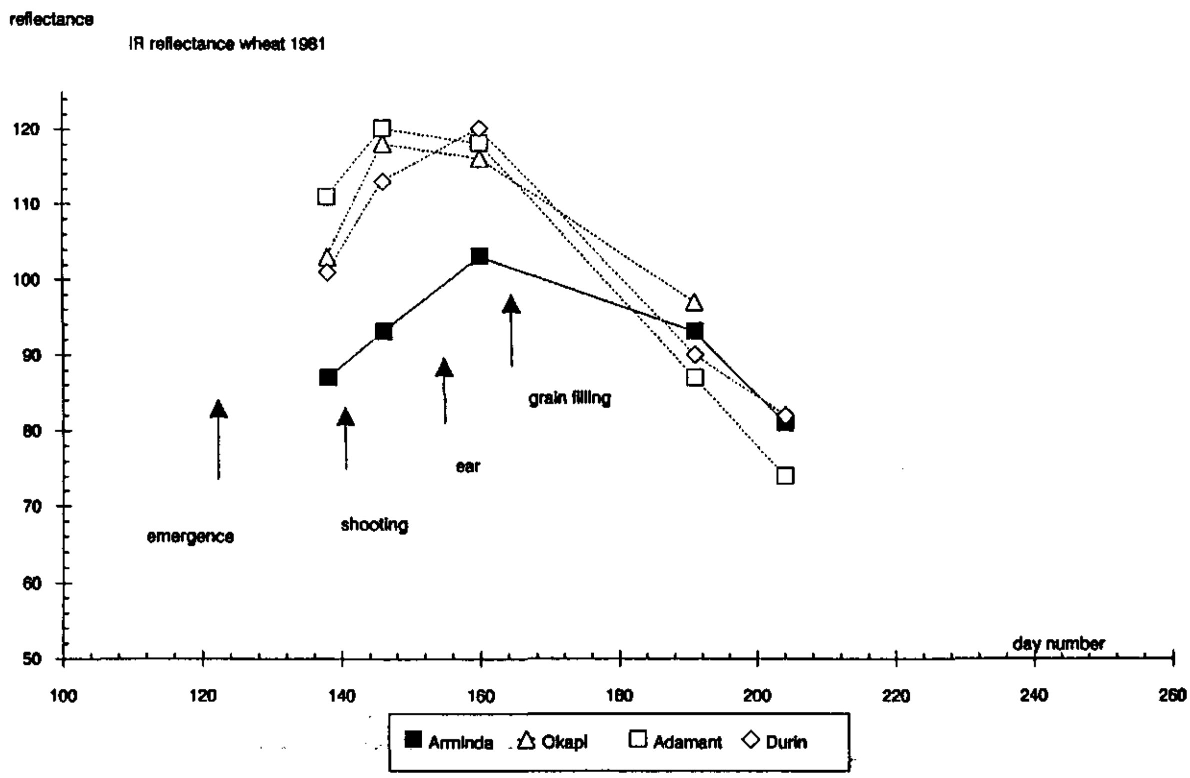


Figure 5.4.a: near-infrared reflectance of Okapi, Durin, Adamant and Arminda, 1981.

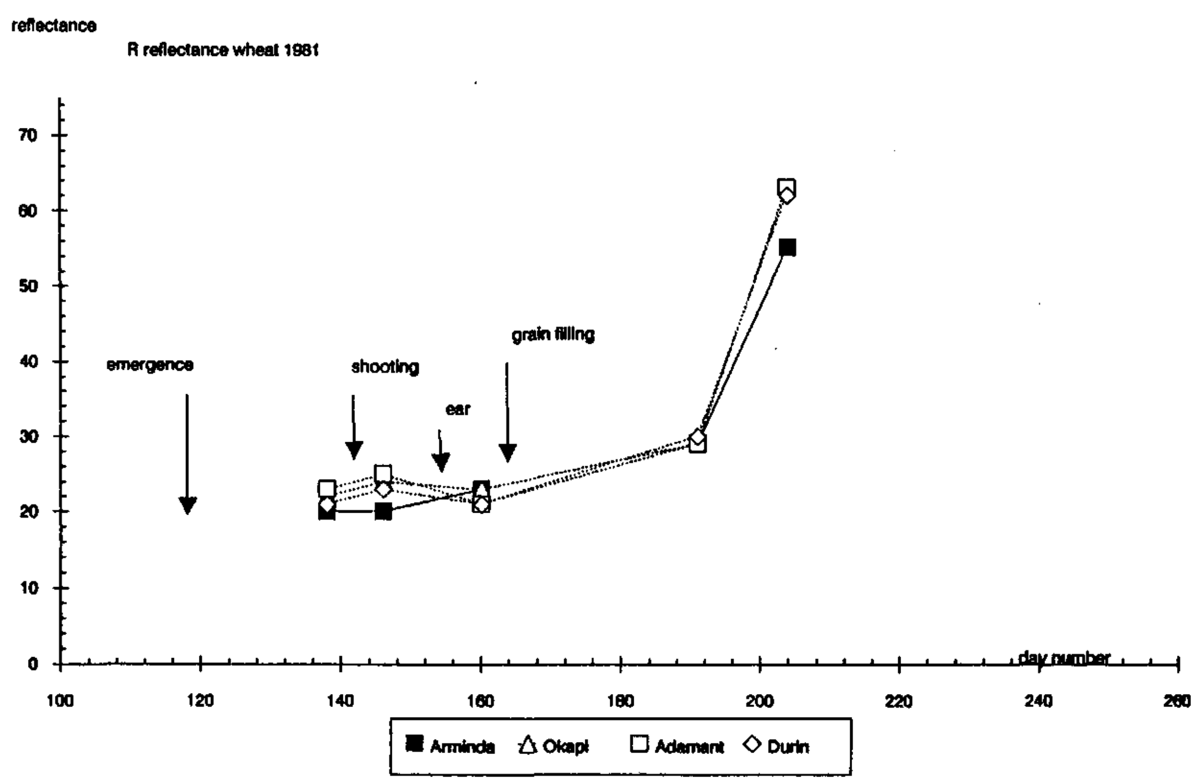


Figure 5.4.b: red reflectance of Okapi, Durin, Adamant and Arminda, 1981.

crops is very clear. The reflectance of Arminda is about 20% lower than that of Durin, Adamant and Okapi during the first half of the growing season. It becomes similar only on day 197. The near infrared band is especially sensitive to differences in biomass, LAI and soil cover. In this example, the differences in reflectance relate to the differences in soil cover since the biomasses of the crops are all comparable. The vertical structure of Arminda results, through the lower level of soil cover in lower values of the near infrared reflectance at the same biomass levels as that of the other crops. In this respect, the similarity between the near infrared reflectance and the radar backscatter at medium angles of incidence is striking. It appears that, in this example, the backscatter at medium angles of incidence correlates with the soil cover, while at low angles of incidence it does not.

5.3 Summary

The differences in radar backscatter (VV) between wheat varieties are relatively largest at low angles of incidence (1.5-3.5 dB) and smallest at high angles of incidence (1.0-2.5 dB). The differences do not correlate with biomass or soil cover, but appear associated with the structure of the crop canopy, e.g. dimension and orientation of the canopy elements. A crop with a relatively short and dense canopy with broad, horizontal top-leaves (Durin) has a relatively high level of radar backscatter. On the other hand, a relatively tall and thin crop with narrow top leaves (Okapi) has a relatively low level of radar backscatter. The variety Arminda has especially erect and small top leaves. In 1981, the backscatter pattern of this crop differs from that of the other crops during the period of vegetative growth. A parallel can be drawn at medium angles of incidence with the near infrared reflectance in the optical wavelength region.

The crops in 1979 have a level of radar backscatter during grain filling which is about 1-3 dB higher than that of the crops in 1981. The relative position of the backscatter curve of Arminda and Okapi is generally the same in both years.

6 External conditions

Under specific circumstances, the structure of a crop canopy can change abrubtly under the influence of varying weather. Heavy wind or rain can cause the lodging of a crop, especially when the canopy is heavy with ears at the end of the growing season. Barley and oats are especially sensitive to lodging. Patches of lodged crop may appear in the field already at the start of grain filling. Wind may also cause variations in the canopy structure which are less dramatic but much more dynamic. Leaves and ears move with the wind and may give the canopy of the crop a specific appearance. Barley is again very sensitive to wind. The typical wavelike motions are a well known sight in barley fields. All these changes in the canopy structure can have an impact on the radar backscatter. The magnitude of this impact depends on the geometry of observation and on the crop type, its stage of development and its general condition. Jiankang et al.(1986) calculated the backscattering power spectral density of a randomly moving vegetation canopy which is dependent on the wind speed, wind direction and the incident wave parameters. Their computations are based on several approximations and on a statistical distribution of the random velocity of stems and leaves. Van Kasteren (1976) investigated the relationship between the radar backscatter of wheat and the predominant wind direction. He found that the backscatter at high angles of incidence corresponds with the wind direction in long periods of the growing season. In periods with a wind direction across that of the radar beam, or with the wind blowing away from the radar, the backscatter is higher than in periods with the wind blowing towards the radar. Bouman and Uenk (1987) even reported a dominant effect of the azimuthal direction of stubbles on the radar backscatter on an image of the Canadian IRIS SAR. The C-band radar backscatter is higher with the stubbles directed away from the radar then with the stubbles directed towards the radar.

Some effects of a change in canopy geometry on the radar backscatter are already discussed in previous chapters. They are elaborated and quantified here to emphasize their importance.

6.1 Lodging

The effect of lodging is very well illustrated by barley in 1980 (fig. 6.1). During grain filling the crop slowly starts to lodge in the midst of July. On day 187 the first observations are made of patches of lodged crop which cause an irregular appearance of the canopy. Differences in height of about 40 cm exist between the lodged and the non-lodged patches. The crop in the non-lodged patches still stands erect with the ears lying horizontally in the canopy. In the lodged patches, the stalks and ears are bend downward and lean against each other. The patches of lodged canopy increase in size and degree of lodging during the rest of the grain filling phase and during ripening. The radar backscatter, however, only reacts to the lodging on day 197 with a sudden increase of 8 and 11 dB at HH and VV polarization respectively. This sudden increase and the lack of a response during days 187-197 indicates that the radar backscatter reacts on specific changes in the canopy architecture during the process of lodging. For the radar, lodging is not just a 'yes-or-no' state with associated levels of backscatter. It is a range of changes in the canopy architecture (orientation of heads, leaves and stalks) of which the nature of theses changes determines the effect on the radar backscatter. In this specific example, the changes in the canopy structure between day 187 and 197 are apparantly not significant enough to affect the backscatter.

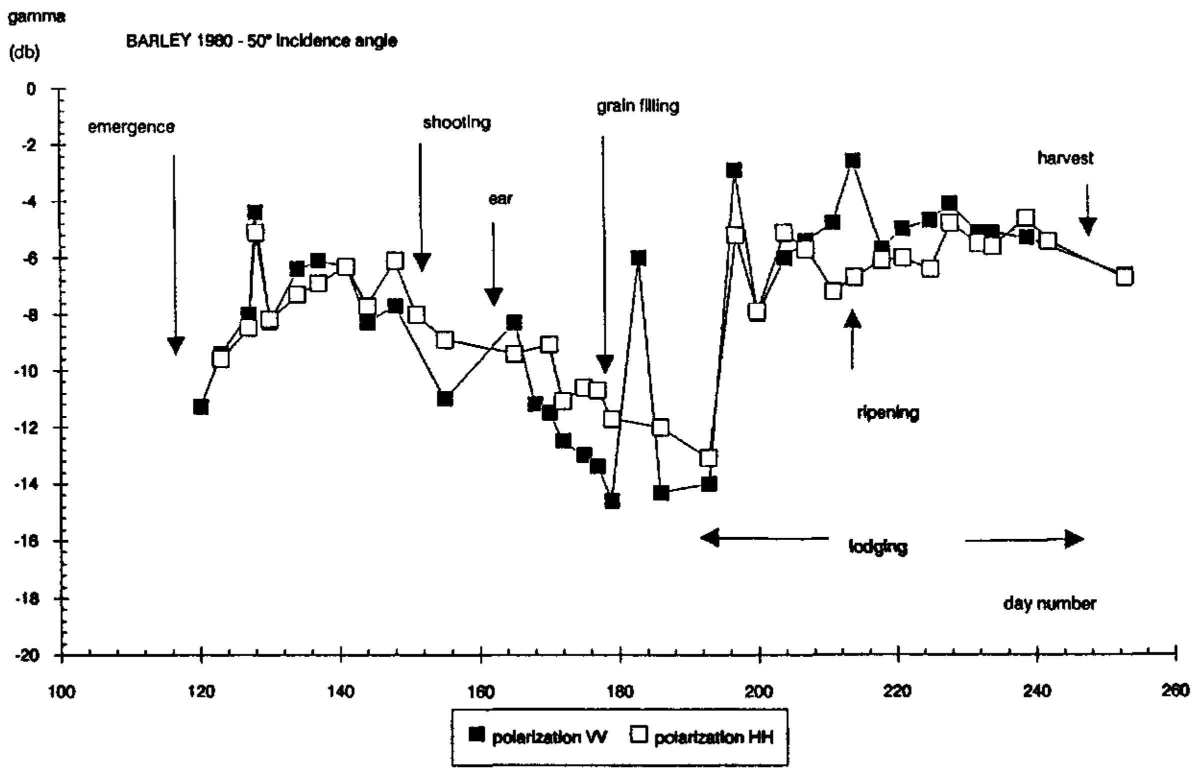


Figure 6.1: VV and HH radar backscatter at 50° incidence angle of barley, Havila 1980.

After day 197, the backscatter initially decreases and then very slowly rises during the rest of the season. More changes in the canopy structure caused by continuing lodging, have no more dramatic effect on the backscatter.

The effect of lodging on the backscatter at both VV and HH polarization is als given as a function of angle of incidence (fig. 6.2). The situation before the dramatic increase is given by the curve on day 193. At both states of polarization the angular-dependency curve is not hollow but the backscatter continuously decreases with increasing angle of incidence. On day 197 the backscatter increases steeply at all angles of incidence except at the low angle of 10°. The effect is more pronounced at VV than at HH polarization. At VV the increase is 4.5, 11 and 11.5 dB at respectively 20°, 50° and 70° incidence angle, and at HH the increase is 3.5, 7 and 10 dB respectively. On day 200, the backscatter decreases again but remains much higher than on day 193. This peak at the onset of (the effect) of lodging is also observed for barley in 1979. However no observations are made in the field to support any explanation of this phenomenon.

The effect of lodging is also observed at the end of the growing season for wheat, summer wheat Adonis 1979 (fig. 6.3). At all angles of incidence and at both states of polarization the backscatter increases with the lodging of the crop. The efffect is a little larger at VV than at HH: 5, 1.5 and 4 dB at respectively 20°, 50° and 70° incidence angle at VV versus 4, 1 and 3 dB at HH. For oats the effect of lodging is given for Leanda in 1979 on the same days as for the summer wheat (fig. 6.4).

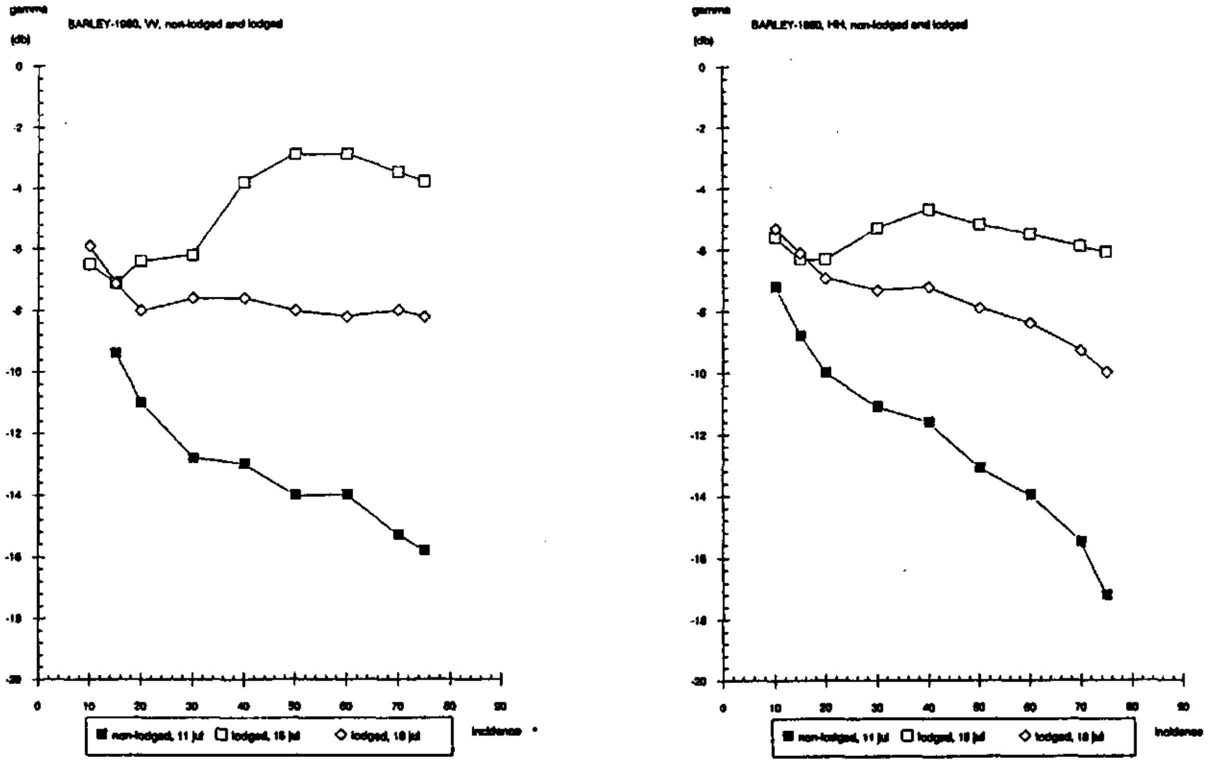


Figure 6.2: VV and HH radar backscatter versus incidence angle of a lodged and a non-lodged canopy of barley, Havila 1980. The crop is in the grain filling stage of growth.

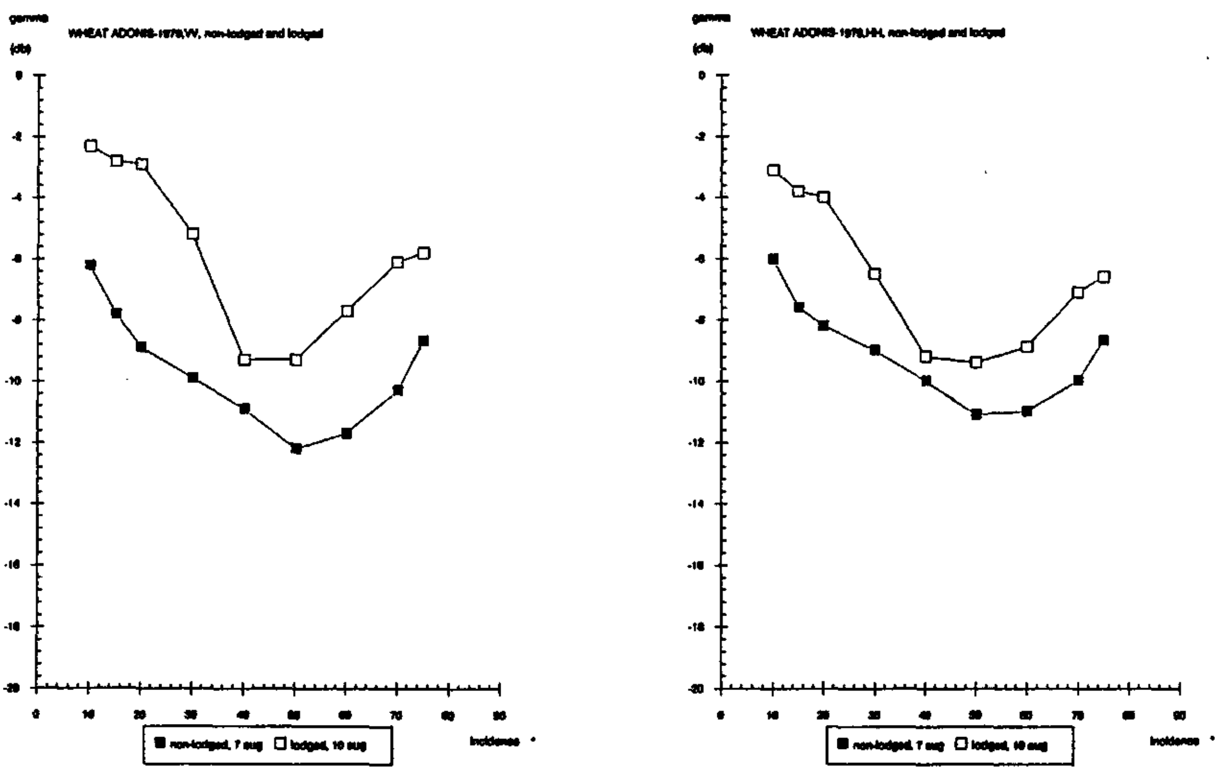


Figure 6.3: VV and HH radar backscatter versus incidence angle of a lodged and a non-lodged canopy of summer wheat, Adonis 1979. The crop is in the ripening phase of growth.

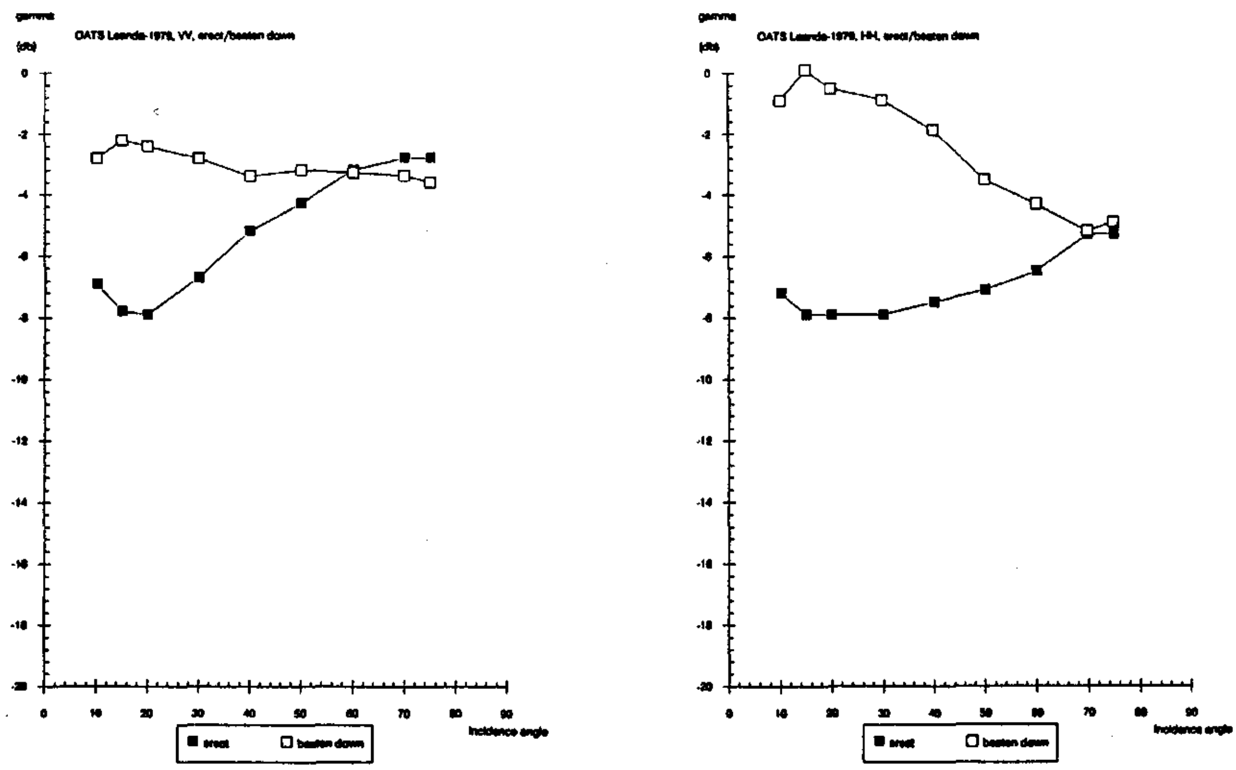


Figure 6.4: VV and HH radar backscatter versus incidence angle of a lodged and a non-lodged canopy of oats, Leanda 1979. The crop is in the ripening phase of growth.

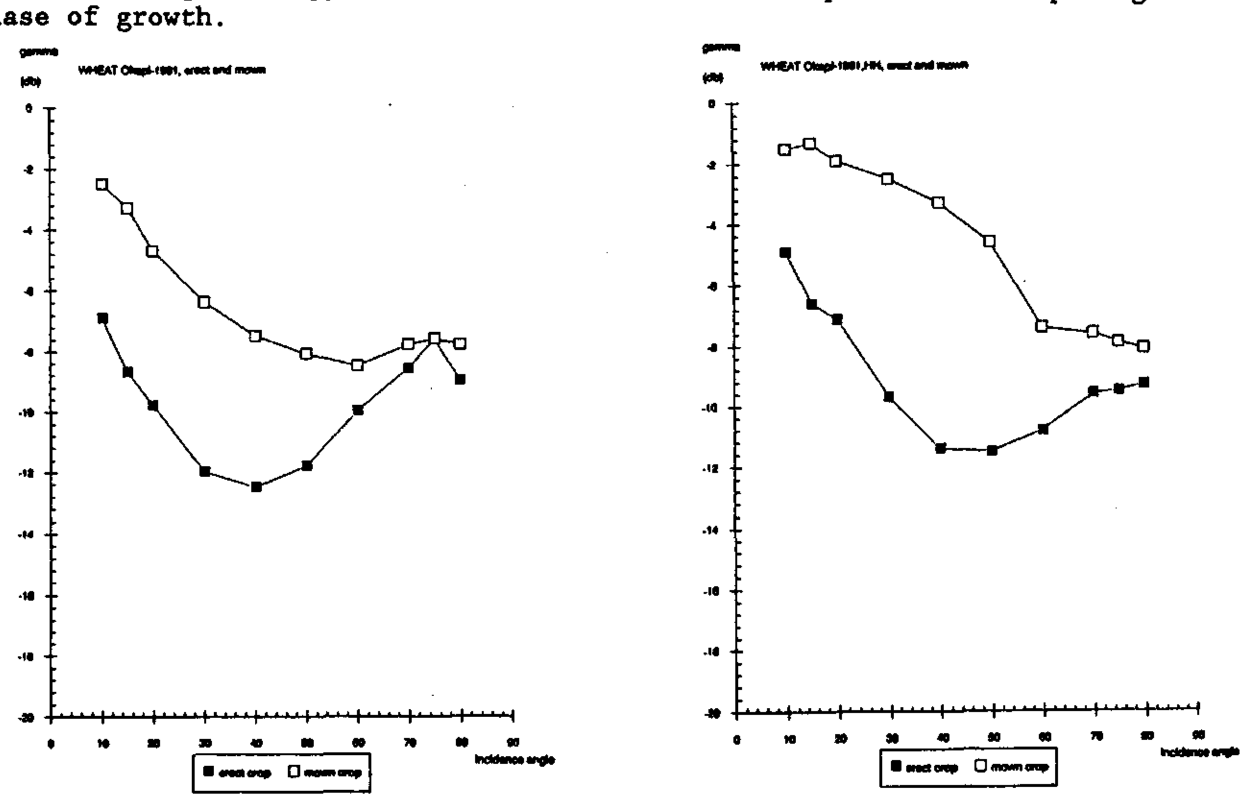


Figure 6.5: VV and HH radar backscatter versus incidence angle of a standing and a mown canopy of winter wheat, Okapi 1981. The crop is in the end of the grain filling period of growth.

To simulate an extreme situation of lodging, this crop is mechanically beaten down to some 30 cm height. At some patches the crop still stands erect and is 100 cm heigh. On the day before lodging the angular backscatter curve is typical for an oats crop in the stage of ripening. Contrary to wheat and barley, the backscatter continuously increases with increasing angle of incidence. This characteristic is especially present at VV and only to a limited extent at HH. With the lodging of the crop the backscatter increases at both states of polarization. This time, the increase is larger at HH than at VV: 5.5, 2 and -0.5 dB at 20°, 50° and 70° incidence angle respectively at VV, and 8, 5,5 and 0.2 dB at HH.

The examples so far were backscatter measurements on different days just before and just after the lodging of the crop. To exclude other effects of temporal variation, like varying conditions of the soil background, which might also influence the backscatter, a special experiment is conducted on the wheat variety Okapi in 1981. At the end of the grain filling period the crop is cut down and left more or less flat on the field. The backscatter is measured before and after the cutting (fig. 6.5). At both states of polarization the backscatter increases with a larger effect at HH than at VV: 5, 5 and 1 dB at 20°, 50° and 70° respectively at VV, and 5, 8 and 2 dB at HH. These results indicate that the observations made on the naturally lodged crops can indeed be attributed to the lodging of the canopy.

The examples indicate the variability of the effect of lodging for different crop types. Beside the common feature of an increase in radar backscatter, the effects are different in magnitude at different angles of incidence and states of polarization. The comparison of the example of barley with that of oats indicates the specific crop type dependency. The opposite shape of the angular dependency curves of the non-lodged crops results in different effects of lodging between the two crops. For barley, the increase in radar backscatter is largest at high angles of incidence and smallest at low angles, while for oats the opposite is true.

6.2 Ear orientation

The large influence of the ears of barley on the radar backscatter of the whole crop is already discussed for an example in 1977 in chapter 3. To emphasize its importance, the effect of this change in ear-direction is repeated here for all angles of incidence and at both states of polarization, field a, 12.5 cm row spacing (fig. 6.6). The angular dependency curve of the crop on day 182, in the beginning of the grain filling phase, generally ressembles that in fig. 6.2. The backscatter deviates only at VV polarization at the high angles of incidence. The ears lie horizontally in the canopy and are directed towards the radar. On day 186 the direction of the ears is reversed and the backscatter increases at all angles of incidence. The increase is largest at VV polarization: 6.5, 7.5 and 7.5 at 20°, 50° and 70° incidence angle respectively at VV, and 3, 2.5 and 2 dB at HH. The dependency of the effect of ear orientation on the row spacing of the crop is already elaborated in chapter 3.2. The increase in backscatter might be compared with visual observations. With a look direction against the direction of the ears, one looks deep into the canopy and the appearance is relatively dark. When the look direction is reversed, one looks straight onto the ears and the line of sight does not enter the canopy deeply. The appearance of the crop is therefore relatively light.

