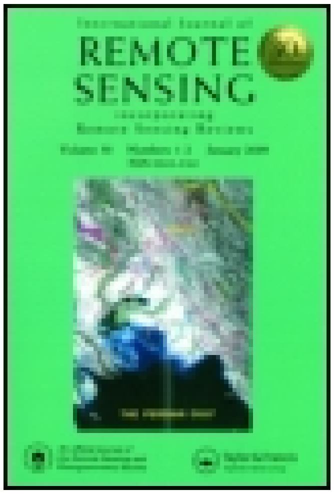

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tres20

Inferences on spatial and temporal variability of the backscatter from growing crops using AgriSAR data

C. C. F. YANASSE [a] , S. QUEGAN [a] & R. J. MARTIN [a]
[a] Department of Applied and Computational Maths/Probability and Statistics , University of Sheffield , Western Bank, Sheffield, S10 2TN
Published online: 27 Apr 2007.

To cite this article: C. C. F. YANASSE , S. QUEGAN & R. J. MARTIN (1992) Inferences on spatial and temporal variability of the backscatter from growing crops using AgriSAR data, International Journal of Remote Sensing, 13:3, 493-507, DOI: 10.1080/01431169208904052

To link to this article: http://dx.doi.org/10.1080/01431169208904052

INT. J. REMOTE SENSING, 1992, VOL. 13, NO. 3, 493-507

Inferences on spatial and temporal variability of the backscatter from growing crops using AgriSAR data

C. C. F. YANASSE†, S. QUEGAN and R. J. MARTIN

Department of Applied and Computational Maths/Probability and Statistics, University of Sheffield, Western Bank, Sheffield S10 2TN

(Received 22 December 1989; in final form 16 August 1990)

Abstract. AgriSAR 86 data from the Feltwell Site, U.K., was affected by a variety of radiometric distortions. These distortions prevent accurate calibration of the images, but analysis of the image statistics, after some radiometric corrections have been performed, permits a number of qualitative inferences about variations in crop backscatter in time and space. Cereals and sugar beet appear to exhibit different incidence angle responses. The separability of wheat and sugar beet varies with time and incidence angle. The separation of spring barley and wheat varies with time. Cereals show greater spatial variability than sugar beet. Individual fields exhibit great apparent variability in their temporal responses; for sugar beet this can in the main be explained by the effects of speckle, but there is some evidence of real variation for winter wheat.

1. Introduction

In the summer of 1986 a microwave remote-sensing campaign entitled AgriSAR 86 was organized by the Joint Research Centre of the European Communities, Ispra. Several sites over Europe were imaged using the VARAN-S X-band SAR developed by CNES, Toulouse. The objective of the campaign was to provide a calibrated multi-temporal and multi-polarization data set over agricultural test sites, in order to investigate the backscatter behaviour of growing crops.

The AgriSAR 86 data have been analysed by several researchers. Le Toan and Laur (1988) investigated the behaviour of the backscattering coefficient of several crops with HH and VV polarization at two dates over the French Camargue test-site; their work suggests the use of the polarization ratio between HH and VV for rice field monitoring. Fiumara *et al.* (1988) analyse the utility of multi-temporal and multi-polarization data for crop classification, using the data from an Italian test site, HH and VV polarization and two dates. Their best results in classifying crops are obtained by multi-temporal observations at VV polarization; they find the classes of sugar beet and wheat separable, using the inter-class pair divergence, but the separability of wheat and alfalfa difficult. Their results are based on backscattering coefficient measurements; it is not clear, however, whether any radiometric corrections were performed on the data before analysis. Foody *et al.* (1988) use HH polarized data over the Feltwell Site, U.K., on four dates. Using supervised discriminant analysis, they conclude that the three main crops (sugar beet, wheat and spring barley) can be classified with accuracy of 88 per cent using two dates (late June and mid-July). In their analysis they applied a correction for the range antenna pattern to the data for

†Under sponsorship by CNPq, Brazil.

each date, and another correction based on the assumed temporal stability of the backscatter from unvegetated fields to relate measurements between dates. Quegan *et al.* (1991) have however shown that the Feltwell data set suffers from several serious radiometric distortions in addition to those caused by the antenna pattern. Similar problems are expected to be present in the other AgriSAR 86 data sets and are likely to affect the conclusions given by the other investigators (particularly those of Foody *et al.* (1988) and Fiumara *et al.* (1988)).