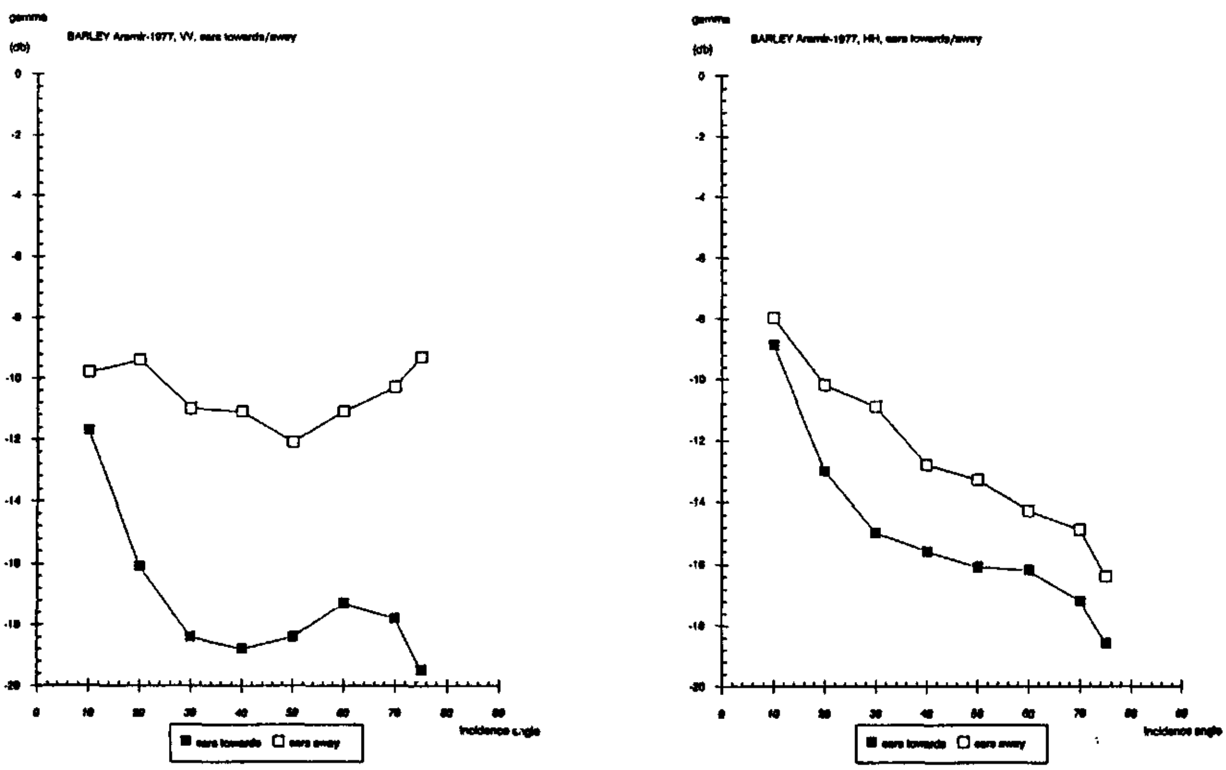


Figure 6.6: VV and HH radar backscatter versus incidence angle of barley with ears directed towards the radar, and ears directed away from the radar, Aramir 1977. The crop is in the grain filling period of growth.

A similar, though less dynamic effect of the orientation of ears is also observed for wheat in 1977. The effect is only notable at high angles of incidence: the backscatter increases about 3 dB at both states of polarization for field a with the small row spacing. No effect is present at medium and low angles of incidence. Compared with wheat, the backscatter of barley is more affected by the changes in the orientation of the ears. This is partly caused by the larger sensitivity of barley to wind, which makes the orientation of the ears change more often and more dramatically. Also this is probably caused by the large awns on the ears of barley. These awns may enhance the polarization-dependent backscatter properties of the ears. Allen and Ulaby (1984) calculated a theoretical attenuation of 3.86 dB for 10.2 Ghz microwaves at 60° incidence angle through an 8 cm layer of wheat ears without awns, and of 4.86 dB for wheat ears with awns. For their calculations they assumed only absorption to be the dominant mechanism for attenuation.

A comparison between the backscatter properties of ears and those of the underlying vegetative material is made in an experiment with the wheat variety Arminda in 1981. At the end of the grain filling stage, on day 204, all ears are clipped off. The backscatter is measured before and after the removal of the ears (fig. 6.7). Surprisingly, the effect of this removal is less dramatic than that of the change in ear orientation of wheat in 1977. At VV polarization the backscatter only decreases 0.1, 0.6 and 1.1 dB at 20°, 50° and 70° respectively, and at HH it increases only 0.2, 1 and 0 dB. The shape of the angular dependency curve at both VV and HH polarization is similar for the crop with- and for the crop without ears. At medium angles of incidence the VV-HH backscatter difference of the crop with ears is about -3.5 to -4 dB, and that of the crop without ears about -4 to -5.5 dB. So, the backscatter properties are also comparable at both states of polarization. For this example, the polarization-dependent backscatter properties of the vertical ears of wheat are similar to, but a bit less pronounced than those of the underlying vegetative material.

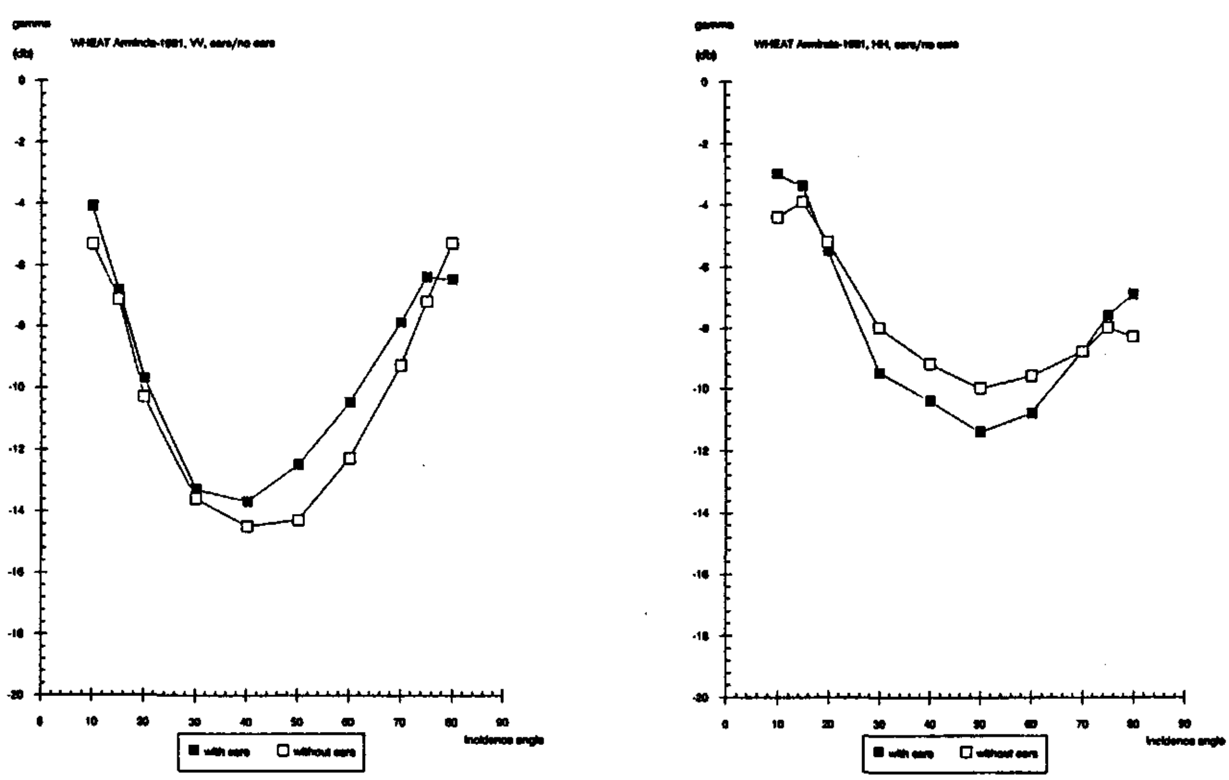


Figure 6.7: VV and HH radar backscatter versus incidence angle of wheat with ears, and with the ears clipped off, Arminda 1981. The crop is in the end of the grain filling stage of growth.

7 Harvest

A special point of interest is the effect of harvest and post-harvest management practices on the radar backscatter. In 1979, some plots are left after harvest as stubble-field with or without straw, some are ploughed and one plot is not harvested at all. This last plot serves as a comparison between an unharvested and a harvested field. This year harvest and management practices for the various plots were as follows:

- Winter wheat Arminda: after harvesting, the plot is left as stubble-field. In the part of the field closest to the radar (in the field of view at the lowest angle of incidence) the straw is left between the rows of the stubbles. In the other part of the field (in the field of view at medium and high angles of incidence) the straw is scattered around the field.
- Oats Leanda: the plot is left as stubble-field with the straw removed from the field. The structure of the rows is well preserved.
- Barley Aramir: the plot is initially left as stubble-field with the straw removed. The stubbles do not stand evenly in the rows and in some places they lie flat on the ground. After three days the stubble-field is ploughed which leaves a rough soil surface.
- Summer wheat Adonis: after harvesting, the field is ploughed. The bare surface is rough and some stubbles still emerge from the soil.
- Summer wheat Okapi: this crop is not harvested at all during the period of radar observation. The canopy is still erect but the ears are bent downwards. The crop has dried out to an average moisture content of 19%, the same order of magnitude as that of stubbles.

The effect of harvesting differs for the various crops and varieties (table 7.1). For Arminda, the transition from ripened crop to stubble-field results in an increase at VV polarization of 2-4 dB at all angles of incidence (fig. 7.1). The angular dependency is similar (hollow) to that of the crop canopy, and deviates from that of bare soil (fig. 7.4). The change in backscatter of bare soil in these days is only about 0.2 dB at all angles of incidence. This means that the change in backscatter of Arminda is the result of the harvesting of the crop and does not derive from changes in the backscatter from the soil background. After harvesting, the temporal curve of the radar backscatter of the stubble-field ressembles that of bare soil at low angles of incidence. The absolute level of the backscatter is not the same because of differences in roughness and of the presence of the stubbles. At medium angles of incidence the similarity in the curves is much less and at high angles no similarity exists at all. At these angles of incidence the field of view of the radar beam is dominated by the stubbles and the straw, and the contribution of the soil background is low to non-existant. The polarization properties of the stubbles and the straw, however, dominate at all angles of incidence. These properties are similar to those of the crop canopy before harvest and differ from those of bare soil (table 7.2). The VV-HH backscatter difference is typically negative at the low and medium angles of incidence, and positive at high angles of incidence for both the canopy and the stubbles. Therefore no differentiation can be made between the unharvested crop and the stubble-field on the basis of the VV-HH backscatter difference (at all angles of incidence).

Table 7.1: change in VV backscatter with the harvesting of the crop, 1979. The change in backscatter of bare soil on the corresponding days is also included.

Crop	transition	incidence angle 20	50	70
Summer wheat Arminda	crop --->stubble	+3.1	+3.5	+2.0
bare soil		+0.1	+0.2	+0.2
Winter wheat Adonis	crop --->plough	-3.5	+2.9	-1.2
bare soil		-3.9	-2.7	-3.0
Barley Aramir	crop --->stubble	+1.4	+1.1	-1.6
bare soil		+0.1	+0.2	+0.2
Barley Aramir	stubble --->plough	+0.2	-0.4	-3.3
bare soil		-3.9	-2.7	-3.0
Oats Leanda	crop --->stubble	-1.7	-2.2	-1.3
bare soil		-3.9	-2.7	-3.0

Table 7.2: backscatter difference VV-HH for the canopy before harvest, for stubble and ploughed fields just after harvest, and for bare soil in the same period, 1979. N.b: soil 1 = relatively smooth surface, soil 2 = relatively rough surface.

Crop		incidence angle 20	50	70
Summer wheat Arminda				
	canopy :	-1.3	-0.9	+1.2
	stubble:	-1.2	-0.2	+2.0
Winter wheat Adonis				
	canopy :	+1.3	-0.6	+1.1
	plough :	0.0	0.0	-0.2
Winter wheat Okapi				
	canopy :	-2.5	-3.1	-0.3
Barley Aramir				
	canopy :	0.0	-0.7	+1.1
	stubble:	-1.1	-1.3	+1.1
	plough :	-0.5	-1.0	-1.4
Oats Leanda				
	canopy :	-3.6	-3.3	+1.3
	stubble:	-0.5	-1.1	0.0
soil 1		+0.5	+2.0	+1.0
soil 2		0.0	-0.1	-0.2

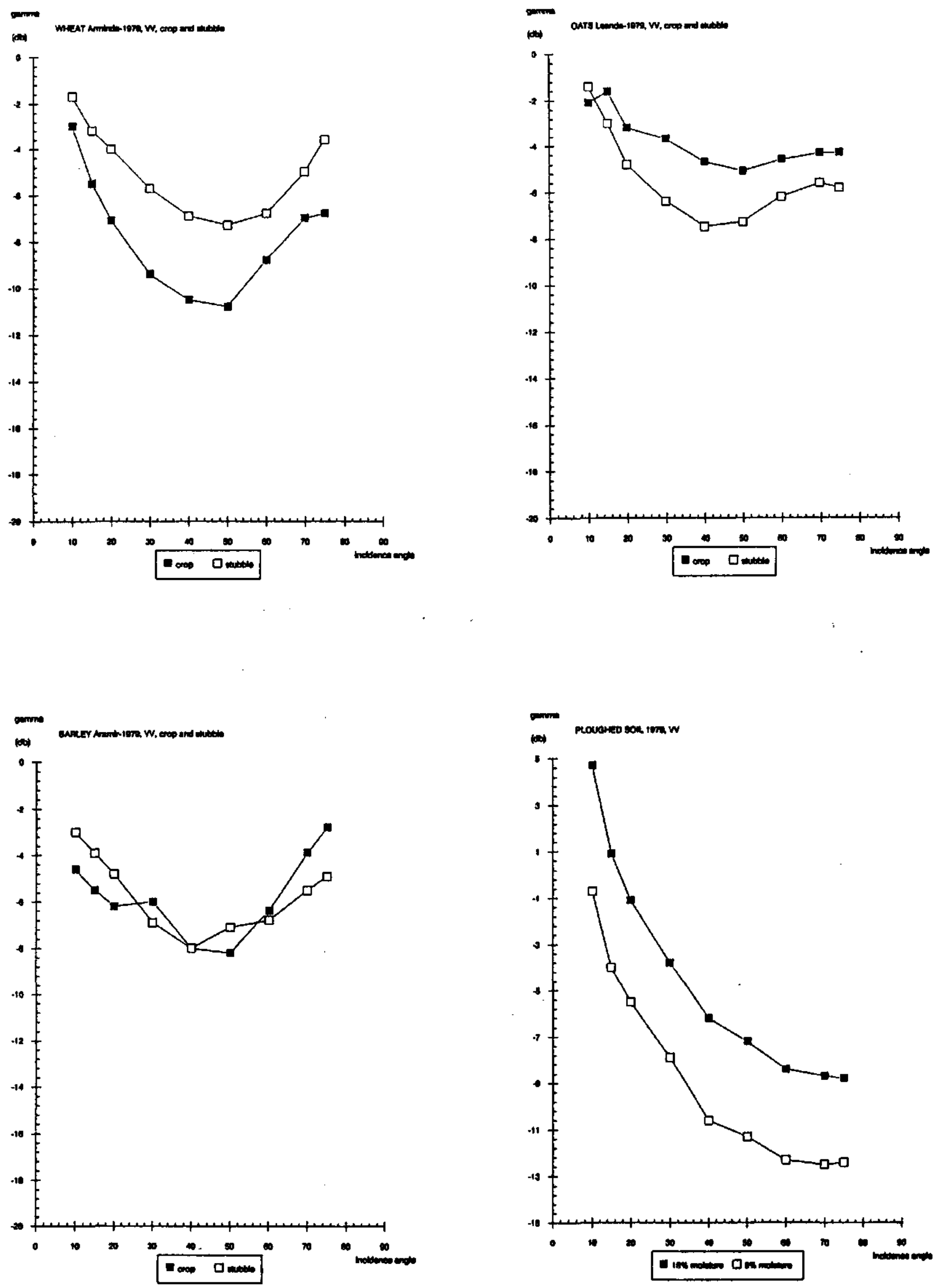


Figure 7: VV and HH radar backscatter versus incidence angle of a ripened crop and the stubble-field after harvest for winter wheat (7.1), oats (7.2), barley (7.3), and that of bare soil (7.4), 1979.

The transition in radar backscatter of the canopy of oats to that of stubble-field after harvesting differs from that of the other crops (fig 7.2). The radar backscatter decreases about 2-3 dB at all angles of incidence, but the angular dependency remains similar to that of the crop. The absolute change best ressembles that of bare soil in the same days (table 7.1). After harvesting, the temporal curve of the stubble-field ressembles that of bare soil at all angles of incidence (unlike Arminda). Even at medium and high angles of incidence the stubbles do not dominate the field of view so as to mask the influence of the soil background. Therefore, the masking of the soil background at these angles of incidence for Arminda is probably caused by the straw left in the field and not by the stubbles.

The VV-HH backscatter difference of the ripe crop before harvesting is similar in sign as for the other crops, but different in magnitude (table 7.2). This difference may be caused by the special structure of oats before harvesting. The crop is not only lodged but also mechanically beaten down to 30 cm height above the ground. After harvest, the VV-HH difference of the stubbles differs from that of the canopy, and is in the order of magnitude of that of the other stubble-fields. Differences of about 0.5-1 dB can be caused by differences in roughness of the underlying soil and in orientation of the stubbles.

For barley, backscatter measurements are made of the ripened crop before harvest, of the stubble-field after harvesting, and of the bare soil after ploughing. Like for Arminda, the change in the backscatter of the crop to that of the stubble does not ressemble that of bare soil in the same days (table 7.1). Therefore, this change is attributed to differences in the canopy/stubble. The change in the backscatter of barley, however, differs from that of Arminda (fig. 7.3). The angular dependency curve of the radar backscatter of the stubbles is very similar to, and on the same level as that of the crop prior to harvest. After the ploughing of the field, the temporal curve ressembles that of bare soil at all angles of incidence (like for Adonis). The polarization properties of the stubbles better ressemble those of the canopy prior to harvest than those of the ploughed field (table 7.2). For barley, the VV-HH difference of the ploughed field differs from that of Adonis and from that of the rough soil surface.

The effect of harvesting on the backscatter of the lodged Adonis differs from that of Arminda. The transition from ripened crop to ploughed field is accompanied by an increase in radar backscatter at the medium angle of incidence, and by a decrease at low and high angles of incidence. This decrease at low angles of incidence coincides with a similar decrease in backscatter of bare soil. After harvesting and ploughing of the field the temporal curve ressembles that of bare soil at all angles of incidence. In this respect, differentiation can be made between a harvested ploughed field and a harvested stubble-field. The polarization properties of the ploughed field also ressemble those of the rough soil surface and differ from those of the ripened crop before harvest (table 7.2). Based on the VV-HH backscatter difference, differentiation can be made between the ripened crop and the harvested, ploughed field.

The backscatter of Okapi increases at low and medium angles of incidence from the period of yellowing until the last radar measurement. At high angles of incidence no changes occur in the (stable) pattern of backscatter from the period of grain filling onwards. The fluctuations that occur in the curves of the backscatter during the last days of measurement (1.5-4 dB) do not match the peaks and dips that occur in the curves of bare soil. Despite the low water content of the ripe crop, there is no influence of the soil background (at any angle of incidence) on the radar backscatter of the crop. The difference in backscatter at VV and HH is the same at all angles of incidence as during the period of ripening before.

From these observations, the following generalizations are summarized:

1) There is no consistent change in radar backscatter in the transition of a ripe crop to a stubble-field or to a ploughed field. The angular dependency curve of the radar backscatter of a stubble-field is similar in shape (hollow) to that of a ripe crop canopy and differs from that of bare soil. The level of the curve may either be higher or lower (+/- 1-3 dB), or on the same level.

2) The temporal curve of the radar backscatter of a stubble-field (without straw) ressembles that of bare soil at all angles of incidence. The level of the radar backscatter, however, is different. Straw left on the field may mask the influence of the soil background at medium and high angles of incidence.

3) The VV-HH backscatter difference of a ripe crop depends on the structure of the canopy, e.g. erect, lodged, flattened. It is generally larger (positive) at high angles of incidence and smaller (negative) at low and medium angles of incidence. The VV-HH backscatter difference of a stubble-field generally ressembles that of a ripe crop, while that of bare soil differs from both that of a ripe crop and that of a stubble-field. The latter depends on the roughness of the surface, e.g. smooth, rough, ploughed.

Based on these generalities, the following conclusion is drawn. No unambiguous information regarding the harvesting of cereals can be derived from the X-band radar backscatter (non-imaging) at both VV and HH polarization. Management practices, such as the leaving-behind or the removal of the straw, or the ploughing of the stubble-field, affect the radar backscatter of the harvested field. The transition of ripe crop to stubble-field can not be determined, even when observations are made at several angles of incidence. With multi-angle observations, the transition to a ploughed field is more easily recognised. If the ripe crop masks the influence of the underlying soil (like the cereals in 1979), the harvested field (stubble-field or ploughed) can be recognised by comparison of the temporal curve with that of bare fields. If the soil background already influences the radar backscatter of the ripe crop, (like for instance wheat in 1977, large row spacing) it becomes difficult to recognise the harvested field.

Part II.

Radar backscatter and crop-growth and development

8. Wheat

8.1. Crop development

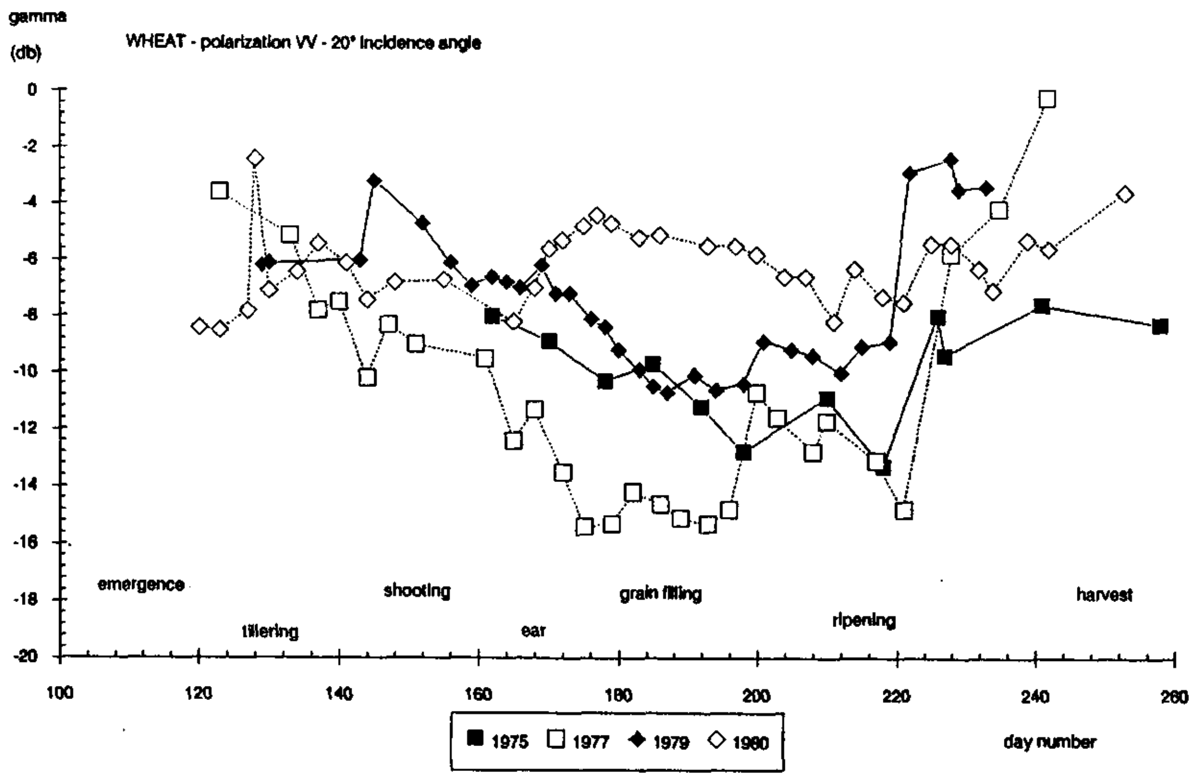
8.1.1 Backscatter curves 1975-1980

A large number of temporal radar backscatter curves is acquired for wheat in the years 1975-1980 (figs. 8.1.a/c). Though there is a similarity in the general shape, a large spread is present between the various curves. This spread decreases with increasing incidence angle. It is about 10 dB at 20° incidence angle, 7 dB at 50° and 5 dB at 70° during the phase of grain filling. This agrees with observations in previous chapters on the effects of row spacing, row direction and crop variety. At low angles of incidence, differences in attenuation and backscatter properties of the canopy result in the largest differences in radar backscatter. On the one hand this is caused by the relatively important contribution of the soil background, and on the other hand by that of the distribution of the scatter elements in the top of the canopy.

The backscatter of wheat in 1980 deviates most from that of the other crops. The familiar pattern of decreasing backscatter from the stage of stem elongation to that of grain filling at both the low and the medium angles of incidence is absent. Instead, the backscatter at 20° and 50° rises after day 165 and decreases slowly during the phase of grain filling. This pattern, and most of the fluctuations in the curves agree with similar features in the backscatter curves of bare soil in 1980. The growth and development of the crop is in all aspects worse than that of the crops in other years. The soil cover, crop height and biomass are the lowest throughout the growing season (figs. 8.2.a/c). The canopy of the crop is very open with a relatively low amount of biomass. This results in a high transparancy for microwaves and a relatively large contribution from the underlying soil surface. Since there was much rain in 1980, the soil moisture content and (thus) the backscatter from the soil background is high. In combination with the relative transparancy of the crop, the resulting backscatter rises above that of the crops in the other years. None of the characteristics of wheat are present in the backscatter curves at either state of polarization. When the backscatter is studied at both VV and HH, the familiar VV-HH differences are only observed at medium and high angels of incidence (fig. 8.3.a/c). At medium angles the backscatter at VV is generally smaller than at HH, and at high angles the backscatter is larger at VV. At these angles of incidence, the polarization properties of the canopy are dominating despite the large influence of the soil background. At low angles, the influence of the soil is too large and dominates the polarization properties of the crop as a whole. The backscatter at VV is similar to 1 dB lower than that at HH while in normal years this difference is much larger.

Like for stubble-fields, it is concluded that the level of the radar backscatter of this crop is dominated by the soil background, while the polarization properties (at high and medium angles of incidence) seem determined by the canopy.

The other interesting example is wheat in 1977 (al, row spacing 12.5 cm). This year, the typical features in the radar backscatter curves are most pronounced. At low and medium angles of incidence the backscatter decreases to the lowest level of all years. At high angles the backscatter first increases to the highest level in the early period of vegetative growth,



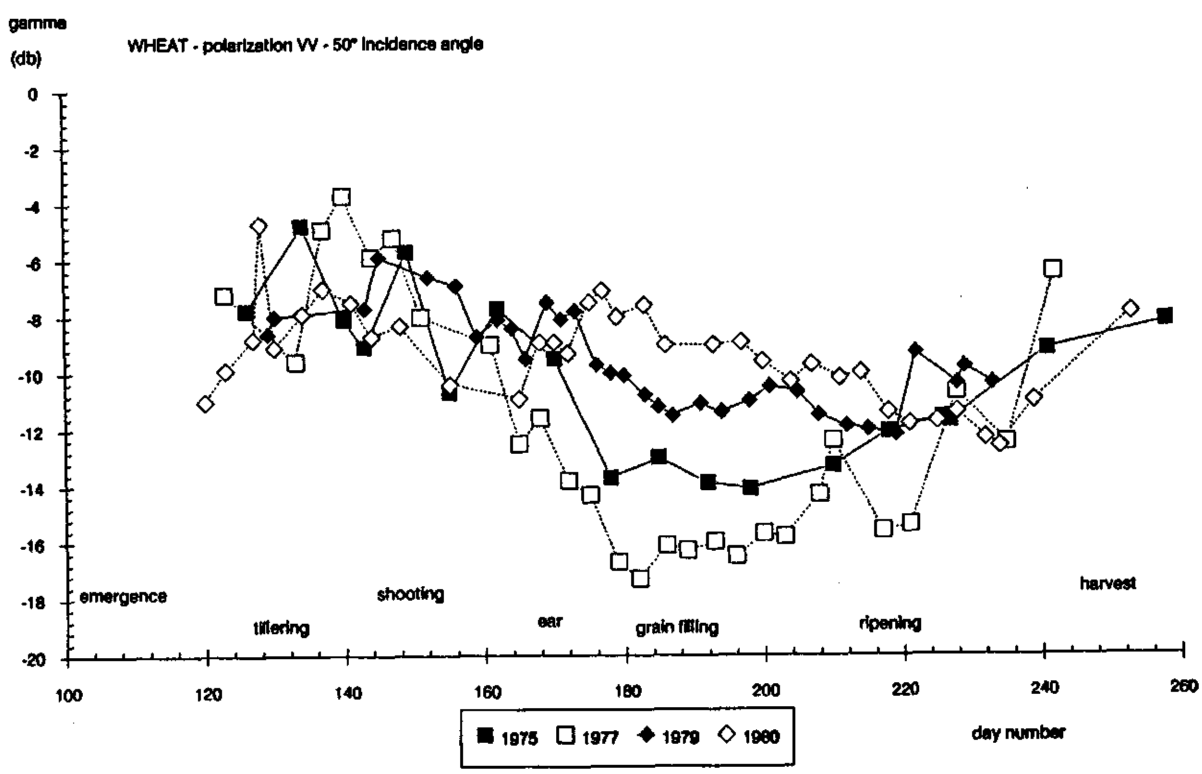


Figure 8.1: VV radar backscatter at 20° (8.1.a) and 50° (8.1.b) incidence angle of wheat, 1975-1980.

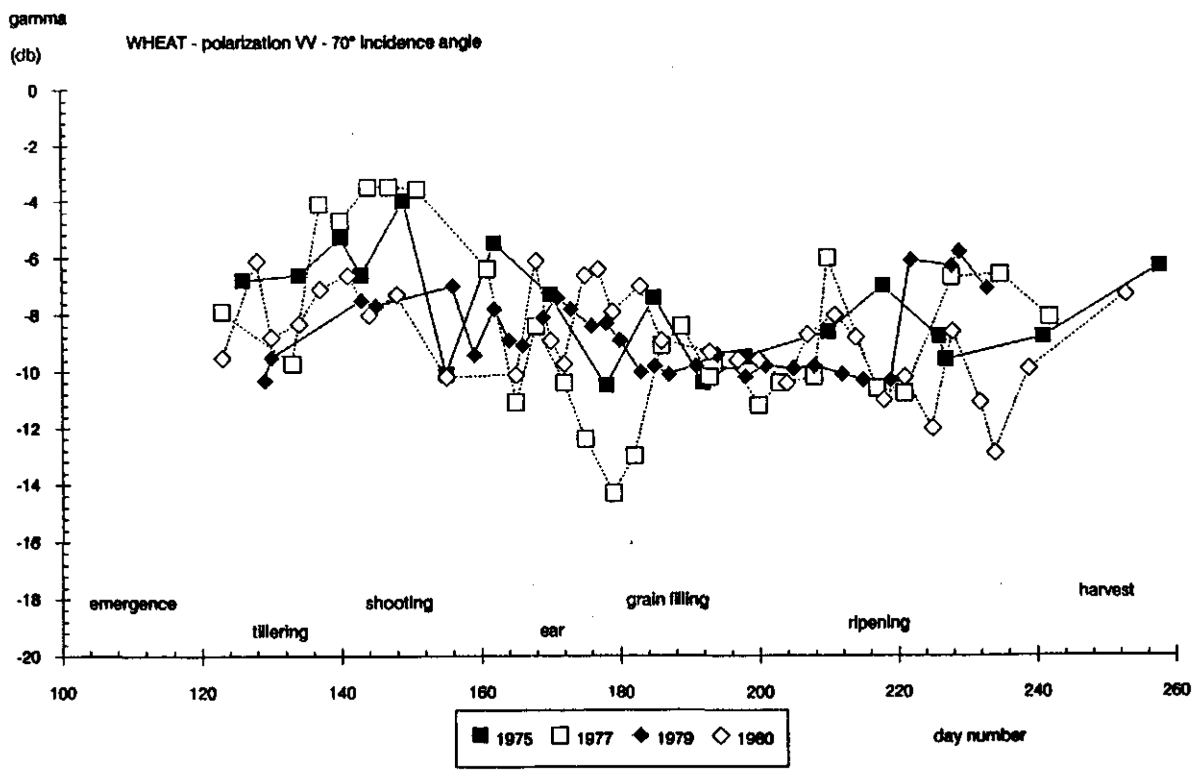


Figure 8.1.c: VV radar backscatter at 70° incidence angle of wheat, 1975-1980.

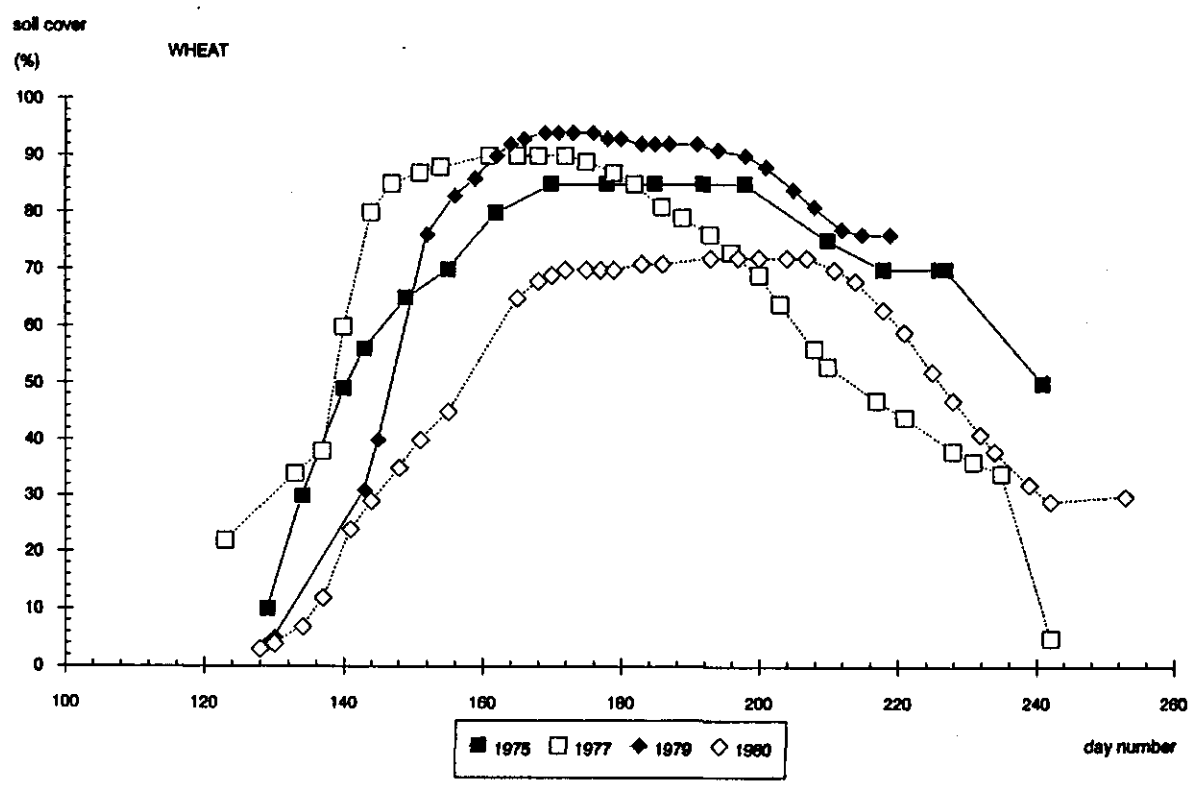


Figure 8.2.a: soil cover of wheat, 1975-1980.

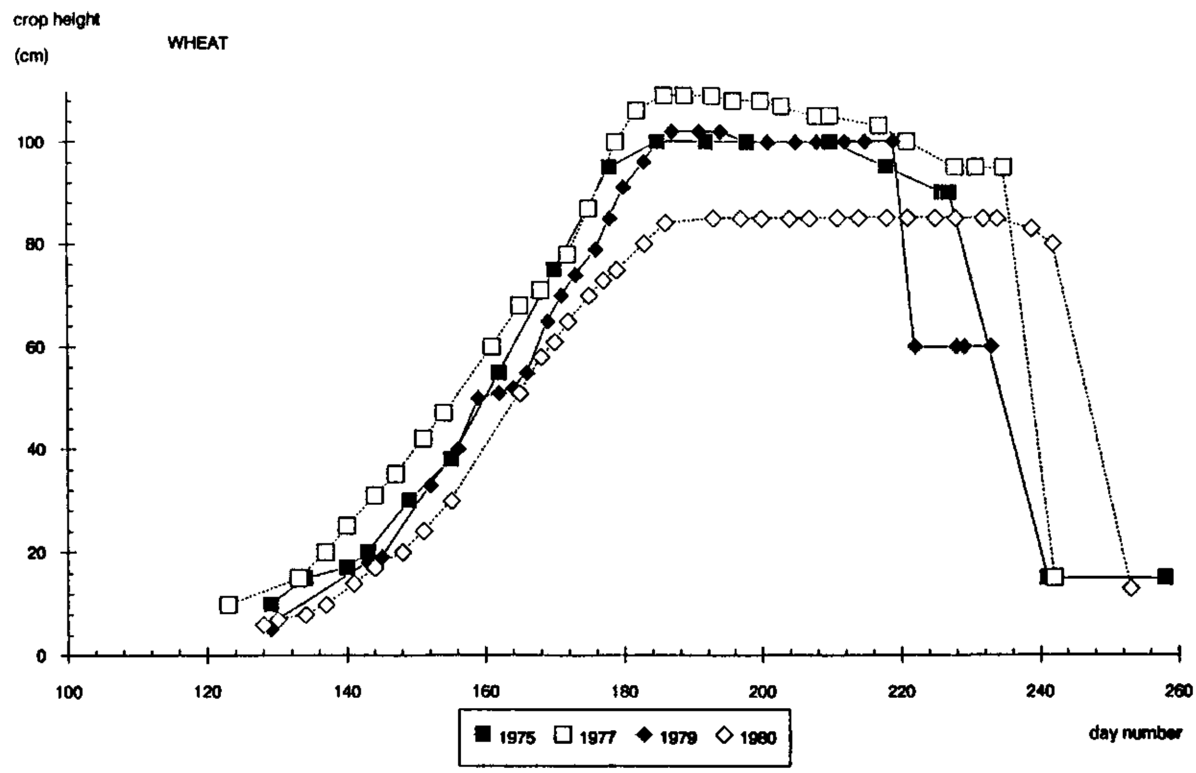


Figure 8.2.b: crop height of wheat, 1975-1980.

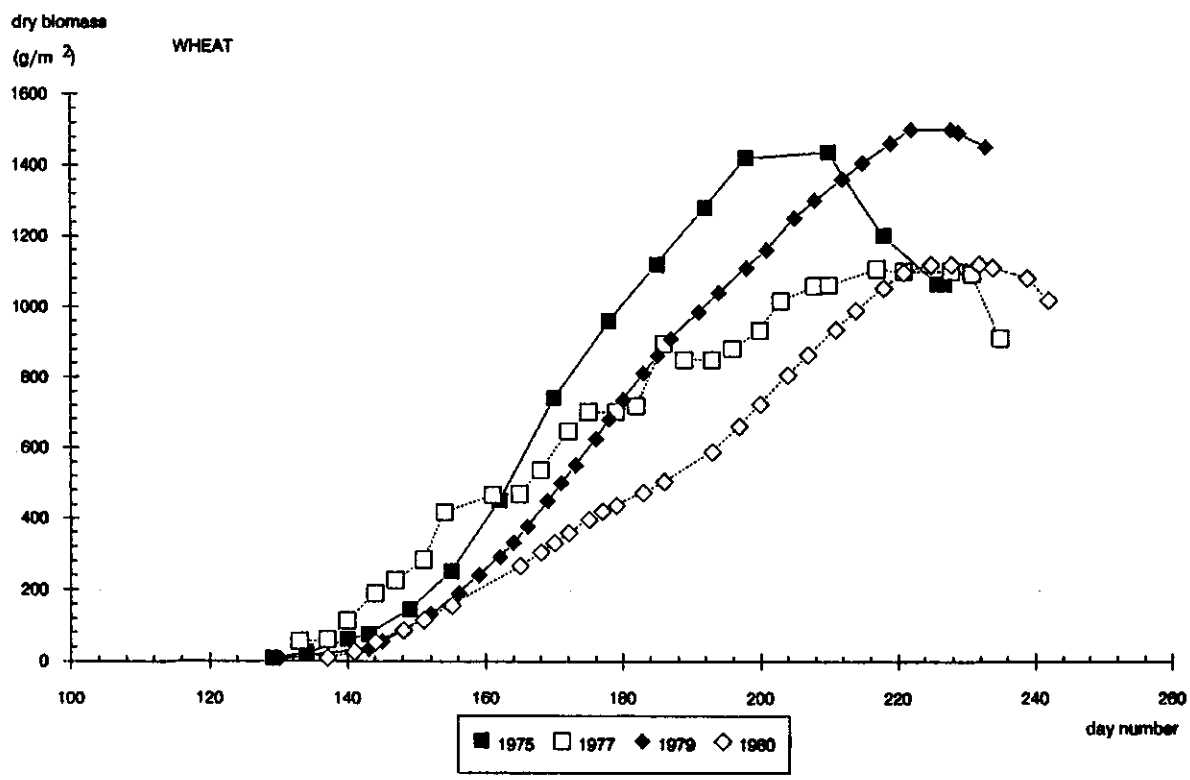
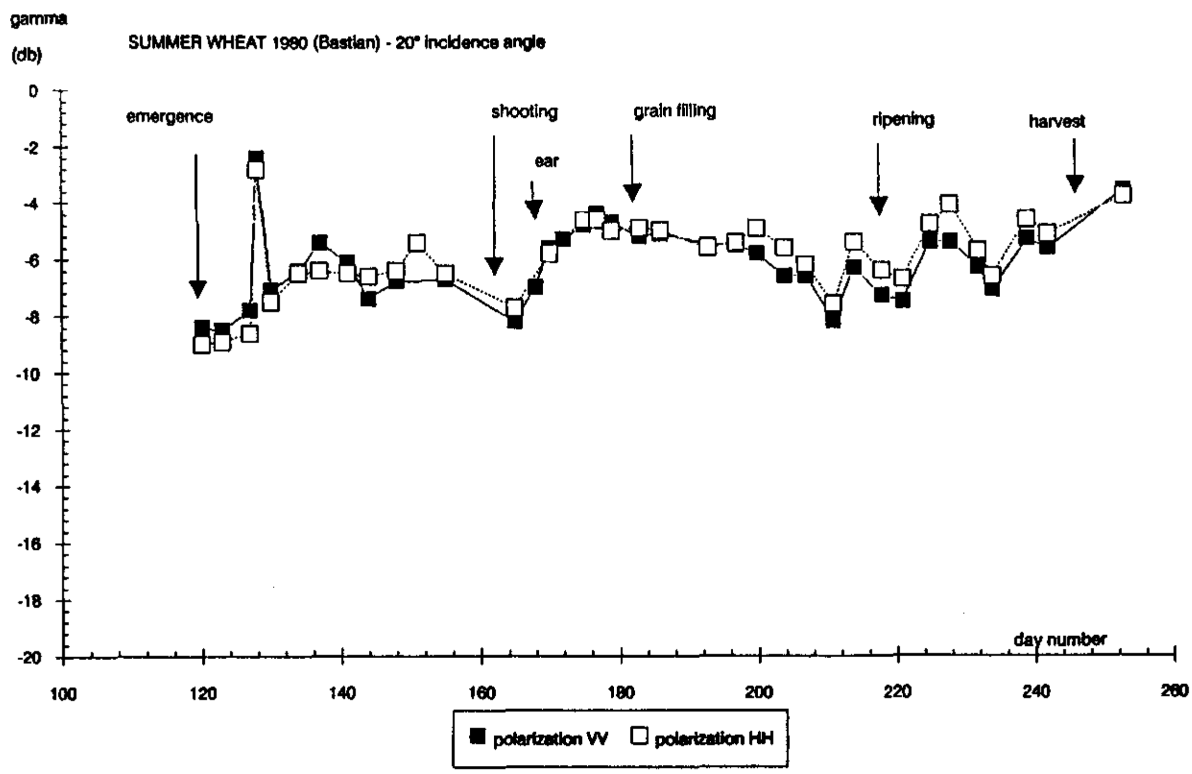


Figure 8.2.c: dry biomass of wheat, 1975-1980.



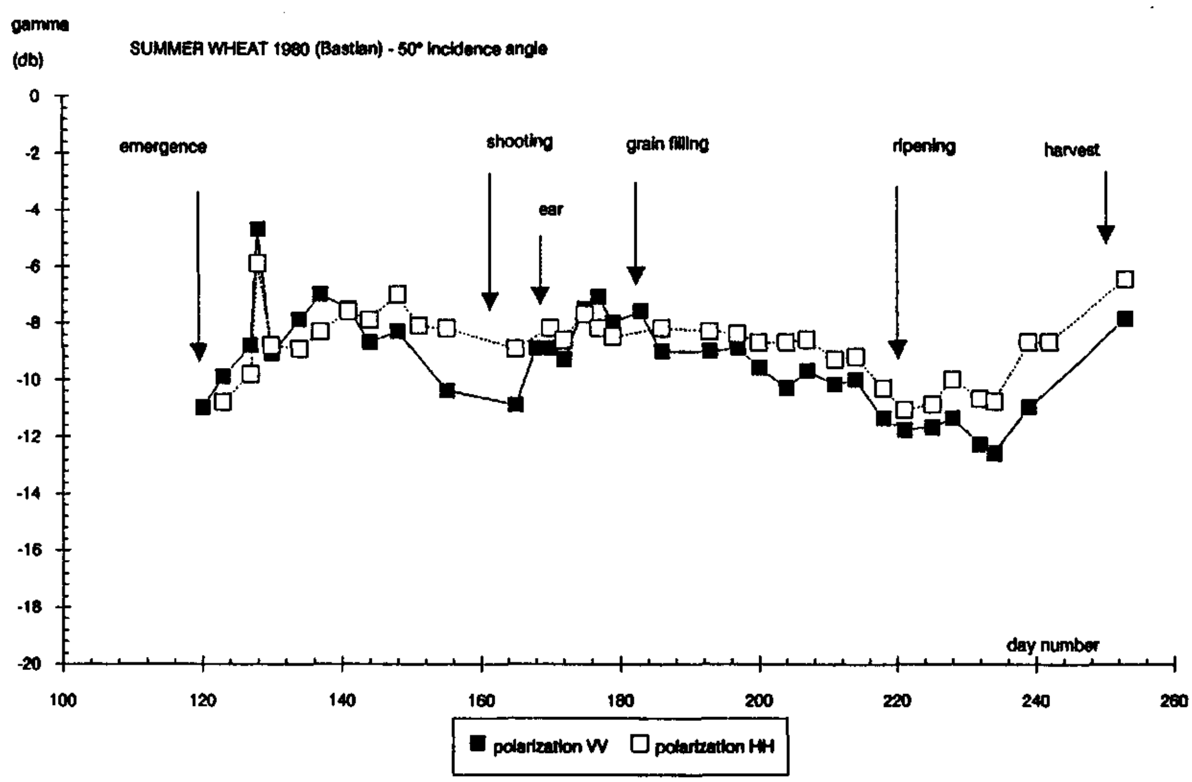


Figure 8.3: VV and HH radar backscatter at 20° (8.3.a) and 50° (8.3.b) incidence angle of wheat, Bastion 1980.

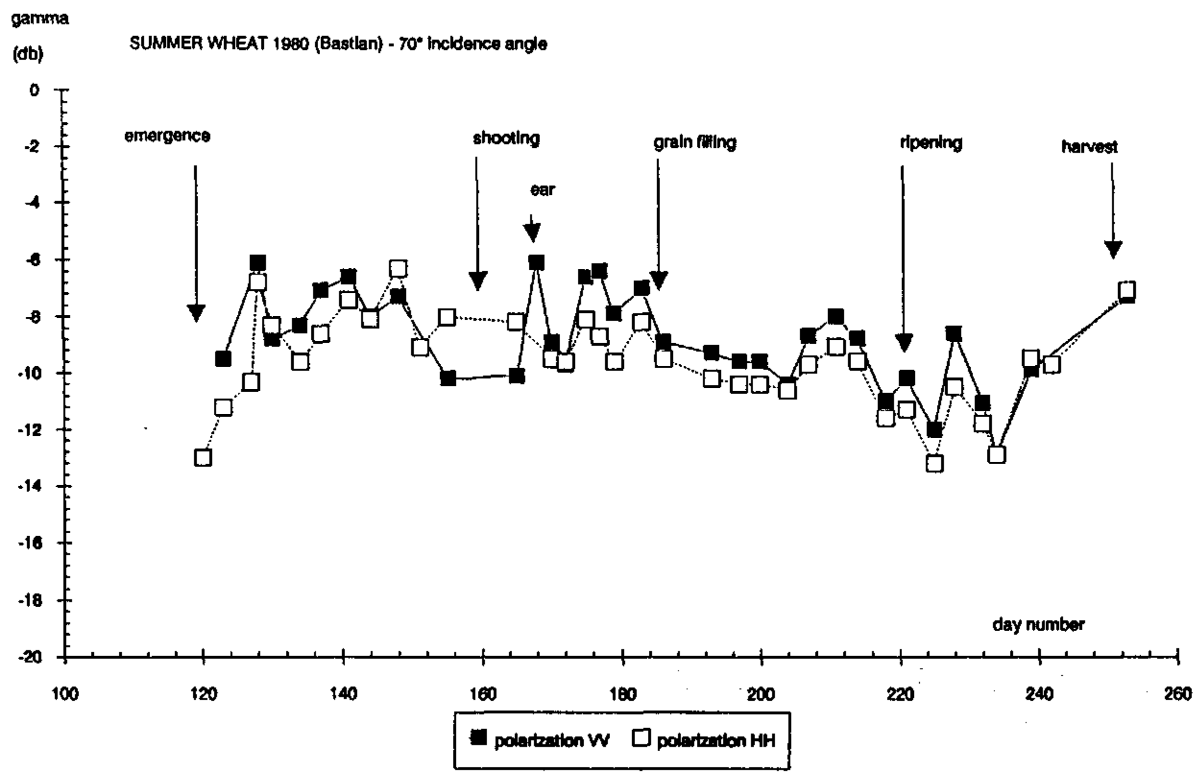


Figure 8.3.c: VV and HH radar backscatter at 70° incidence angle of wheat, Bastion 1980.

and then decreases to about the lowest level in the period of grain filling. These typical features diminish in dynamics with increasing row distance. Despite these pronounced features in the backscatter curves, the canopy appears more transparant for microwaves than, for instance the crops in 1979. The influence of the soil background is dominating from day 200 onwards because of the high soil moisture content. In 1979, hardly any influence of the soil background is notable throughout the growing season.

Compared to the crops in other years, wheat in 1977 does not take an extreme position in growth and development. The growth in biomass is slower than in 1979 and 1975, and the final yield is similar to that in 1980 (low). The increase in soil cover is fast during the early growing season but the decrease starts relatively soon in the period of grain filling. The growth of crop height is average but the final height attained is a little larger than that of the other crops. The combination of these crop parameters indicates a high, thin crop with a relatively high transparancy for microwaves. The fact that the backscatter reaches very low levels at the stage of grain filling is probably partly caused by the dry weather that year. This resulted in low moisture contents of the topsoil, and thus in low contributions from the soil background (until day 200). If the weather was rainier like in 1980, a larger contribution from the soil background might have resulted in higher values of the radar backscatter of the crop. The other cause for the low radar backscatter is the scatter properties of the canopy itself. These properties are not related to crop growth parameters like biomass or soil cover. During the phase of grain filling, after day 180, both the soil cover and the biomass of the crops in

1977 and 1980 are lower than those in 1975 and 1979. However, the backscatter levels of the crops in 1977 and 1980 are respectively much lower and much higher than those in 1975 and 1979. The only crop parameter that ressembles this pattern is that of crop height, e.g. crop height is lowest in 1980 and highest in 1977.

8.1.2 Radar-morphological development scale

The shape of the temporal backscatter curves can be related to the development of the crop. A general development scale for cereals is proposed here to describe this relation. It is based on both the morphological and the radar backscatter characteristics of the crop. Therefore it is not readily comparable with development scales which derive from morpho-physiological characteristics. Table 8.1 gives the description of the proposed development scale and generally indicates comparable phases of development on the Feekes scale (E.C. Large, 1954). Fig. 8.4 pictures the stages of development on both scales with schematisized morphological appearances of the crop.

The stages 1-11 describe the normal of the crop from seed bed to harvest. The stages 21 and 22 designate lodging in respectively the period of grain filling and the period of ripening. Stage 30 indicates the harvesting of the crop. If any details on the management practices after harvest are known, the stages 31-33 can optionally be used to designate respectively a stubble-field, ploughed soil or harrowed soil.

Table 8.1: radar-morphological development scale for the description of crop development of cereals.

stage	description	Feekes scale
0	seed-bed	-
1	soil cover 0-20%	1- 3
2	soil cover 20-50%	3- 5
3	soil cover >50%; beginning stem extension	5- 7
4	shooting 1st and 2nd leaf; booting	8-10
5	ear formation from the opening of the flag leaf sheath	10
6	ear stem formation	10
7	grain filling; yellowing at the bottom	10-11
8	grain filling; yellowing 2nd leaf	11
9	ripening; yellowing 1st leaf; dry weight% ear> 40%	11
10	dying; brown leaves; dry weight% ear> 50%	11
11	thresh ready; ears bent; dry weight% ear> 80%	11.4
21	lodged in grain filling stage (7,8)	10-11
22	lodged in ripening stage (9,10,11)	11
30	harvest	-
optional:	31: stubble field	
	32: ploughed field	
	33: harrowed field	

To relate the temporal signature of the radar backscatter to the development of the crop, the (VV) backscatter is averaged per development stage over all wheat crops. This average is plotted on the introduced development scale (figs. 8.5.a/c). It is derived from ten plots of wheat; one in 1975, six in 1977 and three in 1979. The variation around the average values is given in plus and minus the standard deviation.

At 50° and 70° incidence angle the backscatter initially increases in the early growing season during stages 1-3.

Seedling growth and tillering takes place and the height of the crop remains relatively low. The increase in backscatter is the result of directional scattering in the backward direction from the canopy. The period of stem extension begins at the end of stage 3, and the backscatter at medium and high angles of incidence starts to decrease. At 20° incidence angle the backscatter decreases already from the first stage of development. The appearance of the flag leaf marks the beginning of stage 4 and the onset of booting. From this moment, stem elongation really takes off and the crop increases rapidly in height. The backscatter at 50° and 70° incidence angle sharply decreases. The end of the booting phase introduces stage 5 with the bursting of the flag leaf sheath and the appearance of the first awns. During this stage the inflorence emerges and the backscatter decreases only a little (0.2-0.5 dB) at all angles of incidence. Stage 6 begins with the formation of ear stems and ends with its completion. With this new growth in crop height the backscatter decreases again at low and medium angles of incidence. At high angles the backscatter only decreases during the early phase of stage 6. The physiological process of anthesis generally takes place in this stage but it has no visible effect on the radar backscatter. Stage 7 begins when the formation of the ear stem is completed and no more growth in crop height takes place. The radar backscatter has reached its lowest level and it remains stable throughout this stage.

The physiological process that dominates the next period is that of grain filling and reallocation of organic matter. Newly assimilated organic matter, as well as old organic matter originating from the leaves and the stems, is transported to the grains. The biomass of the ears increases while that of the stems and leaves decreases. Furthermore, the crop looses plant water during dough development and ripening. The filling of the grains has little effect on the radar backscatter but the loss of plant water and green leaves results in a higher transparancy for microwaves. The latter also changes the backscatter properties of the canopy itself. Therefore, the division in development stages during the phases of grain filling and ripening is based on the loss of leaves (yellowing) and the drying of the canopy. In stage 7, only the leaves in the bottom of the canopy turn yellow and no effect on the radar backscatter is notable yet. In stage 8, the yellowing has progressed to the layer of the second leaves but still no large effect is notable. In stage 9 all leaves have turned yellow and the ears have ripened to less than 60% moisture content. At medium and high angles of incidence the backscatter increases by about 1 dB. A similar increase occurs during stage 10 when the canopy withers and all leaves have turned brown. Despite the low angle of incidence, the backscatter at 20° incidence angle increases hardly at all during the stages 8-10. It is therefore concluded that the increase in backscatter during these stages at medium and high angles of incidence does not result from an increase in the contribution of the underlying soil, but from

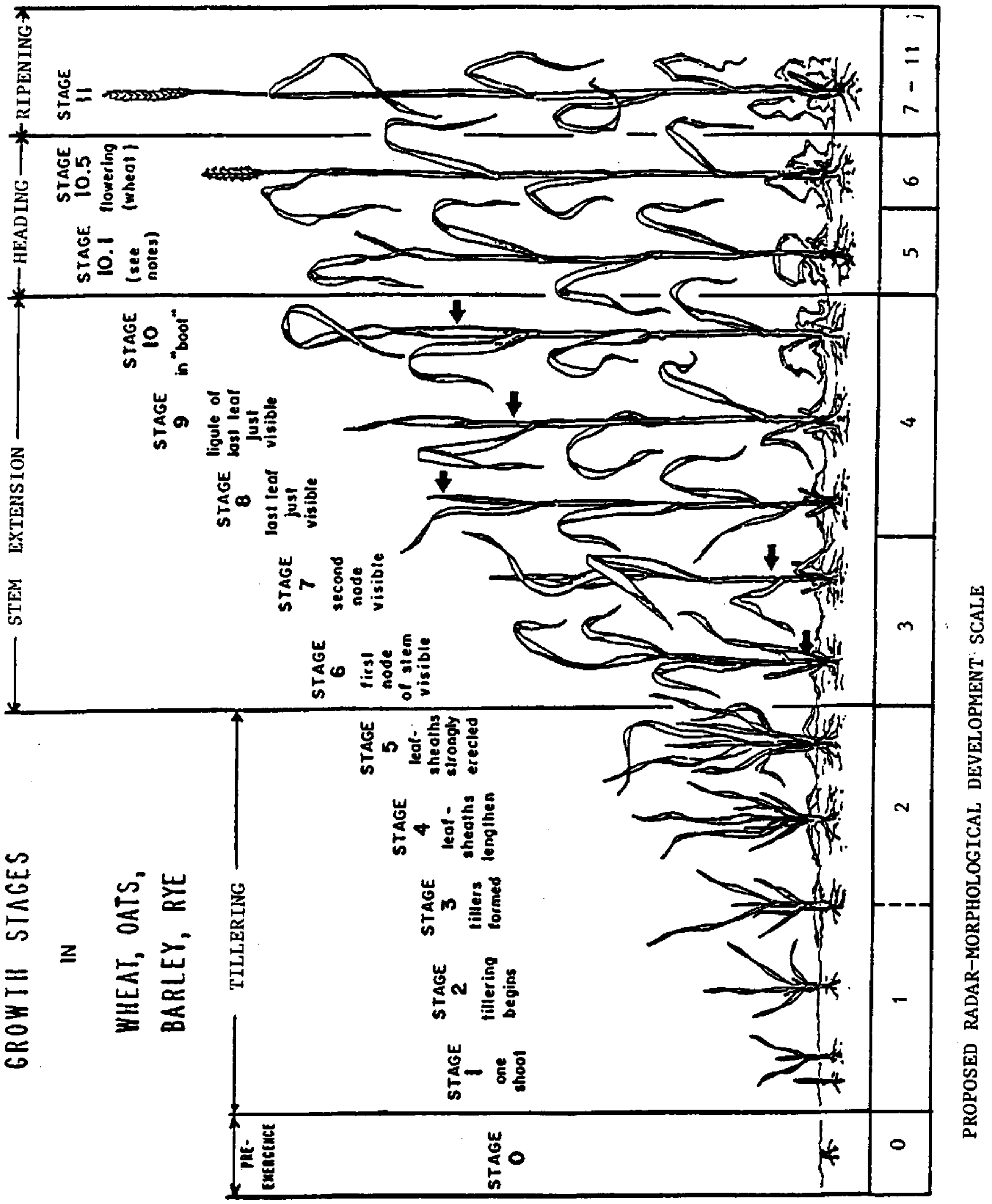


Figure 8.4: development stages of cereals. Illustration of the newly developed radar-morphological development scale and the Feekes scale, taken from E.C. Large, Plant pathology vol. 3, no. 4, december 1954, pages 128-129.

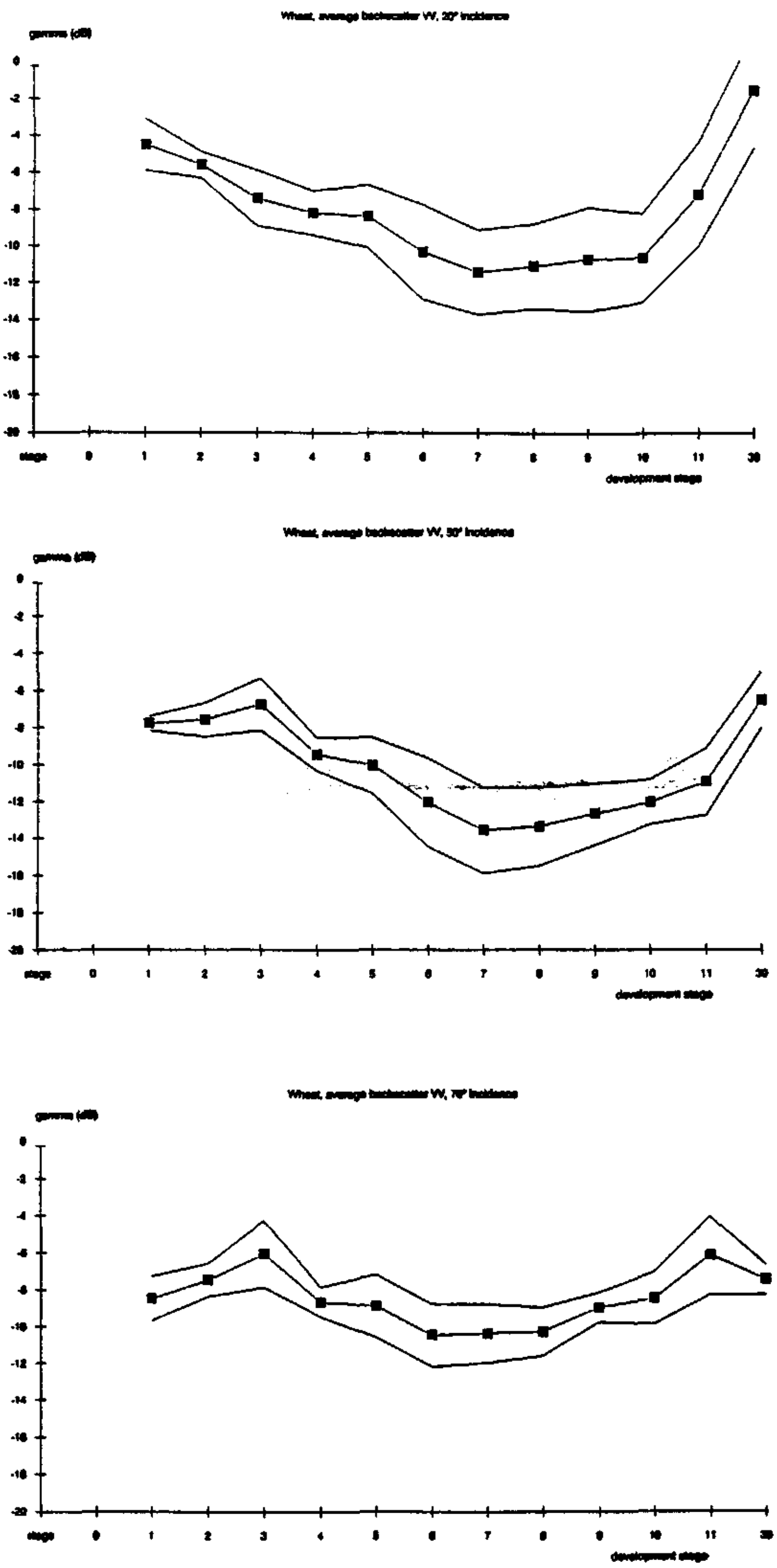
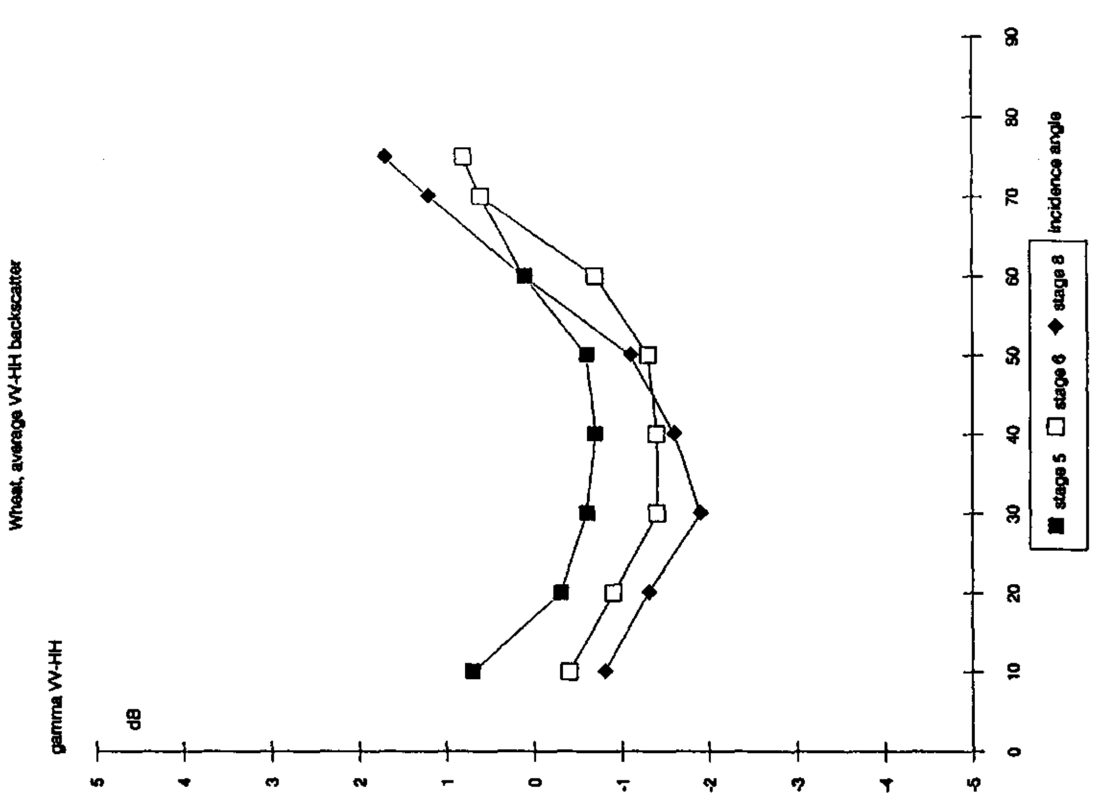


Figure 8.5: average VV radar backscatter at 20° (8.5.a), 50° (8.5.b) and 70° (8.5.c) incidence angle over all wheat crops (1975-1979) versus stage of the radar-morphological development scale. The standard deviation of the average is given by the two surrounding lines.