In this paper the spatial and temporal variations of the backscatter from agricultural crops using AgriSAR 86 data are analysed. The test site used in the study covers a 100 km^2 flat area, centred on the village of Feltwell in Norfolk, U.K., used primarily for agriculture. A crop map for the area was compiled in June 1986 by the Ministry for Agriculture, Fisheries and Food, and is shown in figure 1. During the 1986 growing season, X-band SAR data for this site were recorded on four dates, for two look directions (north and south), using HH polarization. The dates were 6 June, 28 June, 17 July and 14 August. We use only the data from the three latest dates, since

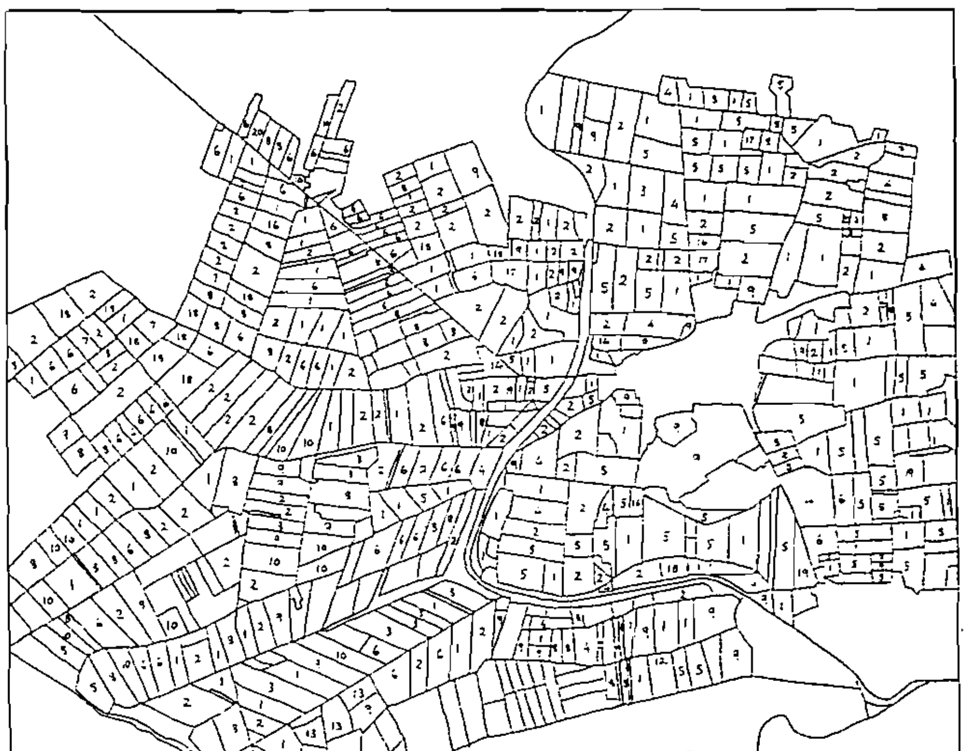

Figure 1. Crop map for the Feltwell area compiled in June 1986 by MAFF. 0, not mapped; 1, sugar-beet; 2, winter wheat; 3, spring wheat; 4, winter barley; 5, spring barley; 6, carrot; 7, oilseed rape; 8, potatoes; 9, grass; 10, dwarf beans; 11, maize; 12, rye grass; 13, celery; 14, beans; 15, cabbage; 16, parsnips; 17, peas; 18, onions; 19, allotments; 20, lucerne; 21, weed; 22, unknown.

at the earliest date only the cereal crops were well-developed, other fields being mainly bare soil; we also use only the south-looking data, which were of higher quality. The corresponding scenes will be referred to as images 222, 322 and 422 respectively.

Here we analyse those crop types for which a significant number of fields are present. Out of 379 fields for which we have crop type, 105 were sugarbeet, 93 were winter wheat and 52 were spring barley. The spatial distribution of these crops was not uniform over the site. The peaty soils (soil type 1) to the west of the prominent drainage dyke (see figure 1) supported mainly sugar beet and winter wheat; the sandy soils (soil type 2) to the east also supported a significant number of spring barley fields. Ground data were collected for a limited selection of fields of these crop types (amongst others) at the time of the overflights, and we have made use of the data gathered by the University of Sheffield, and data kindly supplied to us by M. Wooding and Hunting Technical Services/GEC-Marconi Research Centre.

All results in this paper are based on amplitude images corrected as described by Quegan *et al.* (1991) in order to remove antenna pattern, incidence angle and azimuthal gain variation effects. The corrected values are interpreted as measurements of $\sqrt{\gamma}$ ($\gamma = \sigma^0/\cos\theta$, where σ^0 is the backscattering coefficient and θ is the incidence angle (Ulaby *et al.* 1982)). These corrections preserved the mean amplitude of the original data in each image. No attempt was made to make relative brightness corrections between scenes, since no proper basis for mutual comparison was found. Problems with these corrections are discussed by Quegan and Yanasse (1989).

Our principal concerns in this paper are to assess (i) whether different crops exhibit different behaviour as a function of time and position in the swath; (ii) whether different crops are separable as a function of time and position in the swath; (iii) whether there is evidence for significant spatial variability within a single crop; (iv) whether there is evidence for significant temporal variability within a single crop.