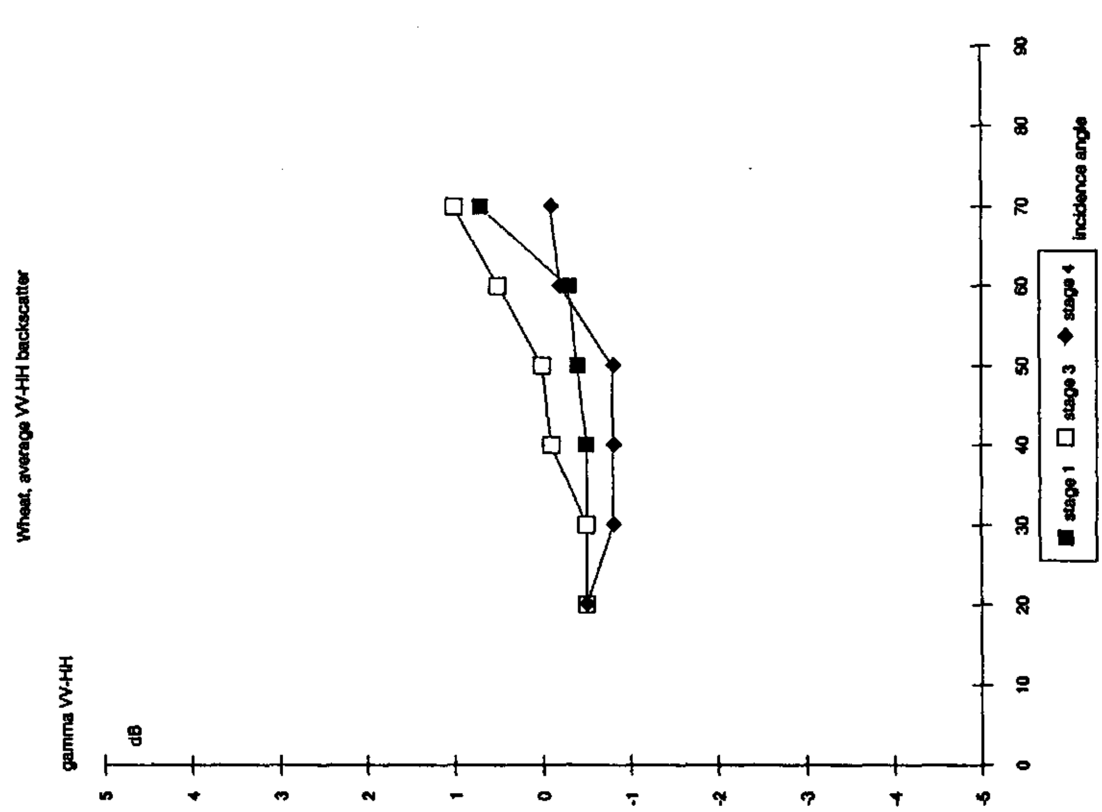


Figure 8.6: average VV-HH radar backscatter difference over all wheat crops (1975-1979) against incidence angle for the development stages 1, 3 and 4 (8.6.a) and 5, 6 and 8 (8.6.b)

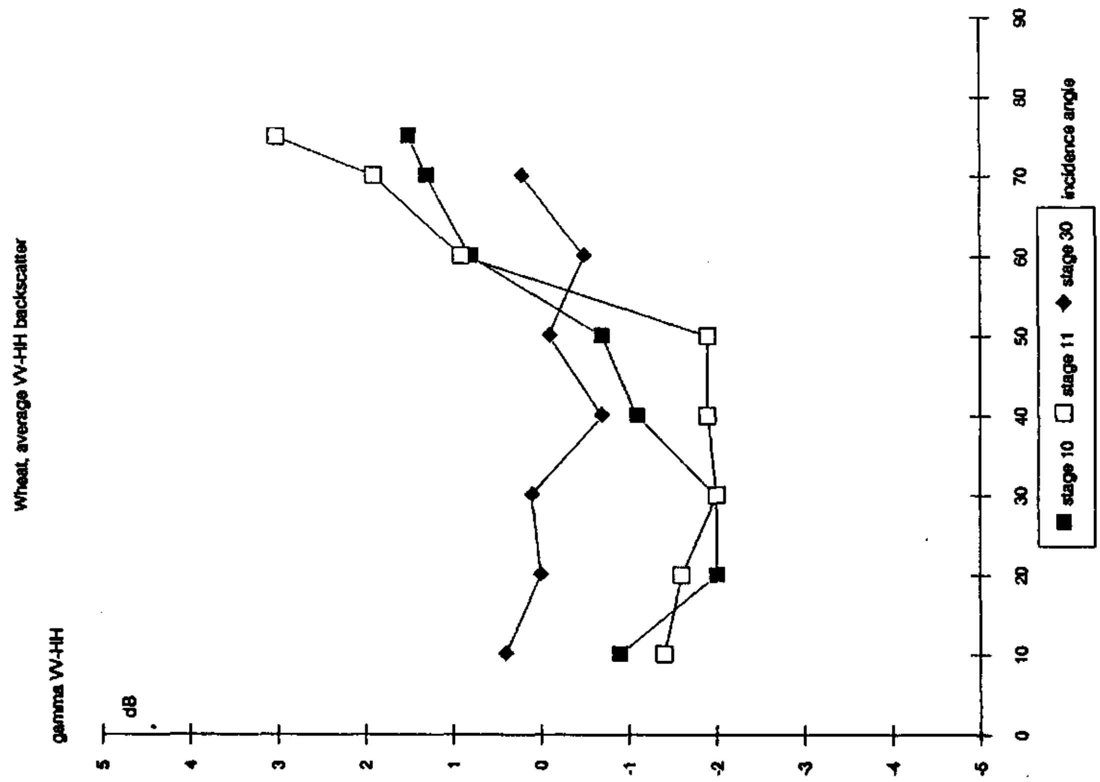


Figure 8.6.c: average VV-HH radar backscatter difference over all wheat crops (1975-1979) against incidence angle for the development stages 10, 11 and 30.

changes in the backscatter properties of the canopy itself. At stage 11 the crop is completely ripe and the moisture content of the ears has decreased to below 20%. Only in this final stage before harvest does the radar backscatter increase sharply at all angles of incidence. At harvest, stage 30, the backscatter has reached the level of that of the bare soil.

The shapes of the individual backscatter curves are similar to these average curves for all crops, except in 1980. The absolute value of the backscatter at the various stages, however, may differ with crop variety, management practice or external conditions. The standard deviation around the average value per development stage averages about 2 dB. Therefore, recognition of development stages by comparison of the absolute backscatter at a single state of polarization with this average curve does not seem feasible. Only some characteristics in the shape of the curve are indicative for the development of the crop. Typical bends in the curves occur around stages 7 and 10 at low angles of incidence, at 3, 7 and 11 at medium angles and at 3, 6 and 8 at high angles of incidence.

Besides the average radar backscatter at a single angle of incidence and a single state of polarization, observations at both VV and HH polarization and at multi-incidence angles are investigated on their information content. In an attempt to reduce the variation caused by management practices and weather influences, the backscatter is standardized by taking the difference between VV and HH polarization. The average VV-HH backscatter difference is given as a function of incidence angle for some stages of crop development (fig 8.6). The standard variation averages about 1-1.5 dB for all stages.

The angular curve of the VV-HH backscatter difference slowly changes in shape with the development of the crop. In stage 1, the curve is a near straight line between 0 and -1 dB. In stage 3, the curve has a small slope from about -0.5 at low angles to 1 dB at high angles. With increasing development, the shape of the curve becomes somewhat hollow in stage 4. With the formation of the ears and ear stems in stages 5 and 6, the curve is typically hollow. The VV-HH difference is relatively small at medium angles of incidence and relatively large at low and high angles of incidence. In the grain filling stages 7-10 the hollow curve becomes skewed. The VV-HH difference is largest at high angles of incidence (about +2 dB), smallest at medium angles (about -2 dB) and intermediate at low angles (about -1 dB). At the high angles of incidence, the field of view is dominated by the vertical ears and ear stems. Directional scattering in backward direction from these canopy elements at VV polarization results in the large positive VV-HH backscatter difference. The skewed shape of the angular VV-HH backscatter curve reaches its limiting form in the last phase of ripening, stage 11. The VV-HH difference is +3 dB at high angles of incidence while it remains about -2 dB at medium and low angles of incidence. After harvesting, stage 30, the VV-HH difference is straightened out at about 0 dB. For individual fields, the shape of the curve in this stage depends on the management practices after harvesting, e.g. removal of the straw, stubble field, ploughed field.

The fact that throughout the growing season, the VV-HH backscatter difference at low and medium angles is relatively small (negative), and at high angles of incidence relatively large (positive) can be used for the discrimination of wheat (or barley, chapter 9) from other crops (e.g. oats, beet, potato). The changes in the angular curve of the VV-HH backscatter difference between the development stages are very gradual, in the order of 0.5 dB only. These changes are of the same magnitude as that of the standard deviation around the average values. Therefore, only a general differentiation between the development phases of a crop seems feasible: the development stages 1-3, 4-6 and 7-11.

8.1.3 Conclusions

A precise monitoring of the development of wheat on the basis of a temporal signature of the radar backscatter does not seem realistic. Observations at a number of incidence angles at both VV and HH polarization do not increase the possibilities over observations at a well chosen single angle of incidence and single state of polarization. With 'normal' growth, an appraisel of the following generalised phases of development is possible from a temporal signature at a medium angle of incidence (table 8.2). 'Normal' growth means here the growth of a crop at non-stressed growing conditions. However, the example of wheat in 1980 illustrates that exceptions exist when the growth of the crop is extremely bad. With a low, transparant crop canopy, the backscatter of the soil background may dominate the total backscatter of the crop. No information on the crop development can then be derived from the temporal signature.

A further subdivision might be achieved in practice through interpolation between the differentiating features in the temporal signature. The difficulty in determining the harvesting of the crop is already discussed in Chapter 7. Dual polarization (VV, HH) measurements at more than one angle of incidence do not add new discriminative power to make any

Table 8.2: general phases of crop development of wheat which can be derived from a temporal backscatter signature at a medium angle of observation for a crop with 'normal' growth.

general phase	stage
emergence - tillering	1- 3
stem extension - heading	4- 6
grain filling - ripening	7-10
ripened crop	11

subdivision in these generalized phases. If only crude, or no temporal signatures are available, angular signatures can be used to discriminate between the same general phases of development.

In line with the findings in paragraph 6.2, the appearance of the ears is not a prominent feature in neither the temporal nor the angular signatures at both VV and HH polarization. A prominent feature is caused by the elongation of the stems in stage 4. The absolute backscatter and the angular signature gradually change until the end of the growth in crop height, without any influence of the appearance of the ears.

The specific differences in the backscatter at VV and HH polarization at medium and high angles of incidence can be used as (extra) discriminative property in the classification of crops.

8.2 Crop growth

8.2.1 Correlations

From the observations in part I of this report, it is concluded that there is no straightforward relationship between X-band radar backscatter and the biomass of the crops to explain the observed differences between the backscatter curves. Also, the level of the radar backscatter at grain filling (stages 7/8) does hardly correlate with any of the following parameters in the same period: crop height, soil cover, plant water and plant water density. The best correlation with the backscatter <u>level</u> still gives the height of the crop, $r^2 \approx 0.67$, with a clear tendency for the level to decrease with increasing crop height.

By correlation of the backscatter with a number of growth parameters during the whole growing season (height, cover, dry biomass, plant water), the single most-explaining factor can be derived (table 8.3). The radar measurements of all crops between 1975 and 1979 are lumped for a) the complete growing season, stages 1-30, and b) the period from emergence to grain filling only, stages 1-7. The crop in 1980 is excluded because of its extremely bad growth.

The negative sign of the coefficients of correlation indicates the decrease in radar backscatter with the increase in crop growth parameters. When the whole growing season is considered, the correlations with dry biomass, plant water and soil cover are low to very low ($r^2 \approx 0.60$-0.16) at all angles of incidence. The correlation is larger with crop height and r^2 attains values of 0.80 at medium angles of incidence. When the correlations are restricted to the first half of the growing season, stages 1-7, r^2

Table 8.3: coefficient of correlation r^2 for the relation between the VV backscatter and crop height, dry biomass, plant water and soil cover of wheat. All crops from 1975-1979 are lumped.

A: development stages 1-30, the number of data sets = 230

incidence angle	crop height (cm)	dry biomass (g/m^2)	plant water (g/m^2)	soil cover (%)
70	-0.50	-0.24	-0.39	-0.17
60	-0.72	-0.51	-0.41	-0.19
50	-0.80	-0.61	-0.32	-0.16
40	-0.81	-0.63	-0.29	-0.16
30	-0.76	-0.53	-0.29	-0.22
20	-0.66	-0.39	-0.36	-0.41

B: development stages 1-7, the number of data sets = 150

incidence angle	crop height (cm)	dry biomass (g/m^2	plant water (g/m^2)	soil cover (%)
70	-0.63	-0.55	-0.43	-0.16
60	-0.78	-0.73	-0.51	-0.30
50	-0.82	-0.76	-0.49	-0.36
40	-0.84	-0.78	-0.48	-0.41
30	-0.81	-0.74	-0.43	-0.45
20	-0.77	-0.69	-0.44	-0.57

increases with all parameters and at all angles of incidence. It is still highest with crop height (0.63-0.84) while it has increased with dry biomass to 0.55-0.78. With plant water and soil cover, the correlations remain low to very low ($r^2 \approx 0.57$-0.16). The low correlation with soil cover is surprising since it appeared as a backscatter influencing factor in the analysis of the cereals in 1977 (chapter 3). The relative large correlation with crop height agrees with the qualitative relationship between the radar backscatter and the growth of the crop. At low and medium angles of incidence the radar backscatter decreases with increasing crop growth until both reach a stable level in the period of grain filling.

Except with soil cover, the correlations are highest at the medium angles of incidence. With soil cover, r^2 increases from high to low angles of incidence. This is caused by the larger influence of the underlying soil at low angles of incidence. Going from medium to low angles, the relative importance of soil cover increases and that of crop height and biomass decreases.

The correlation between the radar backscatter and crop growth parameters does not increase when multiple regression is performed on combinations of these parameters. The coefficients of correlation r^2 only increase by about 0.01-0.03.

The relations between the radar backscatter at medium angles of incidence and the crop growth parameters during the development stages 1-7 are illustrated in figs. 8.7-8.9. The bad relation between the backscatter and plant water is evident (fig. 8.7). No general relation (kwadratic, exponential or logistic) can be fitted through these data points.

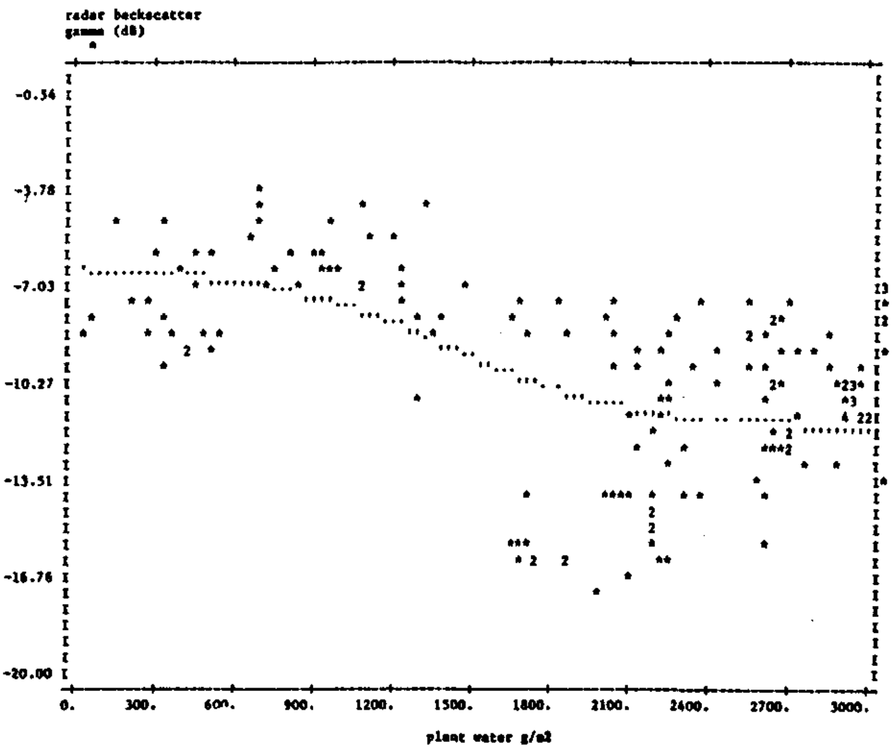


Figure 8.7: VV radar backscatter at 40° incidence angle versus plant water of wheat 1975-1979, development stages 1-7. An * indicates measured values and the line .... is the fitted logistic expression.

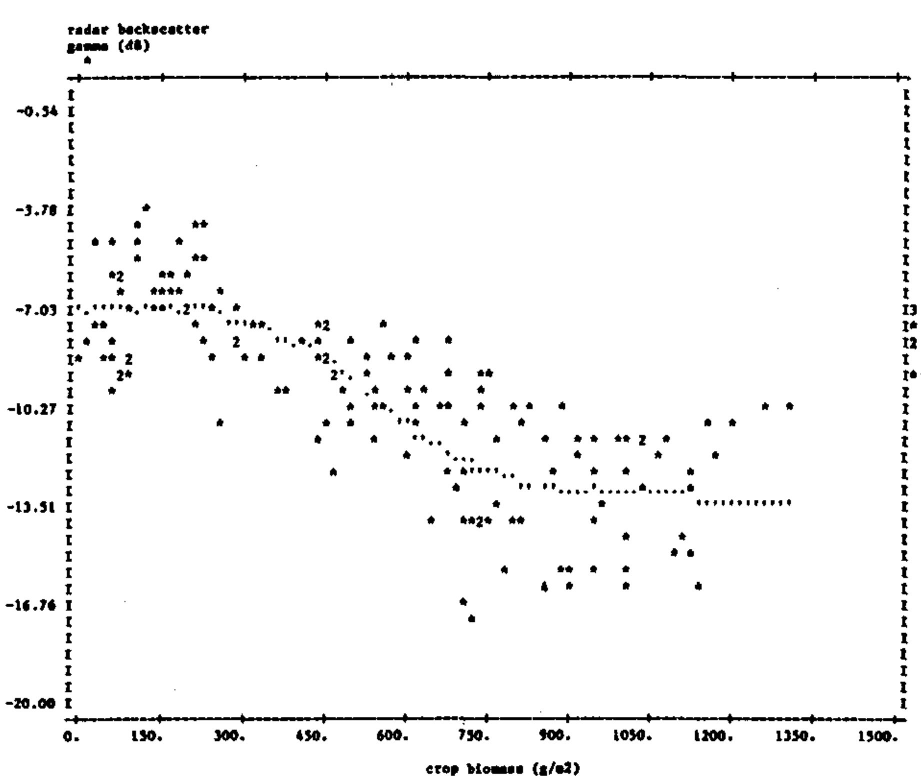


Figure 8.8: VV radar backscatter at 40° incidence angle versus dry biomass of wheat 1975-1979, development stages 1-7. An * indicates measured values and the line .... is the fitted logistic expression.

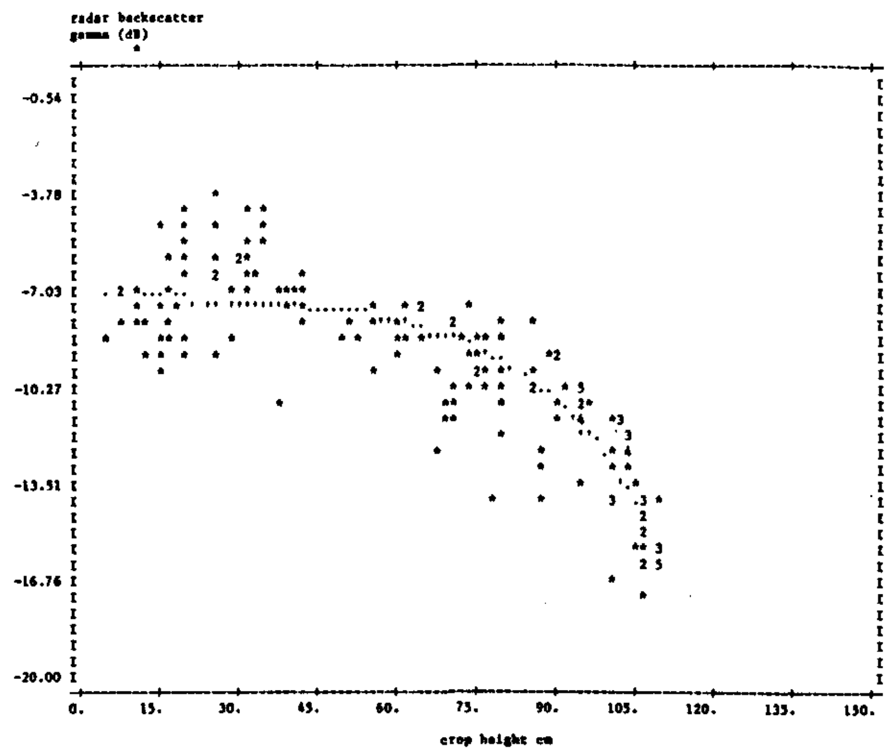


Figure 8.9: VV radar backscatter at 40° incidence angle versus crop height of wheat 1975-1979, development stages 1-7. An * indicates measured values and the line .... is the fitted logistic expression.

A better relationship exists between the backscatter and dry biomass (fig. 8.8). The backscatter decreases with increasing biomass until it stabilizes around -10 to -12.5 dB at biomass values of 1000 g/m^2. At larger biomass values the crop has entered the phase of grain filling and the radar backscatter no longer reacts on the increase in biomass. Therefore, direct monitorning of crop growth during the phase of generative growth is not feasible. Furthermore, because of the large spread in the data points, general kwadratic and logistic expressions only describe a general trend between the backscatter and biomass.

The best relationship with radar backscatter gives the height of the crop (fig. 8.9). After an initial increase of the backscatter with height, it decreases when the crop height exceeds 50 cm. The backscatter stops decreasing when no more growth in crop height takes place. Although the spread in the data points is still considerable, it is smaller than for dry biomass or plant water.

Summarizing, the correlations between the radar backscatter of wheat (all crops together) during the development stages 1-30, and the crop growth parameters soil cover, plant water and dry biomass are low to mediocre. The backscatter correlates best with crop height at medium angles of incidence, ($r^2 \approx 0.80$). When the correlations are restricted to the development stages 1-7, they are medium/fair with both crop height and dry biomass at medium angles of incidence, ($r^2 \approx 0.75$-0.85). The general trend between radar backscatter and dry biomass or crop height can be described with kwadratic and logistic expressions, but the spread in data points remains unexplained. This large spread in the data points is not related to any of the crop growth parameters but results from differences in the physical structure of the crop canopies and from influences of the soil background.

8.2.2 Estimating crop height and dry biomass

Direct monitoring of crop growth of wheat is not feasible after development stage 7. When the crop stops growing in height and enters the phase of grain filling, the radar backscatter reaches a stable level and does not respond to any increase in biomass. The direct monitoring of crop growth before stage 7 is possible, but it is associated with a degree of uncertainty. The crop height h and the dry biomass Wd can be estimated from backscatter measurements at medium angles of incidence by logistic expressions with empirically derived constants, e.g:

h = -5.8 + 115.5/[1+exp(0.50*(VV40+8.25))] (cm) [Eq. 8.1]

Wd = 86.6 + 821.0/[1+exp(0.91*(VV40+9.15))] (g/m2) [Eq. 8.2]

in which VV40 is the VV backscatter at 40° incidence angle. The constants are derived from regression through the data set of all crops together. The results of these estimations are summarized in table 8.4. The estimated values of dry biomass and crop height are plotted against the measured values for the development stages 1-7 (figs. 8.10 and 8.11).

Table 8.4: coefficient of correlation r^2 and standard error of estimate SEE between measured and calculated height and dry biomass of wheat, 1975-1979. The calculations are based on logistic relations between the crop parameters and the radar backscatter at 40° incidence angle.

parameter	development stages	r^2	SEE
crop height (cm)	1 - 7	0.83	19
	1 -30	0.81	19
dry biomass (g/m^2)	1 - 7	0.79	215
	1 -30	0.48	380

The estimations of crop height have the same accuracy when derived for the whole growing season as when derived for the development stages 1-7 only. The standard error of estimate SEE is about 20 cm in both cases. Especially at crop heights smaller than 50 cm, a whole cluster of estimated values deviates from the measured values. This is caused by the different soil types in the various years. The soil background dominates the radar backscatter of the crop in the early period of the growing season.

For the estimation of dry biomass it makes a difference whether the estimations are derived for the whole growing season or for the stages 1-7 only. The dry biomass can be estimated with an accuarcy of 215 g/m^2 only for values up to about 900 g/m^2. For both crop height and dry biomass, the correlations r^2 between estimated and measured values are reasonable, about 0.80.

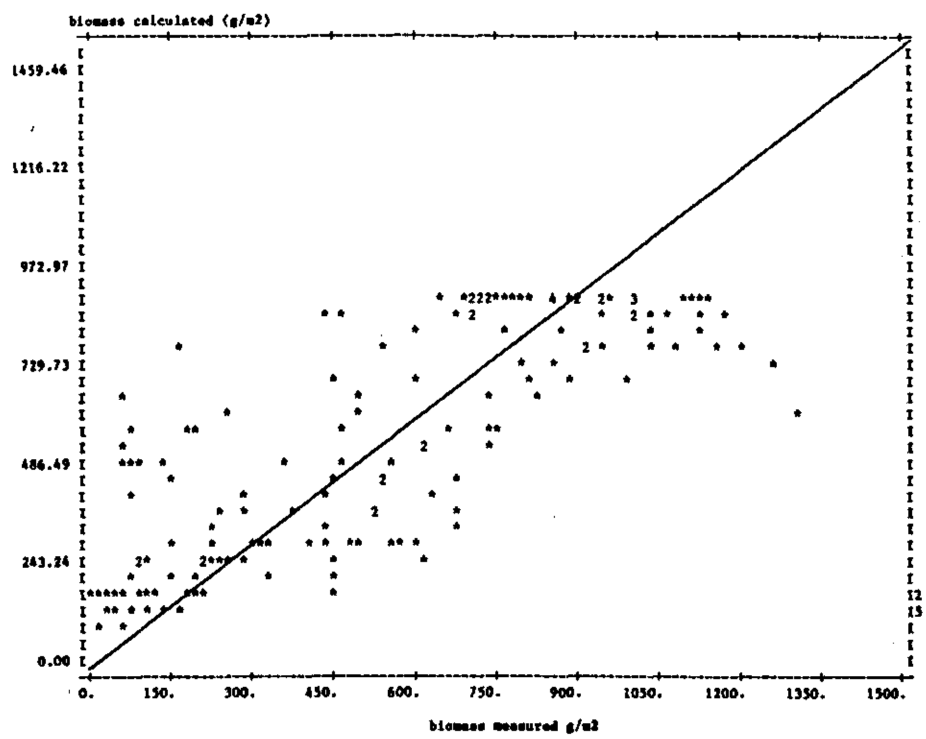


Figure 8.10: measured and calculated biomass from the VV radar backscatter at 40° incidence angle for wheat 1975-1979, development stages 1-7.

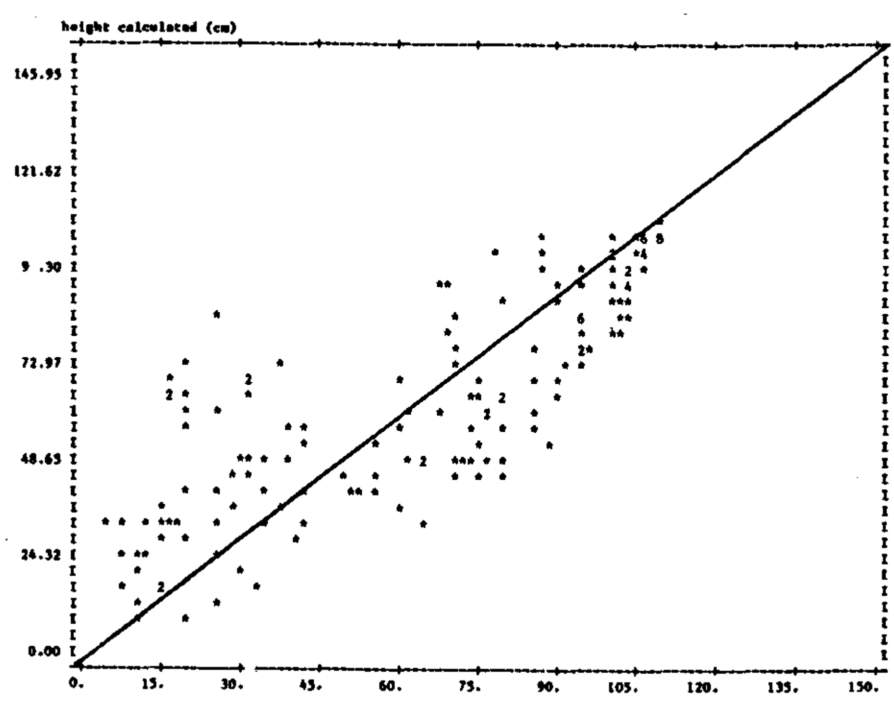


Figure 8.11: measured and calculated crop height from the VV radar backscatter at 40° incidence angle for wheat 1975-1979, development stages 1-7.

The empirically derived relationship between crop height and radar backscatter at 40° incidence angle is used to estimate the crop height of wheat in 1981. The estimated heights are plotted against the measured heights of Okapi, Durin, Adamant and Arminda (fig. 8.12). The coefficient of correlation between estimated and measured values is 0.79 and the standard error of estimate is 18 cm. The crop height is especially underestimated at low values when the influence of the soil background is relatively large. At heights of about 100 cm the estimations become better. Considering the large differences in radar backscatter of these wheat varieties (chapter 5.2), the estimations of crop height are quite consistent.

Summarizing, estimations of crop height and dry biomass can be made during the development stages 1-7, based on one angle of incidence and at one state of polarization, with an accuracy of about 20 cm and 215 g/m^2 respectively. These accuracies are respectively 18% and 23% of the total range in crop height and dry biomass (for the development stages 1-7). They apply to a lumping of different varieties, grown at different locations, with different soils and management practices (row spacing). However, the example of wheat in 1980 shows that exceptions can exist and that estimations of crop growth parameters might not always be possible.

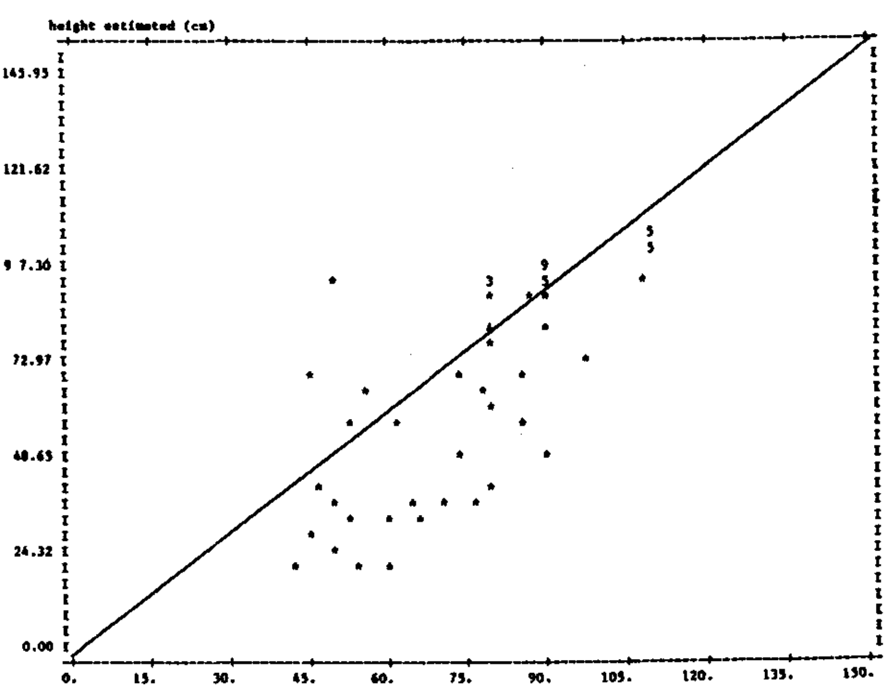


Figure 8.12: measured and calculated crop height from the VV radar backscatter at 40° incidence angle for four wheat varieties in 1981, Okapi, Durin, Adamant and Arminda.

9 Barley

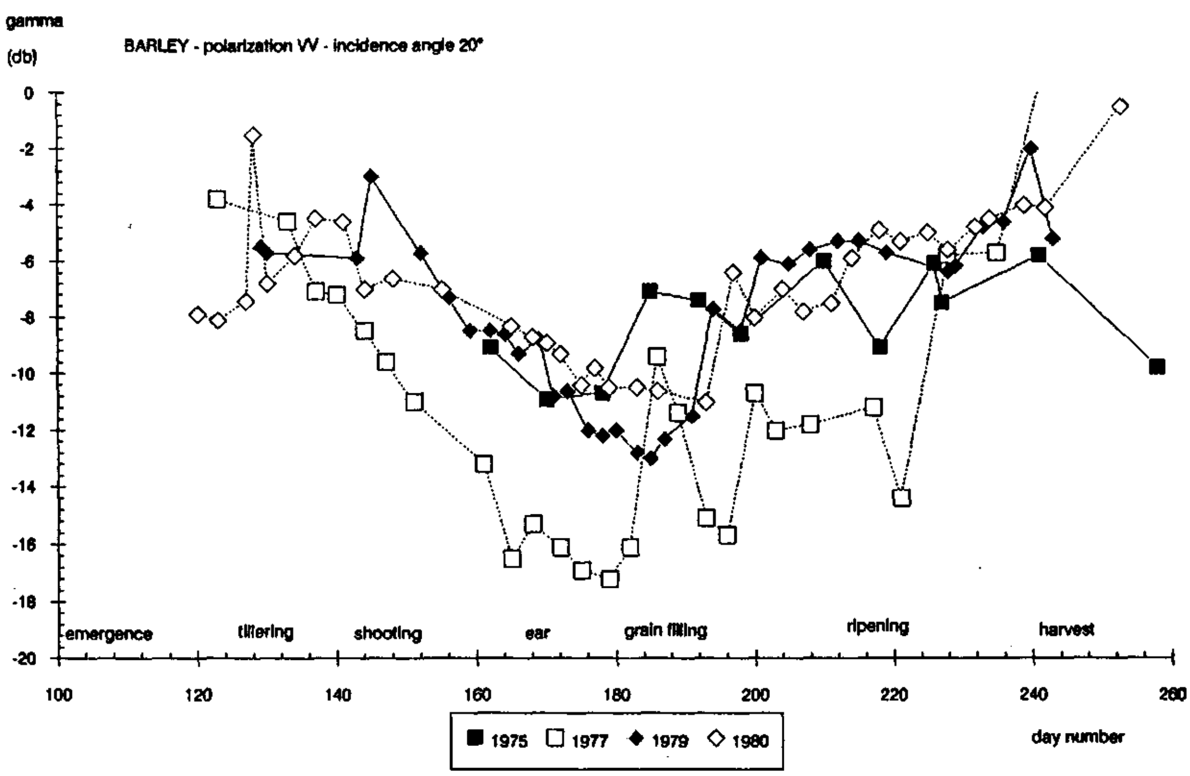
9.1 Crop development

Like for wheat, a number of radar backscatter curves of barley is acquired between 1975 and 1980 (figs.9.1.a/c). Again, a large spread is present between the curves, especially in the stages of grain filling and ripening. The main reason herefore is the relation between the backscatter and the structure of the crop canopy. Differences in the orientation of ears and leaves in the top of the canopy may result in differences in the radar backscatter(chapter 6). Also the lodging of the crop can have a dramatic impact. In 1979 and 1980, the crop lodges on about day 195 and the radar backscatter increases at all angles of incidence. The crop in 1977, on the other hand, does not lodge and the backscatter remains relatively low at low and medium angles of incidence. The spread between the curves is medium at low angles of incidence, 5 dB; largest at medium angles, 5-10 dB; and lowest at high angles of incidence, 3-6 dB.

Two things are remarkable when the backscatter curves of barley are compared with those of wheat (fig. 8.1). First, a larger number of fluctuations is present in the curves of barley. These fluctuations are also larger and may amount to about 10 dB. They are caused by the special sensitivity of the backscatter of barley to momentary changes in the crop canopy. (However, most of the larger peaks in fig. 9.1 can not be related to such changes because of a lack in appropiate ground-truth). Secondly, the backscatter of barley is generally lower than that of wheat in the first half of the growing season. Two explanations are suggested to account for this difference. One is the possibility that the ears of barley have a larger coefficient of absorption for microwaves because of the presence of awns (Allen and Ulaby, 1984). The radar backscatter of barley, however, is already lower than that of wheat before the emergence of ears. The second explanation might be the general difference in canopy structure between the crops. Barley has relatively small and narrow top leaves and a more open canopy structure than wheat. Therefore, microwaves might penetrate more deeply in the canopy where they are eventually absorbed. This results in lower values of the radar backscatter.

To relate the temporal signature of the radar backscatter to the development of the crop, the average backscatter (VV) is calculated per development stage over all crops together. This average value is plotted on the radar-morphological development scale in figs. 9.2.a/c. The average is derived from seven plots: one in 1975, 1976, 1979 and 1980 each, and three in 1977. The variation around the average is given in plus and minus the standard deviation.

The general shape ressembles that of wheat (paragraph 8.1.2), but some characteristic differences are present. At 50° and 70° incidence angle the backscatter initially increases in the early growing season during stages 1-2. This increase is smaller and less pronounced than for wheat: +1 dB at 70° incidence angle for barley, versus +2.5 dB for wheat. At the beginning of stem extension, at the end of stage 3, the backscatter at medium and high angles of incidence starts to decrease. At 20° incidence angle, the backscatter decreases already from the first stage of development. The backscatter decreases then at all angles of incidence through the phases of shooting, booting and ear formation. It reaches its lowest level when the ear formation is completed at the end of stage 5. Since hardly any ear-stems are formed, the radar backscatter of the crop also stops decreasing at this point.



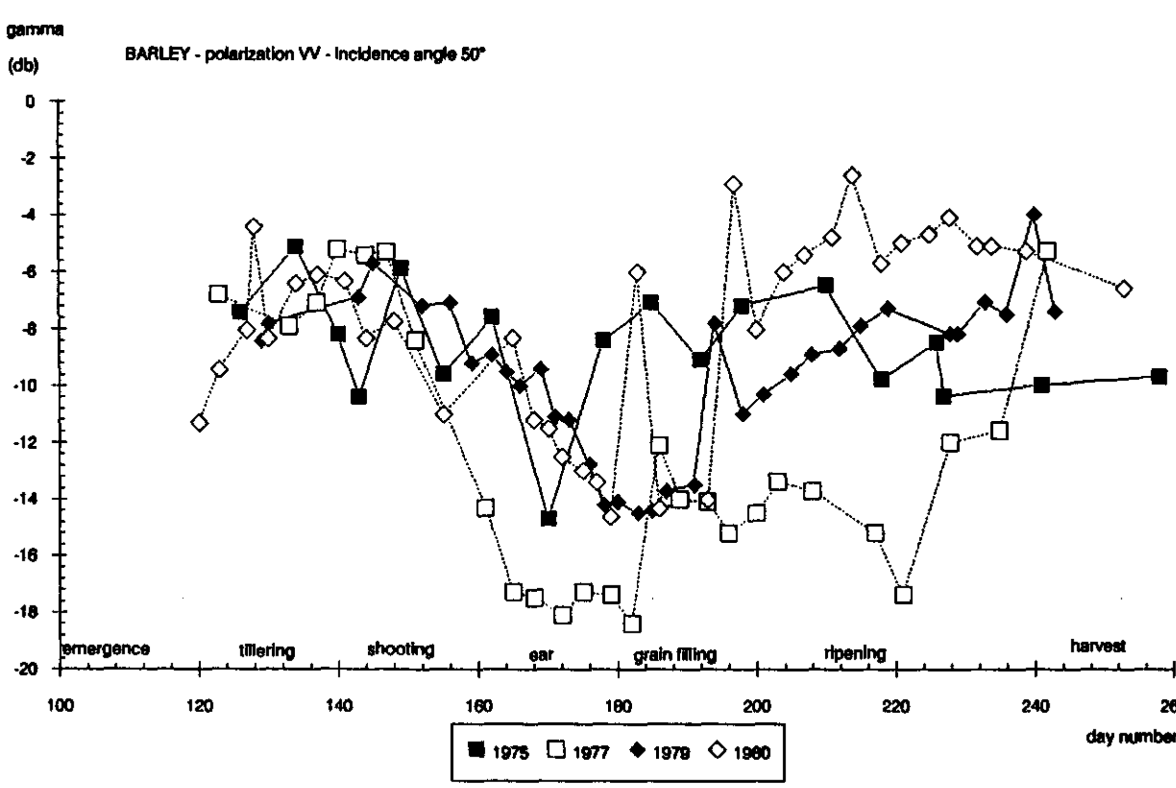


Figure 9.1: VV radar backscatter at 20° (9.1.a) and 50° (9.1.b) incidence angle of barley, 1975-1980.

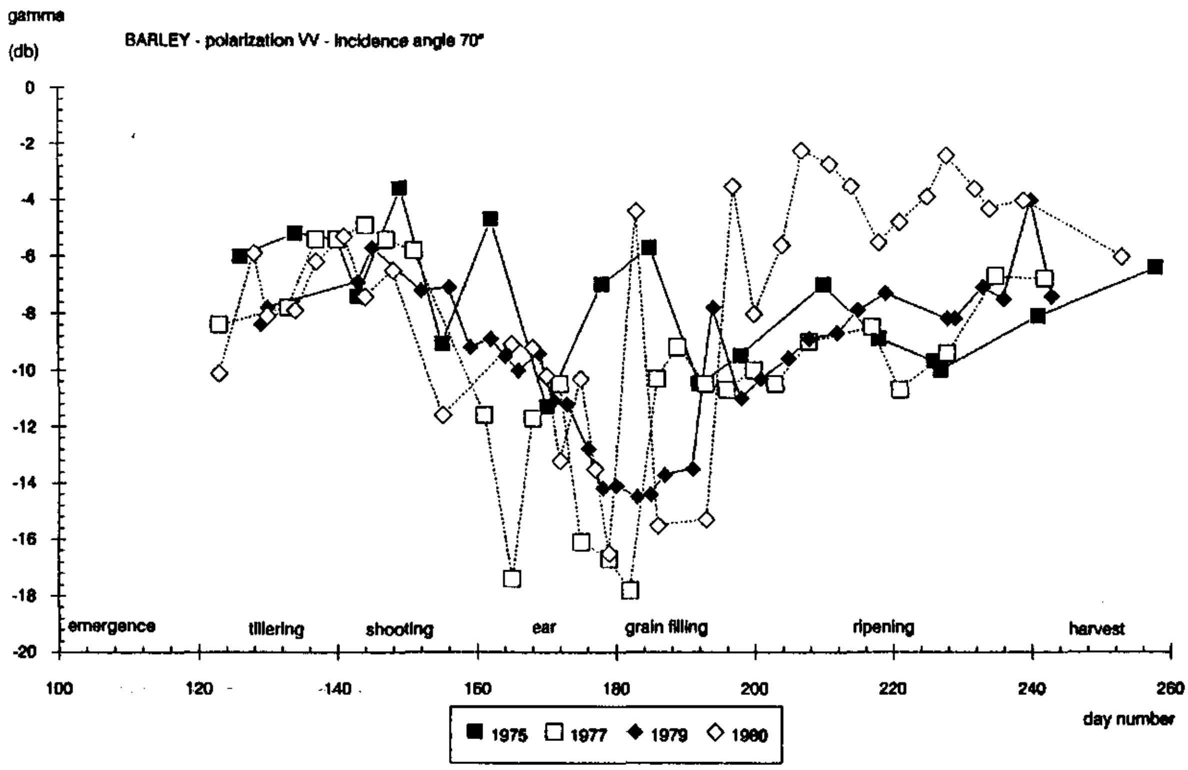


Figure 9.1.c: VV radar backscatter at 70° incidence angle of barley, 1975-1980.

Because wheat does form ear stems, the backscatter of wheat decreases further until the end of stage 6. However, the lowest levels of the radar backscatter of barley are lower than those of wheat: -11.5 dB, -15 dB and -13 dB at 20°, 50° and 70° incidence angle respectively for barley, versus -11.5 dB, -13.5 dB and -10.5 dB for wheat. During the stages of grain filling 7 and 8 the backscatter of barley is less stable than that of wheat. At medium and high angles of incidence, the backscatter already rises from respectively the stages 6 and 7 onward. This increase is mainly caused by the lodging of the crops in 1979 and 1980, stages 21 and 22. During the stages of ripening and dying, 9 and 10, the backscatter also increases some 2 dB at the low angle of incidence (stages 21, 22). At the final stage before harvest, stage 11, the radar backscatter increases strongly at low (7.5 dB) and medium (4 dB) angles of incidence. At harvest, the backscatter has reached the level of that of the bare soil.

The standard deviation around the average curve varies between 1.5 and 3 dB, depending on the development stage and the angle of incidence. The largest variation is present at medium angles of incidence in the stages of lodging, and at the low angles from the stage of grain filling onward. From emergence to grain filling, the temporal signature of an individual crop gives some indication of its development by comparison with the avarage curve. The typical features in the backscatter curves are: the bends at stages 6/7 at low angles of incidence; the bends at stages 2/3 and 6/7 at medium angles; and the bends at stages 3/4 and 5/6 at high angles of incidence. The best single angle of observation is a medium angle because a) there are two 'bending-points', b) there is a large contrast between the

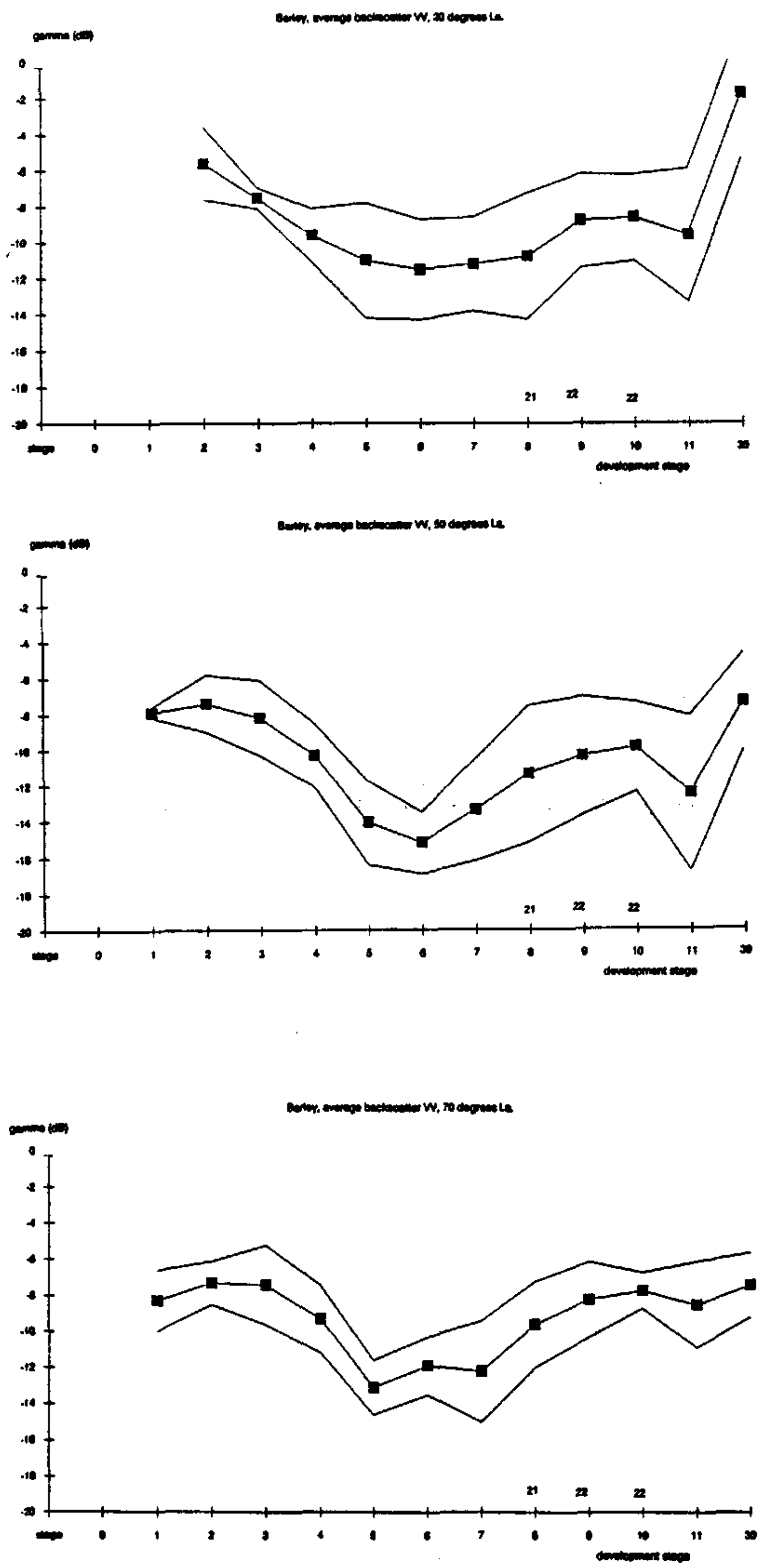


Figure 9.2: average VV radar backscatter with standard deviation at 20° (9.2.a), 50° (9.2.b) and 70° (9.2.c) incidence angle over all barley crops (1975-1980) versus stage of the radar-morphological development scale.

backscatter of the optically thick crop canopy and that of the bare soil, and c) the backscatter curve is quite smooth throughout the growing season. The recognition of a specific stage of development by comparison of the absolute level of the radar backscatter is not feasible because of the large variation in backscatter around the average. After grain filling, the level of the radar backscatter relative to that of the average curve might indicate the lodging of the crop. However, the shape of the individual curves can be very much affected by the structure of the canopy, such as the orientation of the ears. This makes interpretation of the radar backscatter into information on growth and development of the crop hazardeous.

The use of backscatter observations at several angles of incidence and at both states of polarization VV and HH, does not improve the possibilities of recognition of development stages. Unlike for wheat, the changes in the angular curve of the VV-HH backscatter difference are only gradual and inconsistent with the development of the crop. Therefore, a distinction based on the angular backscatter at both VV and HH polarization can only be made between the stages 1-5 ('vegetative growth and ear-formation') and 6-30 ('grain filling and ripening').

A precise monitoring of the development of barley, based on radar backscatter measurements is not feasible. Observations at a single state of polarization and at a medium angle of incidence can be used for an appraisel of the following, generalized phases of development (table 9.1), for a crop with 'normal' growth:

Table 9.1: general phases of crop development of barley which can be derived from a temporal backscatter signature at a medium angle of incidence, for a crop with 'normal' growth.

general phase	stage
emergence-tillering	1- 3
stem extension-heading	4- 6
grain filling-harvest	7-30

A refinement in these general phases might be achieved through interpolation between the characteristic features in the backscatter curve. During the phase of grain filling to harvest, a differentiation between a lodged canopy and a non-lodged canopy can in general be made. The addition of more radar backscatter measurements at other angles of incidence and at both VV and HH polarization does not increase the sensitivity for monitoring crop development.

9.2 Crop growth

Correlation is again used to derive the single most explaining crop growth parameter to account for the variation in the radar backscatter (table 9.2). The radar measurements of the seven crops between 1975 and 1980 are lumped for a) the complete growing season, stages 1-30, and b) the period from emergence to grain filling, stages 1-7.

The negative sign of the coefficients of correlation indicates the decrease in radar backscatter with the increase of the crop growth parameters. When the whole growing season is considered, the correlations between the backscatter and dry biomass, plant water and soil cover are very low at all angles of incidence, $r^2 \approx 0.10-0.50$. The correlations with crop height are medium, $r^2 \approx 0.60-0.75$. Except for the low correlations with dry biomass, these results are similar to those for wheat. When the correlations are restricted to the first period of the growing season, development stages 1-7, r^2 increases with all growth parameters. With dry biomass, plant water and soil cover r^2 is still low, $\approx 0.40-0.70$, and with crop height it increases to medium/fair, $\approx 0.70-0.85$. Again these results are similar to those of wheat except for the low values with dry biomass. With crop height, dry biomass and plant water, the correlations are a little bit higher at low angles of incidence than at high angles. With soil cover, the correlation increases clearly with decreasing angle of incidence, i.e. from $r^2 = 0.41$ at 70° to $r^2 = 0.73$ at 20° incidence angle.

Table 9.2: coefficient of correlation r^2 for the relation between the VV backscatter and crop height, dry biomass, plant water and soil cover of barley. All crops from 1975-1980 are lumped.

A: development stages 1-30, the number of data sets = 145

incidence angle	crop height (cm)	dry biomass (g/m^2)	plant water (g/m^2)	soil cover (%)
70	-0.62	-0.02	-0.42	-0.31
60	-0.73	-0.09	-0.32	-0.32
50	-0.75	-0.17	-0.25	-0.32
40	-0.76	-0.20	-0.26	-0.37
30	-0.76	-0.23	-0.32	-0.45
20	-0.73	-0.21	-0.44	-0.57

B: development stages 1-7, the number of data sets = 95

incidence angle	crop height (cm)	dry biomass (g/m^2)	plant water (g/m^2)	soil cover (%)
70	-0.72	-0.56	-0.55	-0.41
60	-0.81	-0.62	-0.58	-0.49
50	-0.84	-0.67	-0.58	-0.53
40	-0.85	-0.68	-0.60	-0.59
30	-0.85	-0.70	-0.64	-0.64
20	-0.81	-0.68	-0.67	-0.73

The relation between the radar backscatter at medium angles of incidence and plant water and crop height is illustrated in figs. 9.3 and 9.4. It is clear that there is almost no relationship with plant water. The backscatter generally decreases with increasing plant water but the spread in the data points is very large. The relationship with crop height is much better. The backscatter decreases from about -7 dB to -14 dB with increasing crop height, and the spread in the data points is much smaller.

Like for wheat, the direct monitoring of crop growth after grain filling, stage 7, is impossible. It is only possible in the early period of the growing season, stages 1-7, but it is associated with a degree of uncertainty. The crop height h and the dry canopy biomass Wd can be estimated from backscatter measurements by logistic expressions with empirically derived constants, e.g:

$$h = 1.9 + 104.5/[1+\exp(0.45*(VV40+9.46))] \text{ (cm)} \quad \text{[Eq. 9.1]}$$
$$Wd = -7.0 + 851.0/[1+\exp(0.47*(VV40+9.72))] \text{ (g/m2)} \quad \text{[Eq. 9.2]}$$

in which VV40 is the VV backscatter at 40° incidence angle. The constants are derived from regression through the data set of all crops together for the development stages 1-7. The results of the estimations are summarized in table 9.3. The estimated values of crop height and dry biomass are plotted against the measured values in figs. 9.5 and 9.6.

Table 9.3: coefficient of correlation r^2 and standard error of estimate SEE between measured and calculated height and dry biomass of barley 1975-1980. The calculations are based on logistic relations between the crop parameters and the radar backscatter at 40° incidence angle.

parameter	development stages	r^2	SEE
crop height (cm)	1 - 7	0.85	18
dry biomass (g/m^2)	1 - 7	0.73	225

The standard error of estimate SEE of crop height is about 16% of the total range in crop height (115 cm). The estimations of the canopy biomass are only realistic up to 900 g/m^2 and the SEE is relatively large with 25% of this range. The coefficient of correlation r^2 is also smaller for the estimation of biomass than for that of crop height.

This example demonstrates the possiblity of estimating crop height during the development stages 1-7 on the basis of radar backscatter measurements at only one state of polarization and at one angle of incidence. The accuracy of 18 cm applies to a lumping of crops grown at different locations with varying soil backgrounds, management practices and varieties. The accuracy will increase if estimations are based on empirical relations which are derived from observations at the same location under similar conditions. Unlike for wheat, estimations of crop height after stage 7 are not feasible. The influences of lodging and of orientation of ears and leaves in the top of the canopy on the radar backscatter, are too large to allow for reasonable estimations.

Estimations of dry biomass are associated with larger errors and only medium correlations.

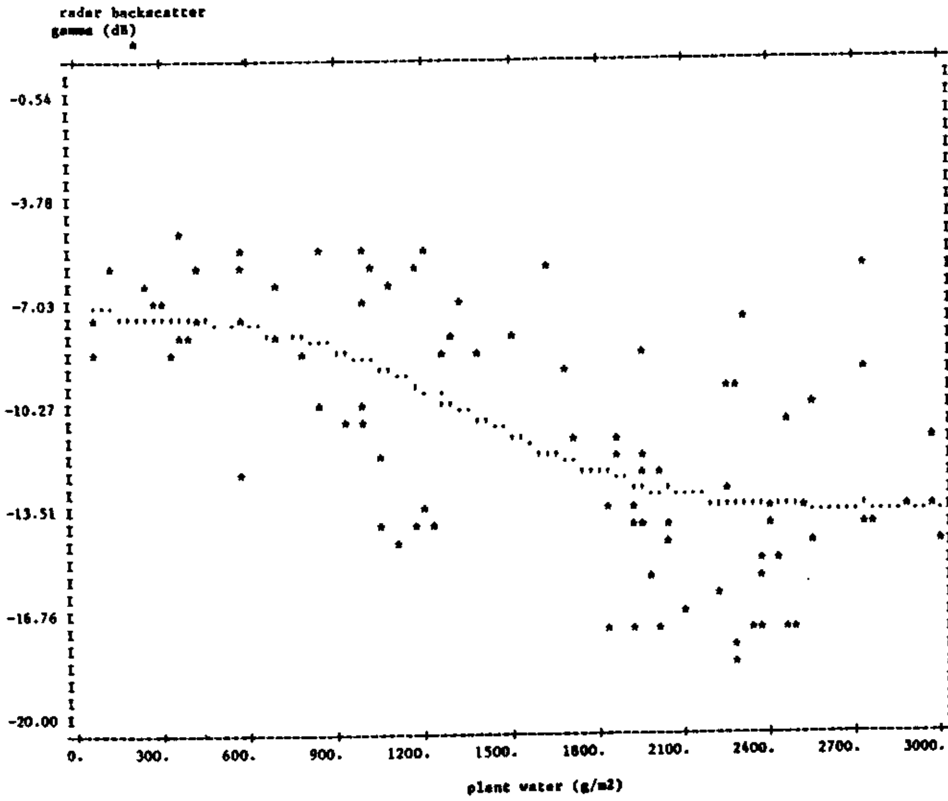


Figure 9.3: VV radar backscatter at 40° incidence angle versus plant water of barley 1975-1980, development stages 1-7. An * indicates measured values and the line .... is the fitted logistic expression.

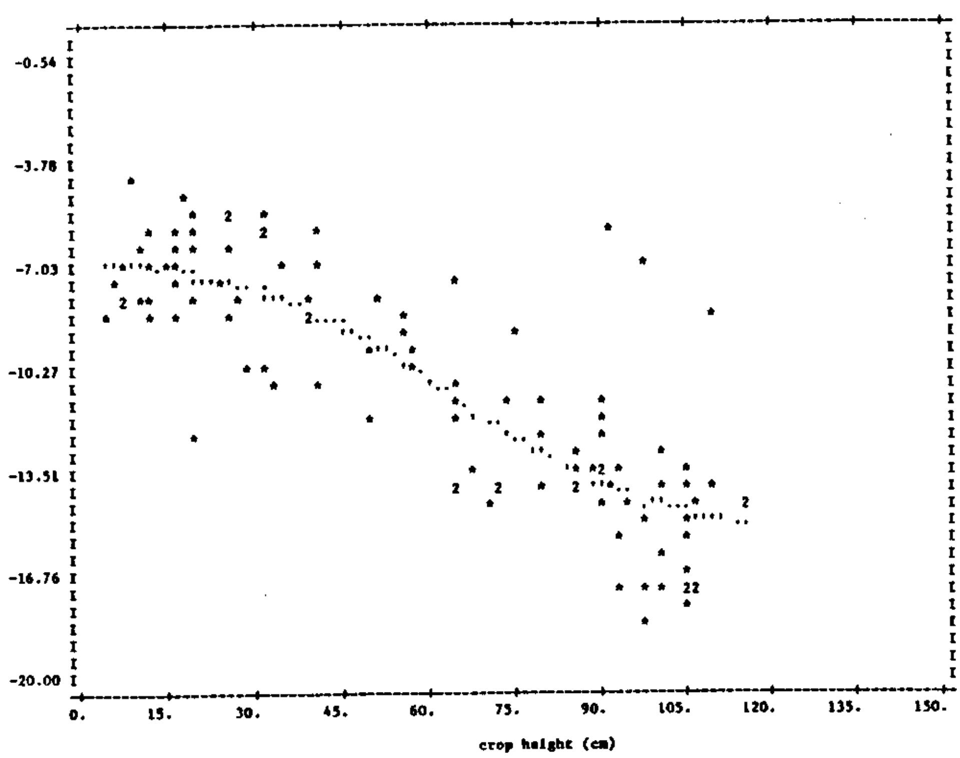


Figure 9.4: VV radar backscatter at 40° incidence angle versus crop height of barley 1975-1980, development stages 1-7. An * indicates measured values and the line .... is the fitted logistic expression.

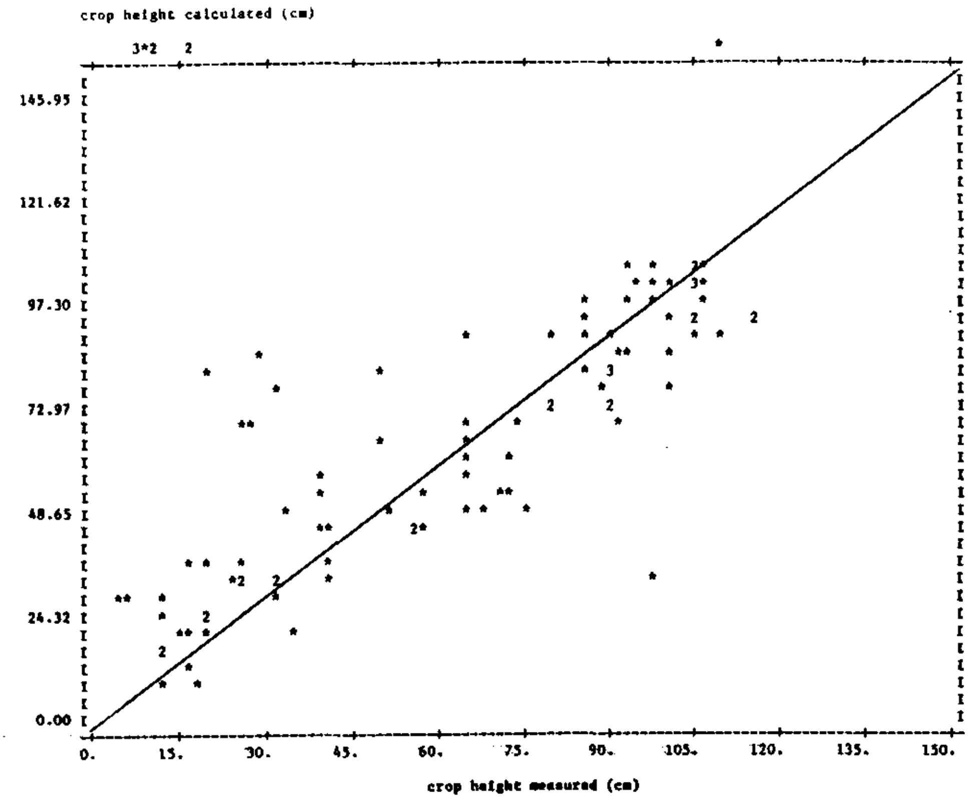


Figure 9.5: measured and calculated crop height from the VV radar backscatter at 40° incidence angle for barley 1975-1980, development stages 1-7.

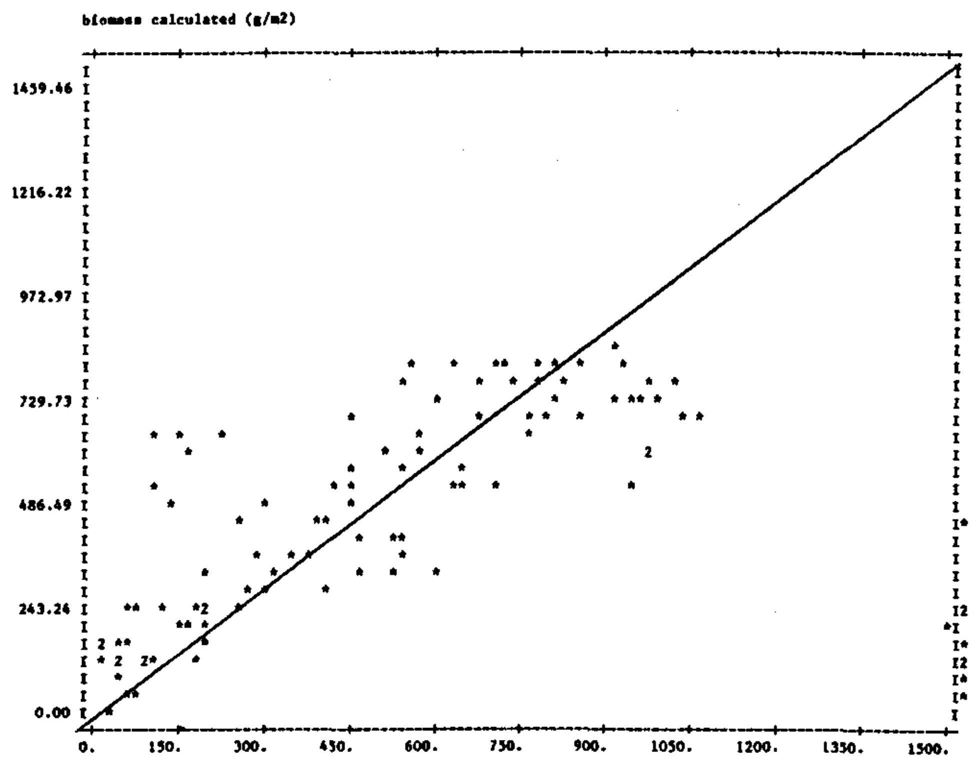


Figure 9.6: measured and calculated biomass from the VV radar backscatter at 40° incidence angle for barley 1975-1980, development stages 1-7.

10. Oats

10.1 Crop development

The temporal curves of the radar backscatter of oats differ from those of wheat and barley. To illustrate this, the example of oats in 1979 is given here (figs. 10.1.a/c). At 20° incidence angle the curve is the most straightforward at both VV and HH polarization. The radar backscatter initially increases at the start of the growing season, days 125-150, with a soil cover of less than 40% and a crop height less than 30 cm. This increase is also present in the backscatter curve of bare soil, and is attributed to an increase in the soil moisture content. After day 150, the backscatter slowly decreases throughout the growing season from about -3 dB to -8 dB. No differentiation can be made in different phases of crop development. The backscatter does not react on the appearance of the panicles, nor on any other change in the structure of the canopy. The curve is smooth and the underlying soil appears completely shielded off. There is hardly any difference between the radar backscatter at VV and at HH polarization throughout the growing season. The backscatter only reacts markedly on day 222 when the canopy is mechanically beaten down to simulate a lodged crop. The backscatter increases some 5 dB at VV polarization and 7 dB at HH.

At 50° incidence angle the radar backscatter displays a typical pattern during the growing season. Again, the backscatter initially increases at the beginning of the growing season until about day 150. With further vegetative growth it decreases from about -6 dB to -10 dB. In this period the crop height increases from 30 to 100 cm and the soil cover from 40% to 90%. The backscatter during this phase is about 1 dB lower at VV than at HH. On about day 180 the panicles emerge from the stems and become visible in the canopy below the layer of the top leaves. The radar backscatter immediately reacts and increases at both VV and HH polarization. At HH, the backscatter increases only 1.5 dB until the panicles have emerged just at the top of the canopy. The panicles just touch each other in the top of the canopy and the row structure of the crop is still visible. The backscatter at VV polarization ceeps increasing with the further development of the panicles until they form a closed cover in the top of the canopy. The height of the crop has increased to 130 cm and the row structure of the crop is no longer discernible. The backscatter at VV has increased from -10 dB at the emergence of the panicles to -3.5 dB at the beginning of grain filling. During grain filling and ripening, the backscatter at both VV and HH remains fairly stable (very slowly decreasing). The difference between the backscatter at VV and HH is about +4.0 dB. With the beating down of the crop on day 222, the backscatter at HH increases some 3.5 dB while it hardly reacts at VV. The backscatter curve is very smooth throughout the growing season.

The curve of the radar backscatter at 70° incidence angle ressembles that at 50° incidence angle. The backscatter increases during the very first phase of vegetative growth, days 125-150 and then decreases until the appearance of the panicles on day 180. With the development of the panicles, the backscatter at HH increases until the panicles touch each other in the top of the canopy. At VV, the backscatter increases further until the panicles form a close blanket and shield off the underlying vegetative material. The backscatter is relatively stable (very slowly decreasing) during grain filling and ripening at both states of polarization. The difference between the backscatter at VV and HH is +3 dB.

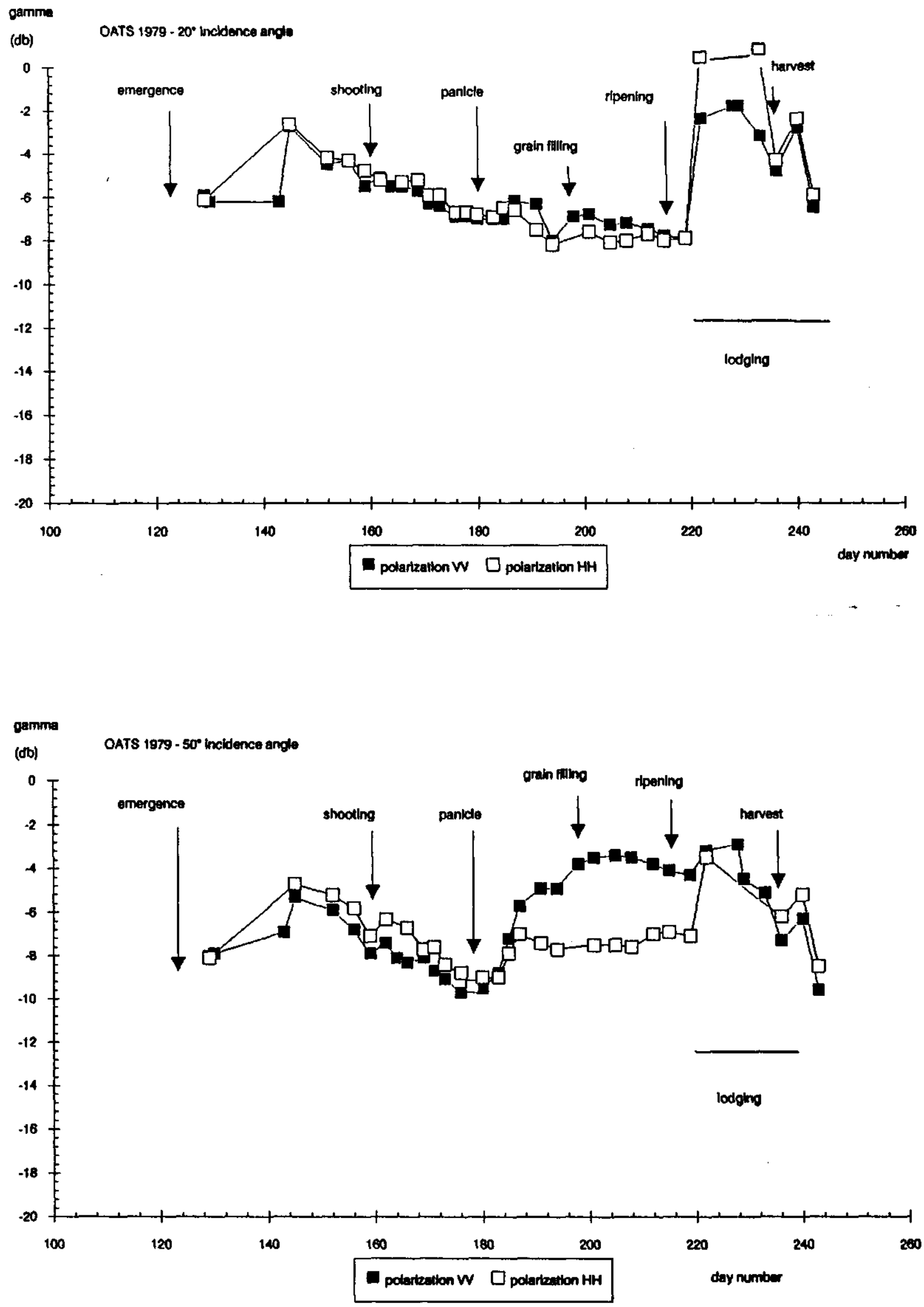


Figure 10.1: VV and HH radar backscatter at 20° (10.1.a) and 50° (10.1.b) incidence angle of oats, Leanda 1979.

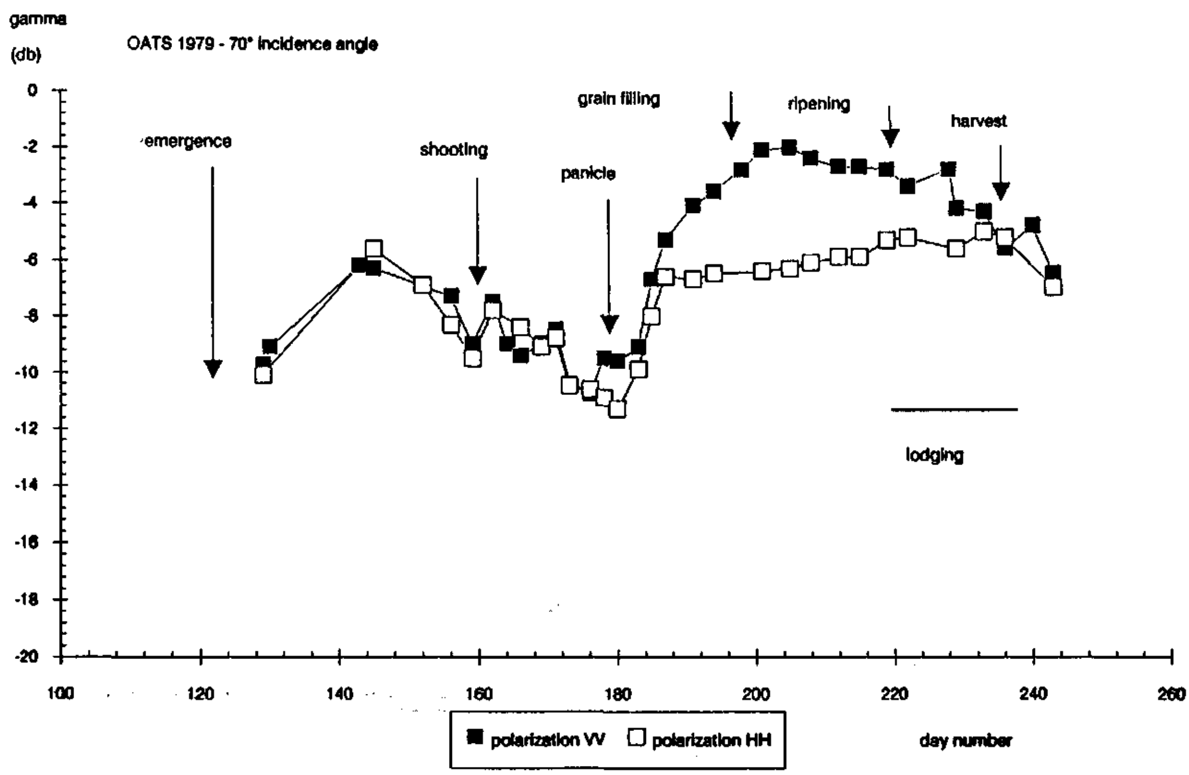


Figure 10.1.c: VV and HH radar backscatter at 70° incidence angle of oats, Leanda 1979.

The down-beating of the crop on day 222 has no effect on the backscatter at this high angle of incidence. The curve of the backscatter is only smooth during the generative period of growth while some peaks and dips are present during the vegetative period.

Oats are grown in only three years, 1975, 1979 and 1980. Because the number of measurements in 1975 is relatively small, and because there are differences in the development of the canopies with regard to lodging, the radar backscatter is not averaged over all three years. However, the shape of the curves are, with some differences caused by lodging, comparable for all three crops. Therefore, the backscatter of the crop in 1979 will serve as further example of the relation with crop development. This relation is more pronounced for oats than for wheat or barley. In fig. 10.2 The (VV) radar backscatter of the crop in 1979 is averaged per development stage and plotted on the radar-morphological development scale.

Until the appearance of the panicles, the trend in the radar backscatter at medium and high angles of incidence ressembles that of the other cereals. The backscatter increases from the first to the second development stage. At the beginning of stem extension in stage 3, the backscatter decreases through stage 4 (shooting, booting) until the appearance of the panicles in stage 5. Contrary to the backscatter properties of the ears of wheat and barley, those of the panicles are very different from the vegetative material of the canopy. Instead of absorbing microwaves, the panicles are elements with strong backscatter properties at

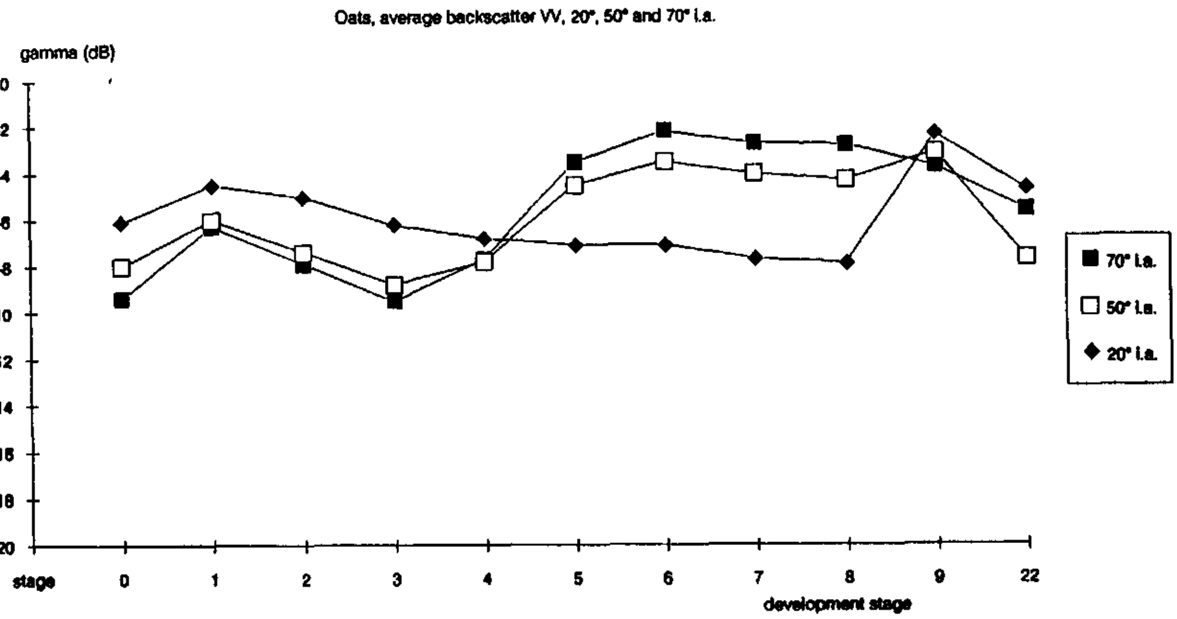


Figure 10.2: average VV radar backscatter at 20°, 50° and 70° incidence angle against development stage, oats 1979.

VV polarization and at medium and high angles of incidence. The backscatter increases in stages 5 and 6 until the period of grain filling in stage 7. At low angles of incidence, the backscatter does not react on the appearance of the panicles and just continues decreasing. During the stages of grain filling and ripening, 7, 8 and 9, the backscatter very slowly decreases at all angles of incidence. At harvest the backscatter has returned to the level of that of the bare soil.

The typical features in the curves are the bends at stages 2/3, 4/5 and 7/8.

The average VV-HH backscatter difference is plotted against the angle of incidence for some development stages in fig. 10.3.

During vegetative growth, stages 2-4, the shape of the curve is somewhat hollow between 0 and -1 dB. Then, with the formation of the panicles and panicle-stems, stages 5 and 6, the VV-HH backscatter increases at medium and high angles of incidence. This increase ranges from about 0 dB at low angles to about 3.5 dB at high angles. The shape of the angular curve does not change further throughout the stages of grain filling and ripening 7-9. With the lodging of the crop in stage 22, the shape of the curve does not change much, but the absolute level drops with 2-3 dB. At harvest the shape of the curve has flattened with some fluctuations between 1 and -1 dB.

Summarizing, the angular curve of the VV-HH backscatter difference can only reasonably be used to differentiate between the stages 1-4, 5-10 and 30. Contrary to wheat and barley, the harvesting of oats appears detectable. This is due to the specific shape of the angular curve before harvesting versus the more or less straight curve after harvesting.

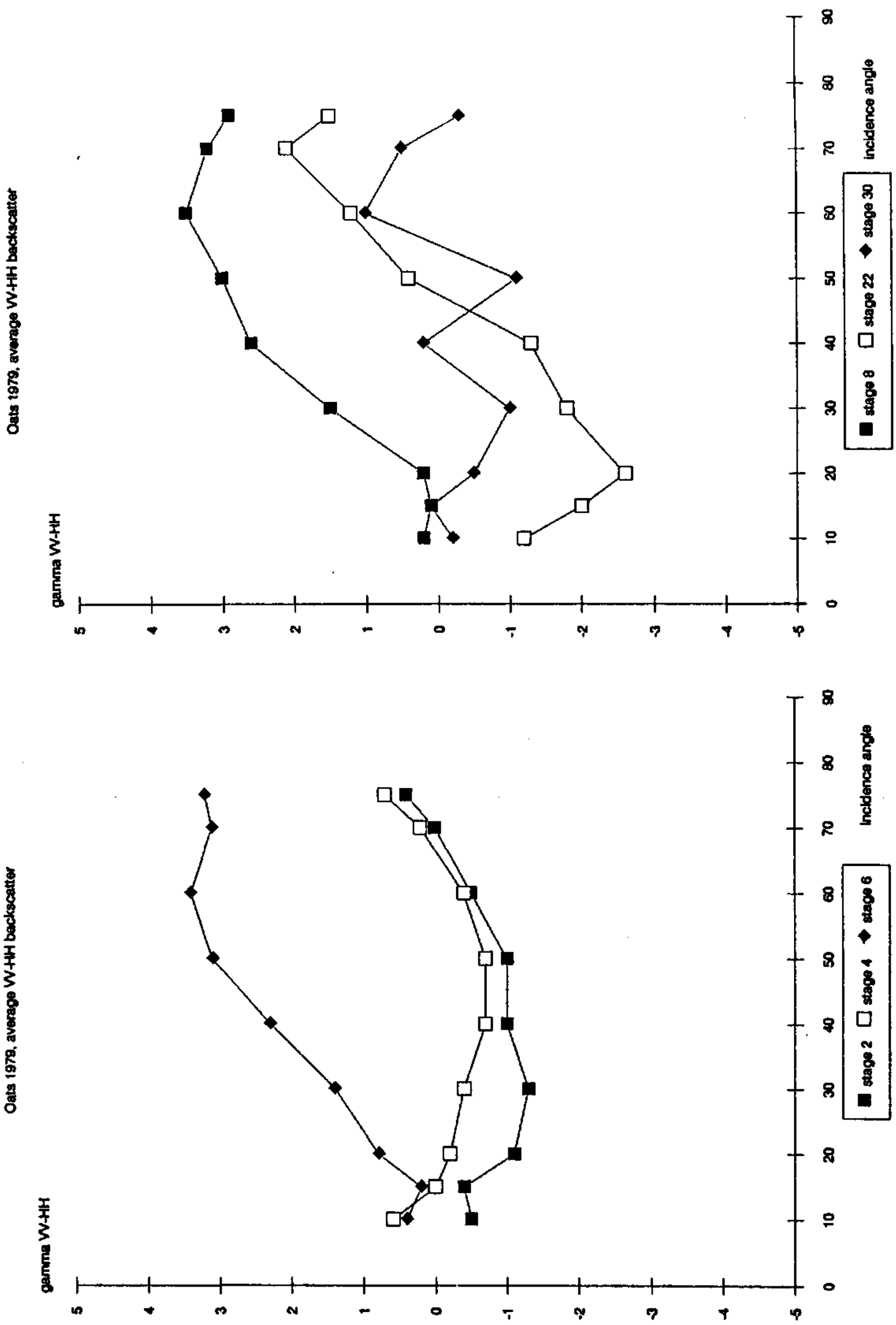


Figure 10.3: average VV-HH radar backscatter difference against incidence angle for the development stages 2, 4, 6, 8, 22 and 30, oats 1979.

With a 'normal' growth of the crop, the following generalized phases of crop development can be derived from a temporal signature of the radar backscatter at a medium or high angle of incidence, and at both VV and HH polarization (table 10.1):

Table 10.1: general phases of crop development of oats which can be derived from a temporal backscatter signature at a medium or high angle of incidence, for a crop with 'normal' growth.

general phase	stage
emergence - tillering	1- 2
stem extension - booting	3- 4
panicle formation	5
panicle stem formation - beginning grain filling	6- 7
grain filling - dying	8-10

The number of phases which can be differentiated is larger than for wheat and barley. This is because of the specific backscatter properties of the panicle which differ from those of the vegetative material.

Radar observations at a number of incidence angles do not improve the monitoring capabilities over a (well chosen) single angle of observation.

10.2 Crop growth

From the previous paragraph it is clear that there is no single crop growth parameter which correlates with the radar backscatter during the whole growing season. The low to very low coefficients of correlation r^2 are given in table 10.2.

Table 10.2: coefficients of correlation r^2 for the relation between the VV backscatter and crop height, dry biomass, plant water and soil cover of oats. All three crops from 1975-1980 are lumped for the whole growing season, number of data sets = 65.

incidence angle	crop height (cm)	dry biomass (g/m^2)	plant water (g/m^3)	soil cover (%)
70	0.52	0.65	0.55	0.49
60	0.50	0.61	0.56	0.46
50	0.48	0.56	0.55	0.46
40	0.34	0.42	0.50	0.38
30	0.09	0.17	0.31	0.25
20	-0.36	-0.24	-0.12	-0.28

The positive signs of the coefficients of correlation for most angles of incidence is caused by the increase in the radar backscatter during panicle formation. Only at 20° incidence angle does the backscatter continuously decrease with crop development. Consequently, the coefficient of correlation has a negative sign.

Because of the small number of measurements on oats, no relations are studied between the level of the radar backscatter at full crop development and any of the crop growth parameters. However, based on the analyses in previous chapters, such relations are not to be expected. The radar backscatter is more influenced by the structure of the canopy than by its biomass. It is concluded that the X-band radar backscatter is not suitable to monitor the growth of oats in any quantitative way. When compared to wheat and barley, more information can be derived on the development of the crop and less on the growth (biomass, height).

11 Model considerations

11.1 The Height model for wheat and barley

In literature, several attempts have been made to model the radar backscatter of vegetation. One of the most widely recognised models is the semi-empirical Cloud model. This model describes the radar backscatter as a function of plant water and the moisture content of the underlying top soil (Attema and Ulaby, 1978). In its most simple form the model uses four empirical parameters: C and D to describe the backscatter properties of the canopy, and G and K to describe those of the soil background. The results for 'broad' leaf crops like beet and potato are good, while they are disappointing for cereals. Therefore, the original Cloud model was extended into the two-layer Cloud model to accomodate the layered structure of cereals (Hoekman et al., 1982). In this model, six model parameters are needed to describe the radar backscatter: D2 and C2 for the top layer of the canopy (ears), D1 and C1 for the lower layer (stems and leaves) and G and K for the underlying soil surface:

$$\begin{aligned}\gamma = {} & C2(\theta).[1-\exp(-D2.Wh2/\cos\theta)] + \\ & C1(\theta).[1-\exp(-D1.Wh1/\cos\theta)].\exp(-D2.Wh2/\cos\theta) + \\ & G(\theta).\exp(K.Ms).\exp[(-D2.Wh2+D1.Wh1)/\cos\theta] \quad (m^2/m^2)\end{aligned} \qquad \text{(Eq. 11.1)}$$

in which: Wh2 = plant water per unit surface (kg/m^2) of the top layer (ears)
Wh1 = plant water per unit surface (kg/m^2) of the lower layer (stems, leaves)
Ms = soil moisture content of top soil (%)
θ = angle of incidence (-)

The model parameters C2, C1 and G are angular dependent and have to be determined for each angle of incidence separately. The parameters D2, D1 and K are assumed to be angular independent. By theoretical and experimental considerations, K≈0.051 for the soil of the test farm "De Bouwing", and ≈0.060 for the soils of the farms "De Schreef" and "Droevendaal". The parameters D2 and D1 have to be experimetally determined.

Some results of the one-layer and the two-layer Cloud model for respectively beet, pea, potato and wheat, oats and barley in 1979 are summarized in table 11.1.

For cereals, the two-layer Cloud model is an improvement over the single-layer model but the complexity has increased. Now, six model parameters are needed per incidence angle instead of four. Therefore, the two layer Cloud model is rather impractical for inverse use for the monitoring of crop growth. This chapter deals with modifications of the original Cloud model to increase its performance for cereals (wheat and barley) without increasing its complexity. The aim is to investigate the possibilities of a physical model to derive better quantitative information on the growth of cereals from radar observations than by empirical relations (chapters 8 and 9).

Table 11.1: coefficient of correlation r^2 and standard error of estimate SEE between calculated and measured γ (VV) for some crops in 1979 (Hoekman et al.,1982). In the original publication, the coefficients of correlation are expressed in r and therefore appear higher than the ones given here.

crop	r^2	SEE (dB)
beet	0.94	0.83
potato	0.90	0.94
pea	0.90	0.86
winter wheat Arminda	0.86	0.85
winter wheat Okapi	0.82	0.88
Summer wheat Adonis	0.87	0.72
barley	0.89	1.00
oats	0.86	0.79

In chapters 8 and 9, it was shown that, for wheat and barley, crop height is the best single parameter correlating with the radar backscatter. The relationship between height and backscatter at medium angles of incidence can adequately be described by logistic expressions. Also, the difference in ear stem formation (crop height) between wheat and barley can account for the difference in the temporal curves (paragraph 9.1). Furthermore, in chapter 6.2, it was concluded that the backscatter properties of the ears of wheat ressemble those of the underlying vegetative material. Therefore, in radar terms, the crop canopy can be considered homogeneous and the differentiation in two layers (ears and vegetative material) can be neglected.

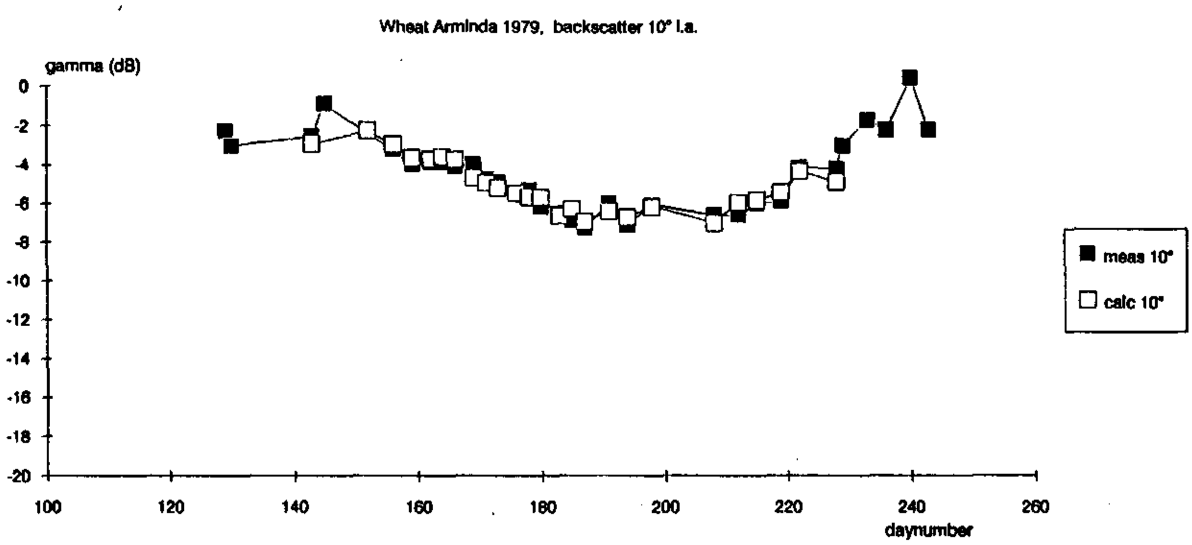
Based on these considerations, a modification of the Cloud model for wheat and barley is suggested by changing the variable plant water Wh in the variable crop height h; the Height model:

$$\gamma = C(\theta).[1-\exp(-D(\theta).h)] + G(\theta).\exp(Ms.K-D(\theta).h) \quad (m^2/m^2) \qquad \text{(Eq. 11.2)}$$

In this formulation, the model parameters C,G and D are angular dependent and K = 0.051. The results of the application of this model on wheat and barley in 1979 are given in table 11.2. By analysing the results at each angle of incidence separately, insight is obtained in the relative contribution of each angle to the total performance of the model. Figs. 11.1 and 11.2 illustrate the results of the model for the winter wheat variety Arminda.

Table 11.2: model parameters G(θ), C(θ), D(θ) and the coefficients of correlation r2 for the Height model for wheat and barley in 1979.

angle of incidence:		60	50	40	30	20	10	mean r2
winter wheat	G(θ)	0.346	0.224	0.196	0.174	0.267	0.440	
Arminda	C(θ)	0.087	0.070	0.056	0.051	0.060	0.134	
	D(θ)	4.72	3.65	2.91	2.41	2.34	2.07	
	r2	0.69	0.76	0.79	0.79	0.88	0.92	0.95
winter wheat	G(θ)	0.339	0.312	0.335	0.276	0.345	0.331	
Okapi	C(θ)	0.056	0.041	0.038	0.037	0.046	0.090	
	D(θ)	3.27	3.18	3.37	2.92	3.07	2.79	
	r2	0.73	0.84	0.90	0.87	0.92	0.94	0.94
summer wheat	G(θ)	0.123	0.123	0.143	0.156	0.185	0.381	
Adonis	C(θ)	0.074	0.061	0.063	0.071	0.084	0.183	
	D(θ)	2.64	2.58	2.58	2.66	2.68	4.70	
	r2	0.71	0.81	0.90	0.92	0.89	0.76	0.93
barley	G(θ)	0.183	0.155	0.161	0.192	0.218	0.349	
	C(θ)	0.026	0.029	0.031	0.037	0.051	0.114	
	D(θ)	3.18	3.01	2.99	3.29	3.70	4.54	
	r2	0.92	0.95	0.97	0.97	0.97	0.96	0.95



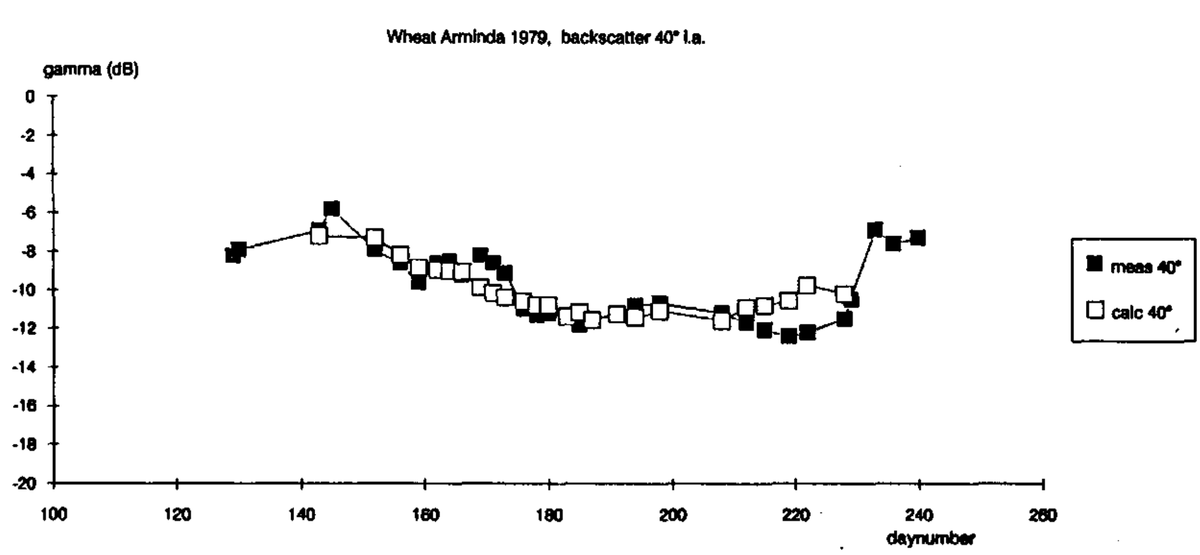


Figure 11.1: measured and calculated (VV) radar backscatter using the Height model, at 10° (11.1.a) and 40° (11.2.b) incidence angle for winter wheat, Arminda 1979.

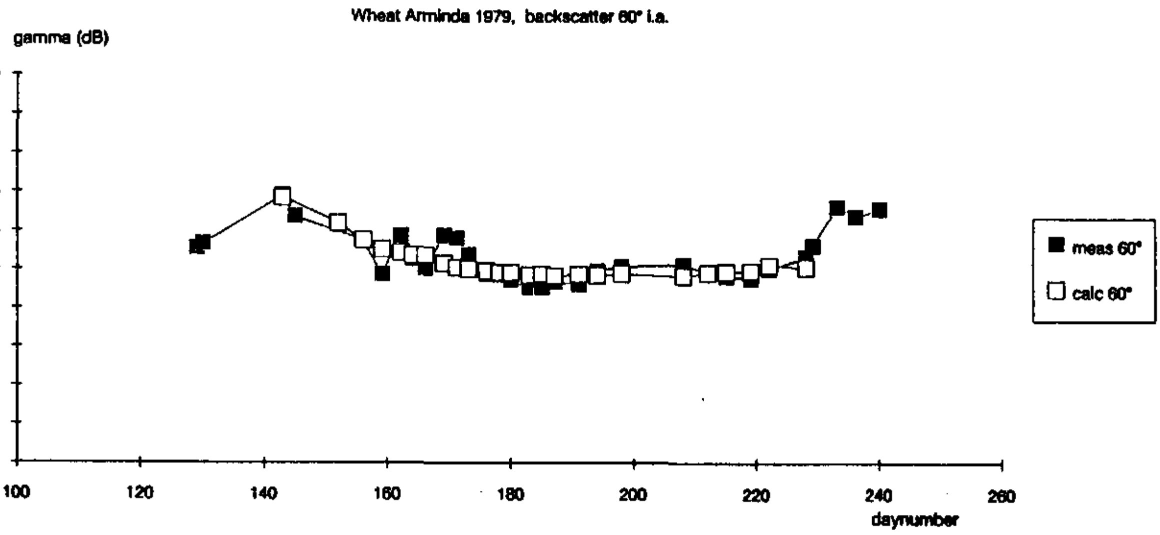


Figure 11.1.c: measured and calculated (VV) radar backscatter using the Height model, at 60° incidence angle for winter wheat, Arminda 1979.

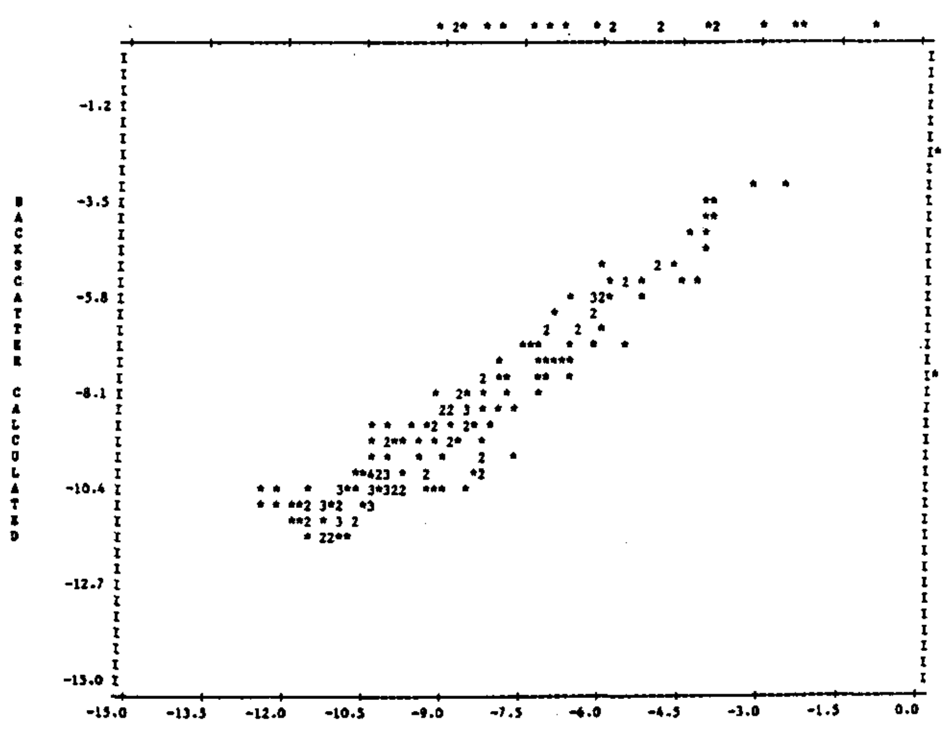


Figure 11.2: measured versus calculated (VV) radar backscatter using the Height model, for all angles of incidence lumped together: 10°, 20°, 30°, 40°, 50° and 60°, winter wheat Arminda, 1979.

Several conclusions can be drawn from these results:

- The relative contribution of each angle of incidence to the total performance of the model increases with decreasing incidence angle. The model performs best at low angles of incidence and the coefficients of correlation become low at incidence angles higher than 60°. There are two causes for this behaviour. First, the model is unable to describe the initial increase in backscatter in the early period of growth. Secondly, at high angles of incidence the radar backscatter is very sensitive to changes in the canopy structure caused by wind. For a truthful evaluation of the model, and that of the original Cloud model, the results at the different angles of incidence should be considered individually and not be lumped together. The (faulty) lumping of the angles of incidence statisticaly results in coefficients of correlation which are too high.
- For each crop, the coefficients of attenuation D are quite comparable at all angles of incidence. There is no consistent dependency on the angle of incidence. For Arminda, D increases a little with increasing angle of incidence, while for Barley D decreases a little with increasing incidence angle. Therefore, as in the original Cloud model, this coefficient can be made independent of angle of incidence. What is even more, is that the term $\cos\theta$ can succesfully be excluded from the Height model. In the original model, the term Wh is diveded by $\cos\theta$ to account for the length of the microwave-pathway through the canopy at different angles of incidence. Apparantly, the dependency of the polarization properties on the angle of incidence counter-effects the length of the microwave-pathway.
- The coefficients of correlation r^2 for the whole model compare favourably with those for the two-layer Cloud model (table 11.1). The standard errors of estimate SEE are in the same order of magnitude.

Based on these conclusions, the Height model is adapted with a coefficient of attenuation D which is independent of the angle of incidence:

$$\gamma = C(\theta).[1-\exp(-D.h)] + G(\theta).\exp(Ms.K-D.h) \quad (m^2/m^2) \quad \text{(Eq. 11.3)}$$

This model is applied on all varieties of wheat and barley from 1977-1980 (tables 11.3 and 11.4). In 1975, no soil moisture is measured and in 1976 the radar measurements are done at the end of the growing season only. To exclude the adverse effects of lodging of the crop on the performance of the model, measurements on lodged canopies are also excluded. Furthermore, since the model is tested for the purpose of monitoring crop growth, only radar measurements on the crops during the development stages 1-9 are included. At the end of the growing season, the crop canopies are dead and the relationships between canopy and backscatter change.

The relatively high coefficients of correlation r^2 and the small standard errors of estimate SEE for the crops in 1979 reflect the smooth curves of the radar backscatter. The coefficients of attenuation D are relatively large which indicate the small influence of the underlying soil. Furthermore, the values of D are about the same for all three varieties, while the values of $C(\theta)$ may differ by a factor 2. In 1977, the backscatter curves have more fluctuations which result in lower values of r^2 and larger values of SEE. On the average, the SEE is about twice as large as in 1979. The SEE is largest for the crops with the small row spacing (a) and smallest for the crop with the large row spacing (c). The coefficient of

Table 11.3: coefficient of correlation r2, standard error of estimate SEE and calculated values D for wheat and barley computed from the radar measurements during growth stages 1-9.

wheat	r2									r2	SEE	D
incidence angle	75	70	60	50	40	30	20	15	10	total		
1977 Melchior, a1	-	0.13	0.45	0.76	0.84	0.90	0.84	-	-	0.85	2.08	2.83
1977 Melchior, b1	-	0.19	0.52	0.71	0.83	0.88	0.88	-	-	0.85	1.78	2.08
1977 Melchior, c1	-	0.25	0.63	0.75	0.81	0.88	0.84	-	-	0.84	1.91	1.46
1977 Melchior, a2	-	0.26	0.59	0.72	0.71	0.71	0.72	-	-	0.83	2.06	2.06
1977 Melchior, b2	-	0.09	0.55	0.72	0.74	0.78	0.85	-	-	0.84	1.75	1.98
1977 Melchior, c2	-	0.06	0.51	0.71	0.78	0.86	0.86	-	-	0.83	1.79	1.63
1979 Arminda	0.52	0.59	0.75	0.77	0.78	0.80	0.91	0.95	0.93	0.92	0.83	2.95
1979 Okapi	0.13	0.37	0.72	0.85	0.88	0.87	0.90	0.87	0.83	0.92	0.78	3.04
1979 Adonis	0.22	0.58	0.72	0.82	0.90	0.92	0.90	0.87	0.75	0.92	0.73	3.00
1980 Bastion	-	0.05	0.23	0.36	0.54	0.51	0.58	0.66	0.62	0.92	1.16	2.43
barley												
incidence angle	75	70	60	50	40	30	20	15	10	total		
1977 Aramir, a	-	0.37	0.60	0.73	0.76	0.79	0.77	-	-	0.84	2.38	3.31
1977 Aramir, b	-	0.26	0.53	0.71	0.81	0.87	0.91	-	-	0.84	2.17	3.00
1977 Aramir, c	-	0.20	0.52	0.70	0.79	0.81	0.81	-	-	0.83	1.89	2.66
1979 Aramir	0.69	0.82	0.92	0.95	0.97	0.97	0.97	0.95	0.95	0.95	0.88	2.54
1980 Havila	0.31	0.54	0.58	0.59	0.61	0.50	0.58	0.67	0.49	0.84	1.93	5.70

Table 11.4: calculated values $C(\theta)$ for wheat and bareley computed from the radar measurements during growth stages 1-9.

crop type $C(\theta)$	75	70	60	50	40	30	20	15	10
wheat									
1977 Melchior, a1	-	0.0819	0.0271	0.0074	0.0122	0.0127	0.0244	-	-
1977 Melchior, b1	-	0.0540	0.0146	0.0010	0.0080	0.0103	0.0270	-	-
1977 Melchior, c1	-	0.0394	0.0001	0.0001	0.0001	0.0001	0.0136	-	-
1977 Melchior, a2	-	0.0594	0.0119	0.0026	0.0139	0.0169	0.0253	-	-
1977 Melchior, b2	-	0.0768	0.0213	0.0086	0.0138	0.0125	0.0253	-	-
1977 Melchior, c2	-	0.0684	0.0163	0.0001	0.0001	0.0001	0.0072	-	-
1979 Arminda	0.1754	0.1232	0.0755	0.0653	0.0556	0.0575	0.0736	0.0932	0.1727
1979 Okapi	0.1624	0.1080	0.0543	0.0394	0.0346	0.0382	0.0462	0.0566	0.0975
1979 Adonis	0.1245	0.0972	0.0776	0.0651	0.0682	0.0756	0.0890	0.1044	0.1669
1980 Bastion	-	0.0854	0.0678	0.0652	0.0667	0.1100	0.2045	0.3367	0.7135
barley									
1977 Aramir, a	-	0.0399	0.0214	0.0103	0.0128	0.0111	0.0206	-	-
1977 Aramir, b	-	0.0382	0.0214	0.0121	0.0153	0.0164	0.0268	-	-
1977 Aramir, c	-	0.0461	0.0248	0.0180	0.0220	0.0210	0.0464	-	-
1979 Aramir	0.0420	0.0331	0.0295	0.0339	0.0366	0.0395	0.0500	0.0645	0.1046
1980 Havila	0.0694	0.0522	0.0506	0.0497	0.0529	0.0721	0.1070	0.1602	0.3047

attenuation D also depends on the row spacing. It is largest for the small-row crops which reflects the relatively low transparancy and the relatively fast increase of the backscatter with crop growth. For the wheat crops with the small row spacings, the factor $C(\theta)$ converges to very small values at medium angles of incidence. In theory this would mean that the backscatter of the crop would decrease to almost infinite negative (dB) values with continuing growth of crop height. In practice the crop does not grow higher than about 1.25 m and these backscatter limits are never reached.

The good average result of the model for wheat in 1980 illustrates the effect of lumping the angles of incidence. The total coefficient of correlation is quite high, 0.92, but for each angle of incidence separately, it varies between 0.20 and 0.65 only. The total coefficients of correlation for the wheat crops in 1979 are similar, but they are made up by individual coefficients of 0.60-0.95. The high total r^2 for the 1980 crop is therefore caused by the summation over all angles of incidence, and does not -a priori- mean a good fit of the model. On the other hand, the relatively small value of the SEE (when compared with 1977) and visual analysis of the results imply a fair fit of the model. Surprisingly, the transparancy of the crop to X-band microwaves (chapter 8.1) is not translated in small values of D. This factor compares well with that of the other crops. The parameter $C(\theta)$ is comparable to those in 1979 for most angles of incidence. Only at incidence angles smaller than 20° does $C(\theta)$ reach relatively large values. Despite the deviating pattern of the radar backscatter curves, the parameters of the Height model compare well with those in other years.

The coefficient of attenuation of barley is generally larger than that of wheat in the same year, with the only exception of Aramir 1979.

It is concluded that the simplified Height model, based on soil moisture and crop height only is succesful in describing the X-band radar backscatter of wheat and barley. However, there is no single set of model parameters which accurately describes the radar backscatter of all the different wheat and barley crops. The parameters D and $C(\theta)$ may differ by a factor 2 - 5, depending on the year and, in this example on the distance between the rows. Therefore, for any practical use, the parameters of the model have to be validated for the specific circumstances in which it is to be used, e.g. geographic location, management practice, crop variety etc. In the next paragraph it is investigated whether the Height model is also useful for monitoring purposes through its inverse use.

11.2 Estimating crop height

Because of its simple structure the Height model can theoretically easily be used to estimate crop height and soil moisture content from radar measurements. It turns out however, that the inverse use of the model is troublesome and that it gives erroneous results. The estimates are associated with a high degree of uncertainty and often exceed realistic values. To illustrate this, the example is given for the wheat variety Arminda 1979. The Height model gives a good description of the radar backscatter of this crop with high values of r^2 per incidence angle, 0.70-0.95, and a small SEE of 0.83. The model is inversely used on the backscatter measurements at all nine angles of incidence from 15° to 75°, with the model parameters derived from the same data set. Non-linear, numerical optimization techniques are used to estimate the values for crop height and soil moisture content (GENSTAT 5). The Height model is used in three modifications:

1) both K and D are angular dependent and experimentally derived:

$$\gamma = C(\theta).[1-\exp(-D(\theta).h)] + G(\theta).\exp(Ms.K(\theta)-D(\theta).h) \quad (m^2/m^2) \quad (Eq.\ 11.4)$$

2) K=0.051; D is angular dependent and experimentally derived: Eq. 11.2

3) K=0.051; D is angular independent and experimentally derived: Eq. 11.3

The approach of modification 1 is the most sophisticated since it uses values for G,C,D and K which are all optimized for each angle of incidence separately. Measurement errors and differences in canopy structure and surface roughness at different distances (incidence angles) from the radar can result in differences in K and D. For instance, the part of the field that is measured at 10° incidence angle lies closest to the edge of the field. Therefore the crop at this place might have a different structure from the crop in the middle of the field which is measured at 50° incidence angle. The approach of modification 3 is the most practical since it only uses one value for K and D for all angles of incidence. The results of these three approaches are given in table 11.5.

The results of the inversion are disappointing. The coefficients of correlation are low, the SEE's are large and the number of inverted measurements is small. Many estimations of crop height and soil moisture exceed the boundary values of respectively 0-150 cm and 0-40%. After day 173, the standard deviations of the estimations become relatively large (15-75 cm) when the backscatter has reached the stable level at grain filling.

Judging from the r^2 and the SEE, the best results are obtained with modification 3 using only one value for K and one for D for all angles of incidence. However, these relatively good results are caused by the small number of inverted values. A great number of backscatter measurements yields estimations for h and Ms which exceed the boundary values. With modifications 1 and 2, a greater number of estimations of h is obtained, especially up to day 180. Between these two modifications, there is hardly any difference. The refinement of modification 1 does not lead to better estimations of crop height or soil moisture. The correlation between the estimated and the measured crop height is very low for both approaches. The SEE is large for all three approaches (23-30 cm), especially when one considers that the crop height varies between 0 and 125 cm only. The error of estimate is about 30% of the total range in height.

There are two causes for these bad results. First, the contrast between the backscatter of the bare soil and that of the opticaly thick crop canopy is low. It is about 4-5 dB at low and medium angles of incidence, and even lower at high angles of incidence. Deviations between model predictions and measured values, which are small on an absolute scale, are large on a relative scale. For instance, the SEE of the Height model in describing the radar backscatter of Arminda 1979 is only 0.83 dB. However, this is about 20% of the total range in backscatter between that of the bare soil and that of the crop canopy. Therefore, with the inverse use of the model, a relatively large SEE of 25-30% of the total range in crop height is not

Table 11.5: measured crop height H and estimated crop height h1, h2 and h3 using the inverse Height model in 3 modifications. S.d.=standard deviation of the estimation, r2=coefficient of correlation, SEE=standard error of estimate, N=number of measurements or estimated values. An * is given when the estimated value for crop height or soil moisture exceeds the boundary conditions: 0^h^1.50 m, 0<Ms<40%.

daynr	H	h1	h2	h3	sd1	sd2	sd3 (cm)
129.0	15	81	*	11	5	-	-
130.0	17	69	76	25	8	10	9
143.0	28	30	29	*	1	2	-
145.0	30	46	57	39	6	7	16
152.0	55	54	54	32	6	10	6
156.0	65	62	64	45	3	3	3
159.0	68	99	103	*	9	9	-
162.0	72	55	53	78	5	6	28
164.0	75	80	83	*	9	11	-
166.0	77	90	92	*	7	8	-
169.0	80	49	47	31	5	7	10
171.0	88	49	44	*	7	10	-
173.0	90	58	56	45	6	10	13
176.0	95	111	102	*	17	14	-
178.0	95	119	121	*	34	22	-
180.0	95	143	*	*	38	-	-
183.0	95	*	*	*	-	-	-
185.0	95	*	*	*	-	-	-
187.0	95	100	*	86	63	-	29
191.0	95	149	120	105	52	24	53
194.0	95	*	*	*	-	-	-
198.0	95	65	*	*	9	-	-
201.0	95	103	108	111	16	13	75
205.0	95	89	94	*	16	15	-
208.0	95	*	*	*	-	-	-
212.0	92	*	*	*	-	-	-
215.0	92	*	*	*	-	-	-
219.0	92	*	*	*	-	-	-
222.0	90	*	*	*	-	-	-
228.0	90	*	*	*	-	-	-
229.0	90	*	*	*	-	-	-
233.0	15	*	*	*	-	-	-
236.0	15	*	*	*	-	-	-
240.0	15	*	*	*	-	-	-
243.0	15	*	*	*	-	-	-
r2		.51	.52	.77			
SEE		30	26	23	(cm)		
N	35	21	17	11			

surprising. Secondly, there is a high correlation between the radar backscatter at the various angles of incidence. The backscatter curves are rather parallel and the n-dimensional space of the model (n=number of incidence angles) is narrow. This means that relatively small variations in the radar backscatter are inverted in relatively large variations in vegetation and soil parameters.

In theory, two options are open to improve these results. Averaging of the radar backscatter in time or in space reduces the influences of random disturbences in the canopy structure. When the fluctuations in the backscatter are smaller, the deviations in the estimated vegetation and soil parameters will be smaller too. Since many measurements were made during the growing season on small plots, averaging in time is appropiate here. The radar backscatter is averaged per development stage, and the Height model is again applied to estimate the height of the crop. The model of modification 1 is used, i.e. one value for K and D each for all angles of incidence. Table 11.6 summarizes the results for the wheat varieties Arminda and Adonis in 1979, and Melchior in 1977 with row distances 12.5 (a2) and 37.5 cm (c2).

In 1979, the calculated backscatter based on the estimations of crop height and soil moisture account for 85-99% of the variance in the measured backscatter. For the crops in 1977 this percentage is considerably lower and varies between 40-80%. The results of the inversion, however, are bad for both years. Only half of the averaged radar measurements yields estimations of crop height and soil moisture content which fall within realistic boundary values. Of this number, only 30% falls within a 10 cm range around the measured average crop height. Especially for Melchior a2, the number of estimations is very small. For Melchior c2 the situation is slightly better, both with regard to the number of the estimations as to the quality of the estimations. This may partly be explained by the relatively small value of D for this crop. The fluctuations in the measured radar backscatter, caused by varying soil moisture content, are returned by the inverse use of the model in the estimations of soil moisture. For the crop a2, the model parameter D is much larger and similar fluctuations are then returned in the estimations of the crop height.

The inversion excercise is also performed with a limited number of incidence angles. It turns out that when this number is already reduced to six, in the range of 40° to 80° incidence angle, almost no realistic values of crop height and soil moisture are obtained at all. Similar results are obtained when the model parameters acquired in one year are used for the inversion in another year.

11.3 Discussion

X-band radar backscatter data at multi-incidence angles, and the empirical Height model are unsuitable for estimations of crop height and soil moisture content. The number of estimations with values within reasonable boundary values, and the associated accuracies are very low. Three reasons account for this unsuitability:

Table 11.6: measured crop height H and estimated crop height h using the inverse Height model. The coefficients of the Height model are taken from Tables 11.3 and 11.4. An - is given when no measurements were taken during the stage of development under consideration, and an * when the estimation for crop height or soil moisture content exceeds the boundary values: $0<h<1.50$ m, $0<Ms<40\%$.

development stage		1	2	3	4	5	6	7	8	9	10	11	22	30
Arminda 1979	H	-	16	29	65	78	92	95	95	92	90	90	-	15
	h	-	16	*	33	21	54	122	*	*	*	44	-	*
Adonis 1979	H	6	19	41	59	77	95	102	100	100	-	-	60	-
	h	61	*	0	23	34	*	*	200	*	-	-	*	-
Melchior 1977, a2	H	-	18	29	64	85	98	107	107	105	104	100	-	15
	h	-	*	33	76	*	*	*	*	*	79	*	-	*
Melchior 1977, c2	H	8	19	35	64	85	98	107	107	106	103	100	-	15
	h	*	136	67	51	84	*	117	*	110	*	*	-	28

1) Fluctuations in the curves of the radar backscatter.
The influence of external conditions on the structure of the crop canopy cause variations in the radar backscatter. Such variations are not taken into account in the model and therefore result in deviations in the estimation of crop height.

2) The low contrast between the radar backscatter of a bare soil surface and that of an optically thick crop canopy.
This low contrast causes the fluctuations in the radar backscatter (due to measurement errors or external conditions) to result in relatively large deviations in the estimation of crop height. The effect of a low contrast is demonstrated in the following example. The Height model can be inverted for each angle of incidence to calculate the height of the crop at any given soil moisture content:

$$h = -\ln[(\gamma-C)/(G.\exp(Ms.K)-C)]/D \qquad (m) \; (Eq.\ 11.5)$$

The sensitivity of the estimation of h on fluctuations in the radar backscatter is illustrated in fig. 11.3. The model parameters are chosen for Arminda in 1979 at 30° incidence angle. The contrast between the radar backscatter of the crop and that of the bare soil is about 5 dB. The crop height is first calculated for a given range of backscatter values and labeled 'true crop height'. It is then calculated with deviations of +/-1 and +/-2 dB from the original backscatter, and labeled 'calculated crop height'. The large deviations between 'true' and 'calculated' height are evident, especially when the 'true' height exceeds 60 cm. The accuracy of the estimation decreases exponentialy with increasing crop height. The average SEE is 17 cm for a deviation in the radar backscatter of +/-1 dB, and 29 cm for a deviation of +/-2 dB.
The same calculations are also done for the crop Melchior a2 in 1977. The contrast between the radar backscatter of this crop and that of the bare soil is about 8 dB. The accuracy of the estimation of h has increased to an average SEE of 12 cm for a deviation in the backscatter of +/-1 dB, and to 24 cm for a deviation of +/-2 dB (fig. 11.4). The larger contrast between the backscatter of the crop and that of the bare soil results in higher accuracies. However, the SEE of the Height model is also larger for this crop: it is 0.83 for Arminda, versus 2.06 for Melchior a2 (table 11.3). This means that in practice, the accuracies of the estimation of crop height will be similar for both crops.

3) The high correlation between the radar backscatter at different angles of incidence.
The temporal radar backscatter curves are highly correlated for wheat and barley at different angles of incidence. The curves are more or less parallel and the contrast between the curves is low. Decorrelation between the backscatter at different angles of incidence only occurs at high incidence angles. However, for angles higher than about 60° the results of the Height model are bad. Therefore, the benefits of a lumping of several angles of incidence are low. The solution of the inverse Height model in estimations of crop height and soil moisture requires at least two independent model equations. Since this requirement is not truly met, the inversion converges only for a limited number of measurements to a solution. The low contrast between the backscatter at medium and low angles of incidence is illustrated in a feature space plot (fig. 11.5). The Height model is used to calculate a range in backscatter values for Arminda 1979 at 20° and 50° incidence angle. The calculations are based on crop heights

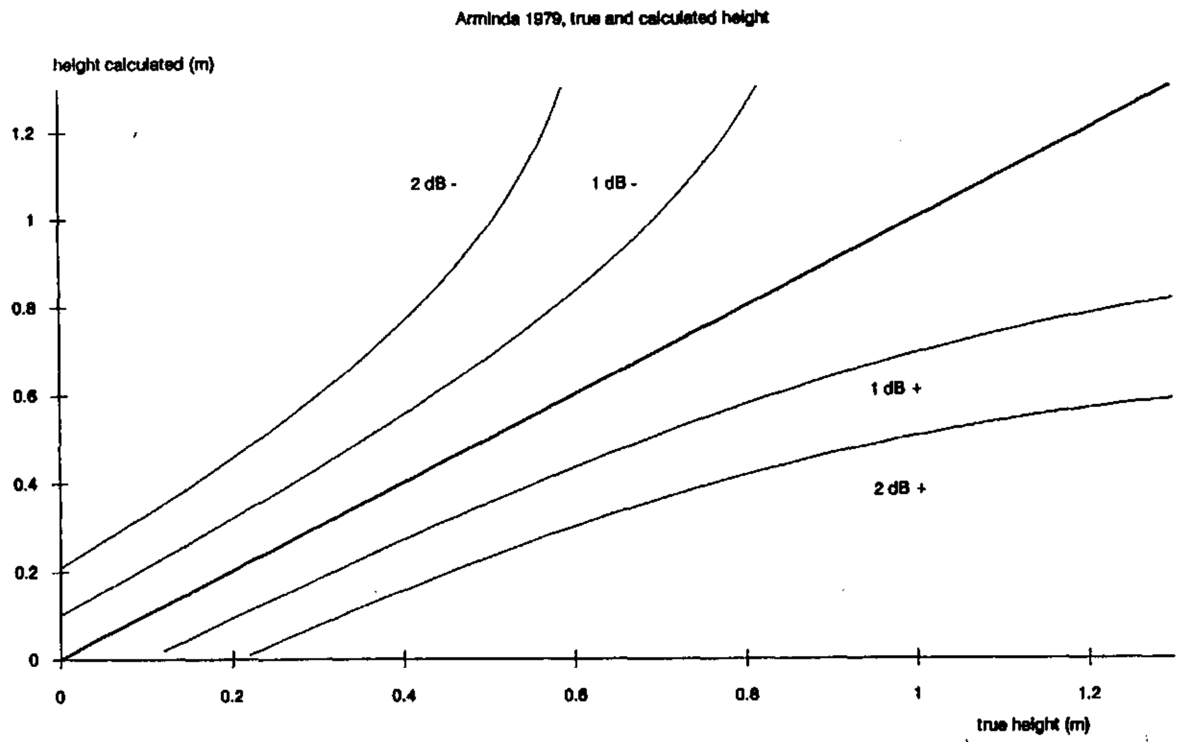


Figure 11.3: true versus estimated crop height using the inverse Height model on radar data at 30° incidence angle, Arminda, 1979.

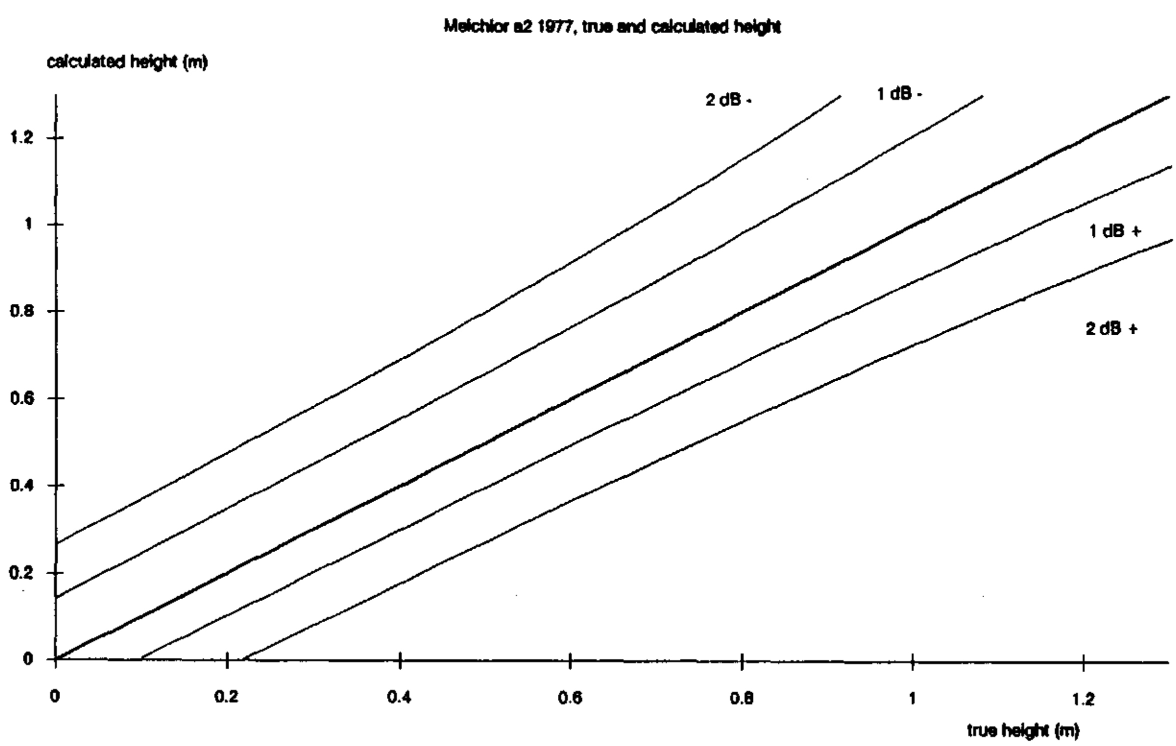


Figure 11.4: true versus estimated crop height using the inverse Height model on radar data at 30° incidence, Melchior a2, 1979.

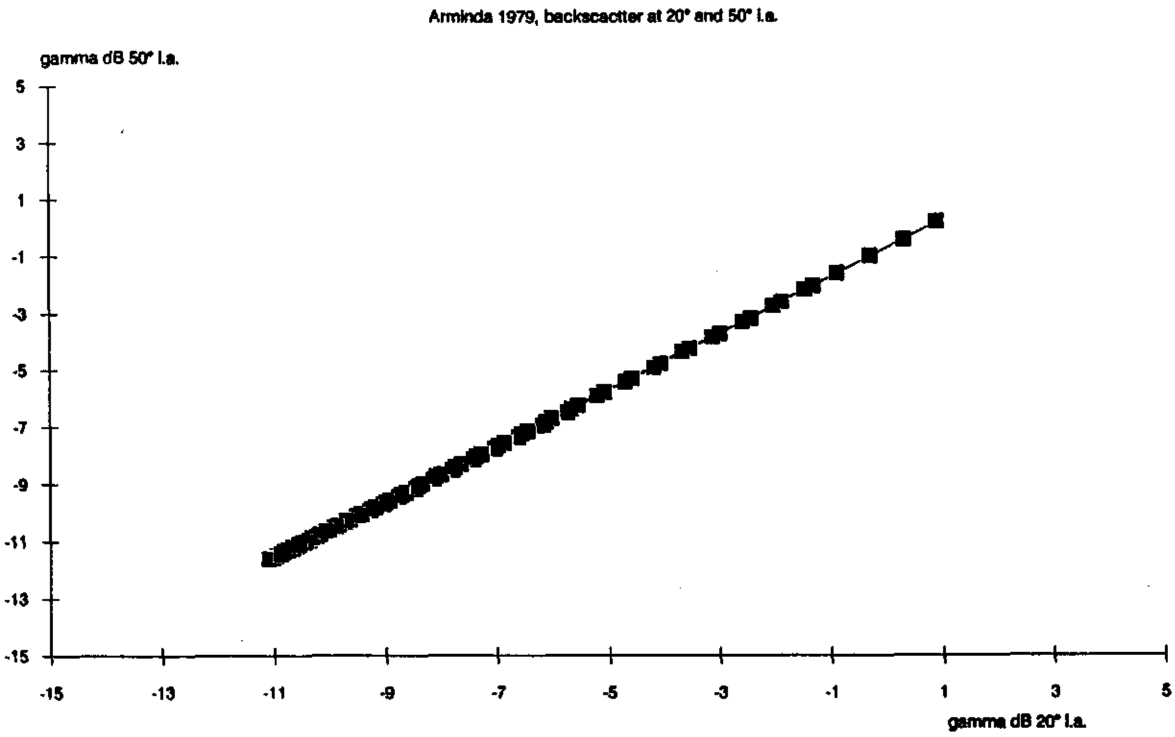


Figure 11.5: calculated radar backscatter at 50° incidence angle versus that at 20° incidence angle, Arminda 1979

between 0 and 1.20 m, and soil moisture contents between 0 and 40%. The radar backscatter decreases at both angles of incidence with increasing crop height and decreasing soil moisture content: the data points lie on a nearly straight line. Therefore, a solution of the Height equations in two unknown variables, crop height and soil moisture content, in this two-dimensional space is hardly possible.

Since no extra information is gained by considering multi-incidence backscatter data, estimations of crop heigt can best be made on the basis of radar data at one angle of incidence only. The Height model can be inverted to yield estimations of crop height for any input of soil moisture content. This latter can either be estimated from other sources of information or from general weather conditions. Also an average value can be given for the whole growing season. The associated accuracy of the estimation depends on the contrast between the radar backscatter of the crop and that of the bare soil. This contrast determines the measure in which inaccuracies in the backscatter or in the fit of the model, are translated in inaccuracies of the estimations. For individual crops, the average SEE of the estimated crop height will vary around 20 cm.

Part III.

Discussion

12 Summary and discussion

12.1 Canopy structure

Crop variety, management practices and external conditions have an effect on the (ground based) X-band radar backscatter of cereals. The magnitude of these effects depends on the type and the growth stage of the crop, and on the angle of incidence and the state of polarization. The average variation in radar backscatter at VV polarization during the period of grain filling and ripening of the crop, is summarized for some effects in table 12.1. The average variation between the radar backscatter in different years is also included.

Table 12.1: average variation in X-band radar backscatter (dB) at VV polarization during the period of grain filling and ripening for cereals in 1975-1981.

effect	crop	incidence angle 20°	50°	70°
row spacing 12.5-37.5 cm	wheat 1977	3	1.5	2.2
	barley 1977	6.5	2.5	0.5
row direction parallel-perpendicular	barley 1976	2.5	0.5	0
	wheat 1981	2.5	0.5	0.5
crop variety	wheat 1979	1.5	1	0.5
	wheat 1981	3.0	3.0	2.0
lodging	barley 1980	4.5	11	11.5
	wheat 1979	5.0	1.5	4.0
	oats	5.5	2	0.5
ear orientation	barley 1977	6.5	7.5	7.5
	wheat 1977	0	0	3
annual variation	wheat 1975-1979	5	5	4
	barley 1975-1980	6	6	3
	oats 1975-1980	3	1.5	1.5

The radar backscatter of crops is largely determined by the geometry of the top of the canopy, e.g. the size, shape, orientation and distribution of its elements. The effects of <u>row spacing</u> are the result of changes in the attenuation and scatter properties of the canopy, and of subsequent changes in the contribution from the underlying soil surface. A small row spacing generally results in an enhancement of the typical features in the temporal curve of the radar backscatter. For wheat and barley, these are the relatively high backscatter during early vegetative growth at medium and high angles of incidence, and the low backscatter during grain filling and ripening at low and medium angles of incidence. The backscatter of barley is more influenced by the variation in row spacing than that of wheat.

The effects of <u>row direction</u> are less pronounced than those of row spacing. At medium and high angles of incidence there is practically no difference between the backscatter of parallel and of perpendicular row crops. At low angles the backscatter of the perpendicular crops is consistently lower than that of the parallel row crops.

Different wheat varieties influence the radar backscatter according to the geometry of the canopy. A crop with a relatively short and dense canopy, and with broad top leaves with a large horizontal component, has a relatively high level of radar backscatter at low and medium angles of incidence. A relatively tall and thin crop with narrow top leaves with a small horizontal component, has a relatively low level of radar backscatter. Crops with a very erect canopy structure can have deviating backscatter curves during the period of vegetative growth.

Except for the effect of row spacing on barley at low angles of incidence, the effects of management practice and crop variety (found in this study!) are not very large on an absolute scale and vary between 0.5 and 3 dB. They are relatively largest at VV polarization and at low angles of incidence. The difference between the radar backscatter at VV and at HH polarization is also largest at low angles of incidence. This difference appears related to the absolute level of the backscatter: lower levels of backscatter during generative growth are associated with larger VV-HH backscatter differences. This is caused by the larger sensitivity of the backscatter to management practices at VV than at HH.

The effects of external conditions, like wind and rain, on the backscatter of the crop are larger than those of management practices and crop variety. The backscatter can change up to 11 dB for barley and up to 5 dB for wheat and oats.

External conditions influence the radar backscatter through their effect on the structure of the canopy, e.g. lodging and changes in the orientation of the canopy elements. The variation in backscatter due to these changes is largest for barley and similar between wheat and oats. Even minor changes in the orientation of the ears can dramaticaly change the backscatter of barley. This relatively large influence for barley is attributed to its sensitivity to external conditions and to the presence of large awns on the ears. The sensitivity to external conditions makes the structure of the canopy change more often and more dramaticaly, and the presence of the awns makes the backscatter more sensitive to these changes. Contrary to the effects of management practice and crop variety, the effect of external conditions on the backscatter of wheat and barley is largest at high angles of incidence. For oats it is largest at low angles of incidence. With some exceptions, the effects on the radar backscatter are similar at VV and at HH polarization.

The combined effect of management practice, crop variety and external conditions, results in a relatively large annual variation between the backscatter levels of crop types. At low to medium angles of incidence, this variation averages 6 dB for barley, 5 dB for wheat and 1.5-3 dB for oats. For wheat and barley, this variation nearly equals the total average range in radar backscatter caused by the growth of the crop from emergence to a closed canopy (table 12.2). The variation for oats is smaller, probably because of the smaller number of crops measured (3) compared to that of wheat (10) and barley (6).

Table 12.2: average range in the radar backscatter (dB) of an emerging crop to that of a closed crop canopy.

	incidence angle		
crop	20	50	70
wheat	7	6	4.5
barley	6	7.5	5
oats	3	5	7

12.2 Application possibilities

12.2.1 Crop classification

The temporal signature of the X-band radar backscatter at one or two angles of incidence, respectively medium, and medium and high, can be used in the discrimination of wheat and barley from other crops as beet, potato or grass (Binnenkade and Uenk, 1987; Uenk et al., 1987). If the measurements are made at both VV and HH polarization, the typical VV-HH backscatter difference at these angles of incidence increase the sensitivity for discrimination. The differences between the backscatter properties of wheat and barley are relatively small and differentiation between these crops will remain troublesome. On the other hand, the typical backscatter properties of oats will result in a high probability of identification. Especially the positive difference, during the stage of grain filling, between the backscatter at VV and at HH at medium and high angles of incidence is a specifically discriminating feature. For wheat and barley, this difference is typically negative.

The specific sensitivities of each cereal type to external conditions may result in possibilities for classification under specific conditions. For instance strong winds may cause preferential orientation of the ears of barley while those of wheat remain unaffected. The differences in ear orientation may then lead to differences in the radar backscatter, on the basis of which the crops can be identified. This requires however 'intelligent' ground truth collection which can not be extrapolated from one location to another.

Some examples of discrimination between cereal types are given by M.G. Wooding, 1988.

12.2.2 Crop development

A precise monitoring of the development of wheat and barley on the basis of a detailed temporal signature of the X-band radar backscatter is not possible. For oats, the possibility for estimating crop development is somewhat larger. In general, only generalized phases of crop development can be identified from a temporal signature at medium angles of incidence (table 12.3).

The classification of these general phases of crop development can not be derived from absolute backscatter values. It has to be inferred from the shape of the whole temporal signature. For wheat and barley, the division is based on the typical bends in the temporal signature at either VV or HH polarization. For oats, the division is not only based on such bends, but also on typical differences between the backscatter at VV and at HH polarization. For all three crops a further subdivision might be achieved

Table 12.3: general phases of crop development which can be derived from a temporal backscatter signature at a medium angle of incidence, for a crop with 'normal' growth.

general phase	radar-morphological development stage
wheat:	
emergence - tillering	1- 3
stem extension - heading	4- 6
grain filling - ripening	7-10
ripened crop	11
barely:	
emergence - tillering	1- 3
stem extension - heading	4- 6
grain filling - harvest	7-30
oats:	
emergence - tillering	1- 2
stem extension - booting	3- 4
panicle formation	5
panicle stem formation - beginning grain filling	6- 7
grain filling - dying	8-10

in practice by interpolation. Furthermore, possibilities exist for the detection of lodging of the crop. Backscatter measurements at more angles of incidence do not add new discriminative possibilities. If only crude, or no temporal signatures at all are available, detailed angular signatures can be used to discriminate between the same general phases of development.

Because of the relatively large fluctuations in the curve of the radar backscatter in the early growing season, the emergence of the crop can not be exactly determined. Also, unambiguous detection of harvesting is generally not feasible. Management practices such as the leaving-behind or the removal of the straw, or the ploughing and harrowing of the stubble field affect the backscatter of the harvested field. Because of the similarity in backscatter properties, the transition from ripe wheat or barley to a stubble field can not be determined, not even at several angles of incidence and at both VV and HH polarization. With multi-angle observations, the transition to a ploughed or harrowed field is more easily recognised. For oats, the possibility for the detection is somewhat larger and depends on the degree of lodging of the crop.

12.2.3 Crop growth

The level of the radar backscatter of wheat and barley during grain filling does not correlate with the average biomass, soil cover, plant water or plant water density in the same stage. The differences in backscatter level result from differences in canopy structure.

For both wheat and barley, the radar backscatter during the whole growing season (all crops between 1975 and 1980 lumped together) does not correlate with soil cover, plant water or dry biomass, $r^2 \leq 0.60$. The highest correlation is with crop height at medium angles of incidence, $r^2 \approx 0.80$ for wheat and $r^2 \approx 0.75$ for barley. When only the period of growth from emergence to grain filling is considered, the coefficients of correlation increase with all parameters. However, the correlation with soil cover and plant water is still low, $r^2 \leq 0.60$. For wheat, the correlation is medium with dry biomass, $r^2 \approx 0.77$, and relatively high with crop height, $r^2 \approx 0.83$. For barley, the correlation is still low with biomass, $r^2 \approx 0.67$, but also relatively high with crop height, $r^2 \approx 0.85$.

For oats, no crop growth parameter correlates at all with the radar backscatter during the whole growing season. The backscatter changes too much with the appearance of the panicles to succesfully relate it to any growth parameter.

Direct monitoring of crop growth of wheat and barley is not possible after the crop has entered the stage of grain filling. In this stage, the radar backscatter reaches a stable level and does nor respond to any further increase in biomass. The direct monitoring of crop growth before grain filling seems possible, but is associated with a large degree of uncertainty. The crop height h and the dry biomass Wd can be estimated from the radar backscatter at medium angles of incidence by logistic expressions with empirically derived constants, e.g:

$$h \text{ or } Wd = A + B/[1+\exp(C.(\gamma+D))] \quad (\text{cm or g/m}^2) \quad (\text{Eq. } 12.1)$$

No such expression can be used to estimate the amount of plant water or soil cover. The average standard error of estimate (SEE) of crop height is 19 cm and of dry biomass 220 g/m for all crops lumped together. For crop height, this is about 18% of its total range (from emergence to grain filling), and for biomass it is about 23%. These values apply to a lumping of crops grown at different locations, with different management practice and different soil backgrounds.

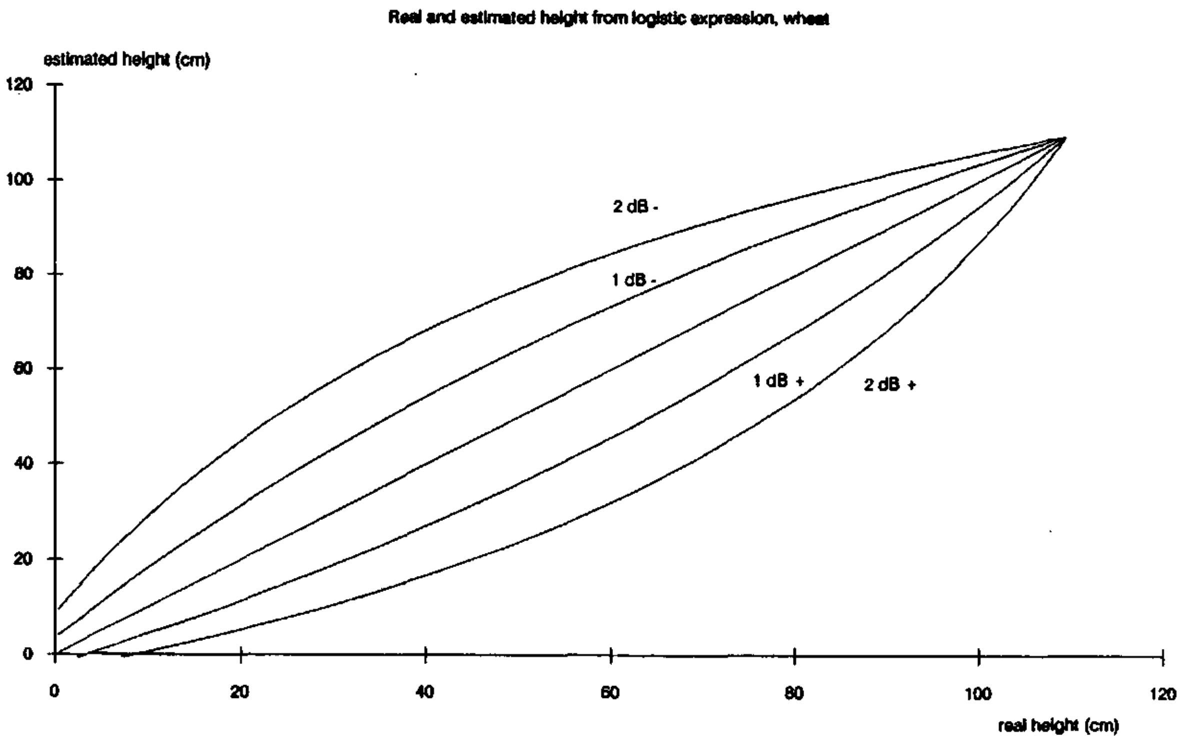


Figure 12.1: the effect of fluctuations in the radar backscatter on the estimation of crop height of wheat, using a logistic expression fitted on all wheat crops together.

The effect of fluctuations in the radar backscatter on the estimation of crop height, using Eq. 12.1 fitted on the whole data set of wheat, is graphically presented in fig. 12.1. If the backscatter fluctuates with 1 dB, the SEE averages 8 cm. If it fluctuates with 2 dB it increases to 15 cm. In practice, fluctuations can be much larger than 2 dB, leading to an average SEE of 19 cm for all crops together (chapter 8 and 9).

The crop height h can also be estimated from backscatter measurements at one angle of incidence by the inverse Height model:

$$h = -\ln[(\gamma - C)/(G.\exp(Ms.K) - C)]/D \quad (cm) \quad (Eq.\ 12.2)$$

The model parameters are derived from fitting the calculated backscatter from the Height model to the measured backscatter of the crop-soil system. For an estimation of h, an input must be given for the soil moisture content Ms. This value can either be estimated from weather conditions or from another source of information, or an average value can be given for the whole growing season. Significant errors caused by a wrong input for Ms will only occur during the early period of growth (small values of h). The average SEE's of crop height, caused by fluctuations in the radar backscatter, are similar to the ones given above. The distribution, however, of the SEE with crop height is fundamentally different (figs. 11.3 and 11.4 versus fig. 12.1). When h is derived from logistic expressions, the associated SEE is smallest at low and high values of h. When h is estimated from the inverse Height model, the associated SEE is largest at low and high values of h.

With either the logistic expression or the inverse Height model, the accuracy of the estimation depends on a) the contrast between the radar backscatter of the bare soil and that of the optically thick crop canopy, and b) the fluctuations in the backscatter curves.

If the contrast is low, like for wheat in 1979, relatively small fluctuations in the backscatter curve cause relatively large deviations in the estimated crop height. On the other hand, if the contrast is high, small deviations in the radar backscatter result in only small deviations in the estimated crop height. Table 12.4 lists the average SEE of crop height for a low and a high backscatter contrast at 30° incidence angle. The calculations are based on the inverse Height model with model parameters fitted for both crops individually.

Table 12.4: SEE of crop height (cm) with deviation in the radar backscatter (dB), based on the inverse Height model.

deviation:	+/- 1 dB (cm)	+/- 2 dB (cm)	crop-soil contrast (dB)
Arminda 1979	17	29	5
Melchior a2	12	24	8

The fluctuations in the temporal curves of the radar backscatter are larger for Melchior than for Arminda. The SEE of the fitted radar backscatter by the Height model is 2.06 dB for Melchior and 0.83 dB for Arminda. Therefore, in practice, the errors in the estimation of crop height will be larger for Melchior (24 cm) than for Arminda (17 cm), despite the larger contrast in radar backscatter for Melchior.

The SEE's of crop height in table 12.4 are somewhat larger than the average SEE's of crop height calculated from the logistic expressions. This is caused by the nature of the formula's. With the inverse Height model, the errors in the estimation diverge with increasing crop height (fig. 11.3), while they converge with the logistic expression (fig.12.1). The average SEE for the range in crop height from 0 to 120 cm is therefore theoretically larger with the inverse Height model.

These theoretical calculations illustrate the best obtainable results for the estimation of crop height. Estimations based on backscatter measurements at more than one angle of incidence do not lead to larger accuracies. Neither can both the crop height and the soil moisture content be estimated from multi-angle observations. The temporal curves of the radar backscatter at low to medium angles of incidence are more or less parallel and the contrast between these curves is low. Decorrelation between the backscatter curves only occurs at high angles of incidence, but then the results of the Height model are bad. The solution of the inverse Height model, in estimations of crop height and soil moisture content, requires at least two independent equations. Since this requirement is not truly met, the inversion does generally not converge to a solution. For the same reason, the more elaborate two-layer Cloud model is also unsuitable for inversion. Here, three independent model equations are necessary for a solution since three crop and soil parameters need to be determined; the water content of the ears, that of the vegetative material and that of the top soil.

12.2.4 Constraints

The above mentioned possibilities for classification and monitoring of growth and development apply to crops grown under average, non-stressed conditions. The example of wheat in 1980 illustrates the difficulties when this is not the case. This year, the development of the crop was slow and poor. The soil cover was a meagre 70% and the height of the crop only 85 cm. The open structure of the crop resulted in a high transparancy for microwaves and a large influence of the underlying soil. As a result, the temporal curve of the radar backscatter does in no way ressemble that of the average wheat crop. The crop can only be recognised by detailed multi-angle observations at both VV and HH polarization. No classification of development stages or quantitative monitoring of growth is possible. The radar observations can only in a qualitative way tell the relatively poor development of the crop from the lack of the characteristic backscatter features and the large influence of the soil background. However, the final yield of the crop, though relatively low, is similar to the final yield of wheat in 1977. That year, the development of the crop was normal, with all the characteristic features in the radar backscatter curves. The soil cover varied between 80 and 95% and the height was 110 cm. The low yield was caused by the relatively early ripening and dying of the crops.

12.2.5 System specifications

For any practical application of X-band radar in agriculture, the following system parameters are most suitable:

1) Incidence angle: medium between 30° and 60°.
For most applications, one single angle of incidence will generally suffice since no, or little extra information is gained from multi-angle observations. For the classification of crops, radar observations at both medium and high angles of incidence have proven their value (Uenk et al,

1987). However, multi-temporal observations at only medium angles of incidence are also efficient (Binnenkade, 1987), and more practical in spaceborne applications.

For crop growth monitoring and the estimation of surface parameters, measurements should be made at medium angles of incidence. The contrast between the radar backscatter of the bare soil and that of the optically thick canpy is largest while disturbing influences of management practices and external conditions are relatively low. If, for example, the management practices in a certain area are the subject of study, then low angles of incidence are appropiate. However, low angles of incidence will result in a relatively small ground resolution.

2) Polarization: VV, or both VV and HH.
For crop growth monitoring and the estimation of surface parameters, measurements at either VV or HH will generally suffice. However, measurements at both states of polarization are helpful in the identification of crop type, development stage, and canopy structure. At medium angles of incidence, the difference in backscatter at VV and HH is typically negative for wheat and barley during the stage of grain filling, while at the same stage it is typically positive for oats. The effects of external conditions, like ear-orientation, are better recognized with measurements at both states of polarization. The possibilities for differentiation between a ripened crop/stubble field and bare soil can also be enhanced.

3) Observation frequency: once per four to five days.
Because of the many fluctuations in the temporal signatures, a high frequency of observation is necessary to recognize general trends and to identify external influences.

4) Measurement accuracy: preferably $\leq$ 1 dB.
Measurement inaccuracies weigh relatively heavily in the quantitative monitoring of crop growth, e.g. dry biomass or crop height. This is caused by the low absolute contrast in dB between the radar backscatter of bare soil and that of the optically thick crop canopy. With an accuracy of 1 dB, the smallest errors in the estimation of crop height or biomass are about 19 cm and 220 g/m respectively.

12.3 Conclusion

Overall, the prospects for a precise monitoring of crop growth and development on the basis of X-band radar backscatter data (ground based scatterometer) alone are not bright. Even when observations are made at several angles of incidence and at both VV and HH polarization, the situation does not improve.

X-band radar observations do not seem suitable for the quantitative assessment of crop parameters of cereals like biomass, plant water or soil cover. The radar backscatter is mostly influenced by the structure of the crop canopy, e.g orientation and dimensions of the canopy elements. However, an ambiguity appears in the data on this point. On the one hand, the backscatter appears dominated by structural effects. For instance, the radar backscatter may react strongly on changes in the canopy structure caused by external conditions like wind. Lodging of a crop generally results in an increase in the backscatter. For barley, the azimuthal orientation of the ears may affect the backscatter in the order of 10 dB. For oats, the appearance of the panicles has a dramatic effect and the backscatter sharply increases at high angles of incidence. More generally, differences in crop variety can be related to the differences in radar backscatter level by a comparison of the canopy structure. As a simple growth parameter, the crop height is somewhat related to the overal canopy structure and correlates best with the backscatter. On the other hand, however, the radar backscatter appears insensitive to changes in the canopy structure which are visually apparant. The appearance of the ears goes unnoticed in the temporal signatures of wheat and barley. The emergence of the crops can not precisely be determined and even the change from a ripe crop to a stubble field can not readily be detected.

These examples illustrate the problems in the interpretation and the application of X-band radar backscatter data. Features which have no relevance to agricultural applications (the orientation of ears) may be prominent in temporal signatures while relevant aspects (harvest) go unnoticed. If radar remote sensing is to be useful for the monitoring of crop growth, these problems have to be better understood. It is clear, however, that radar has the potential to characterize the structure of a crop canopy. New methods and tools like polarimetry and the introduction of other frequency bands may open these possibilities. Furthermore, if radar imagery is considered instead of only scatterometer data, other aspects play a significant role and may contribute to a better interpretation of the data.

This study has furthermore identified the constraints in the X-band radar data for a precise quantitative assessment of crop parameters. These are notably the low contrast between the backscatter of a bare soil and that of an optically thick crop canopy, and the fluctuations in the curves of the radar backscatter. The identification of these constraints can give direction to the study of the radar backscatter at other frequency bands.

Finnaly, it is stressed that the conclusions from this study are derived from ground-based scatterometer data only. Radar imagery of a SLAR or SAR nature may have other aspects which are not taken into consideration in formulating the conclusions.

References

Allen, C.T., F.T. Ulaby, 1984. Modelling the polarization dependence of the attenuation in vegetation canopies, Proceedings of IGARSS'84 Symposium, Strassbourg 27-30 August 1984, 119-124.

Attema, E.P.W, and F.T. Ulaby, 1978. Vegetation modeled as a water cloud, Radio Science 13, no. 2, (March/April) 357-364.

Binnenkade, P., D. Uenk, 1987. Gewasidentificatie met behulp van microgolven (uitwerking SLAR-gegevens 1985), BCRS report bcrs-87-13.

Bouman, B.A.M., 1988. Microwave backscatter from beets, peas and potatoes throughout the growing season, Proceedings of the 4th International Colloquium on spectral Objects in Remote Sensing, Aussois, France, 18-22 January 1988, 25-30.

Bouman, B.A.M., 1987. Radar backscatter from three agricultural crops: beet, potatoes and peas, CABO report no. 71.

Bouman, B.A.M. and D. Uenk, 1987. Quick-looks van IRIS op Flevoland, CABO report no. 73.

GENSTAT 5 REFERENCE MANUAL, 1988. Oxford Science Publication.

Hoekman, D.H., L. Krul and E.P.W. Attema, 1982. A multilayer model for radarbackscattering from vegetation canopies, Digest of the 2nd IEEE International Geoscience and Remote Sensing Symposium, Munich, West Germany, 1-4 June.

Kasteren, H.W.J. van, M.K. Smit, 1977. Measurements on the backscatter of X-band radiation of seven crops, throughout the growing season. Comparison of the return parameter Gamma with some properties of the crops and with the density on a SLAR image, ROVE-report 1975, NIWARS publication 47.

Kasteren, H.W.J. van, 1981. Radar signature of crops. The effect of weather conditions and the possibilities of crop discrimination with radar. Signatures spectrales d'objets en télédétection, Avignon, 8-11 September 1981.

Large, E.C., 1954. Growth stages of cereals, illustration of the Feekes scale. Plant Pathology, volume 3, no 4, pp. 128-129.

Loor, G.P. de, P. Hoogeboom and E.P.W. Attema, 1982. The Dutch ROVE program, IEEE Transactions on Geoscience and Remote Sensing, GE-20, 1.

Lopez, A., T. le Toan, 1985. Effet de la polarisation d'une onde électromagnetique dans l'attenuation de l'onde dans un couvert végétale. Proceedings of the 3rd International Colloquium on spectral Objects in Remote Sensing, Les Arcs, France, 16-20 December 1985, 117-122.

Uenk, D., 1982. Bepaling van grondbedekking en biomassa met behulp van een reflectiemeter, CABO report no. 41.

Uenk, D., H.W.J. van Kasteren and P. Binnenkade, 1987. Classificatie van landbouwgewassen met radar. Radarvluchten 1983 en 1984 in Groningen, Oostelijk-Flevoland en West Brabant. CABO report no. 70.

Wooding, M.G., 1988. Imaging radar applications in Europe, ESA TM-01.