We consider single images, and then look at the changes occurring between images. Our commentary is based on scatter plots of the mean amplitude values of blocks of pixels, and on regressions of the amplitude means on range and azimuth. Each block is a 10 by 20 rectangle (range × azimuth) of pixels, situated within a single field, and well away from the field boundaries, in order to avoid any changes in the structure of the soil or crops there. In the larger fields several samples were taken, in all cases separated by many resolution cells. We use the term observation to refer to the amplitude mean of such a 200-pixel block. We then discuss multi-temporal measurements from individual fields, and present the conclusions; this includes a discussion of the sample size required for detecting differences in mean backscatter useful for agricultural monitoring.

2. Results from individual images

In this section we investigate spatial variation in the backscatter from the different crop types. Systematic trends with range, azimuth or soil type are studied using regression surfaces. Unsystematic variation is investigated by means of the coefficient of variation. The simplest model for speckle predicts that the pixel amplitude values from a field will have a Rayleigh distribution (Ulaby *et al.* 1982). If the distribution has mean μ then the variance of the mean of N independent samples is given by

$$\sigma^2 = \left(\frac{4}{\pi} - 1\right)\frac{\mu^2}{N} \tag{1}$$

and the expected coefficient of variation of the amplitude mean is then

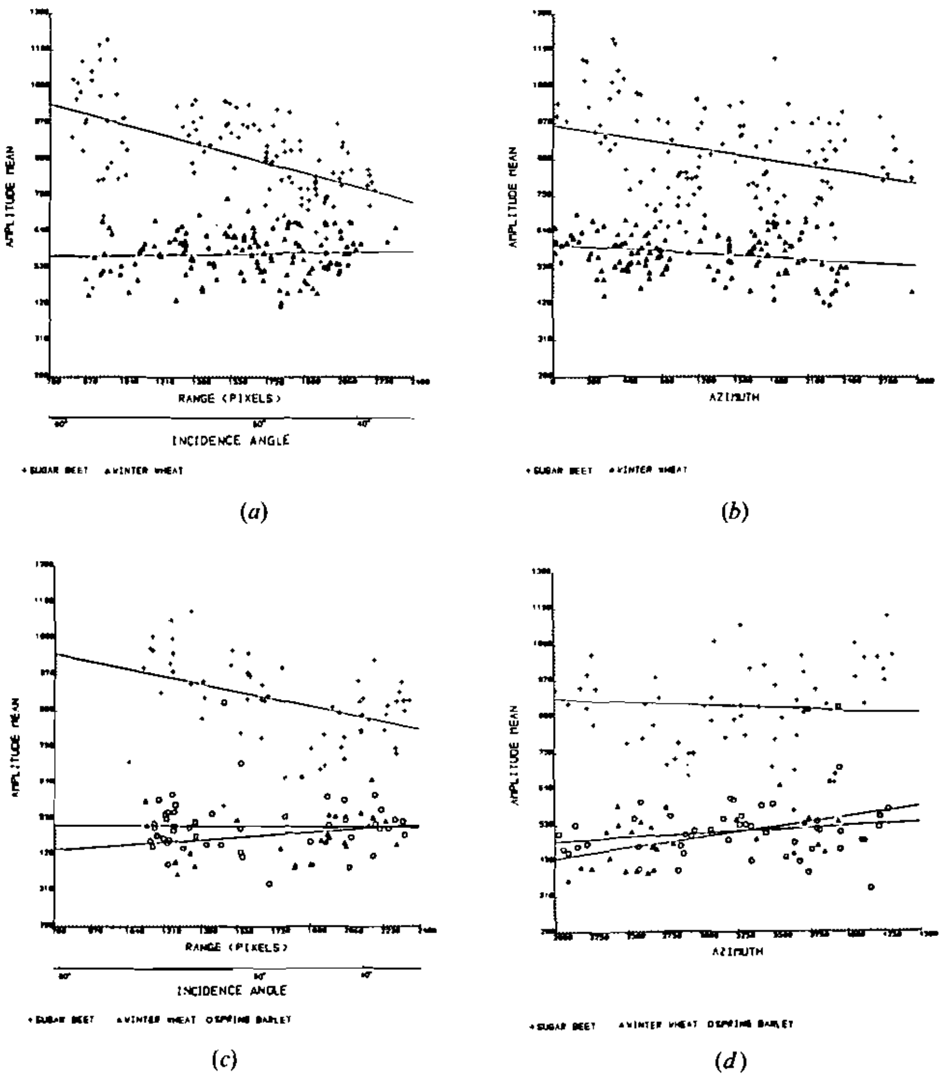

Figure 2. Mean values of blocks of 200 pixels within fields of a single crop type from scene 222 (*a*) plotted against range, peaty soils; (*b*) plotted against azimuth, peaty soils; (*c*) plotted against range, sandy soils; (*d*) plotted against azimuth, sandy soils.

$$\frac{\sigma}{\mu}=\sqrt{\left[\frac{1}{N}\left(\frac{4}{\pi}-1\right)\right]} \qquad (2)$$

Taking $N=200$, and taking account of the measured correlation between pixel values (Quegan and Yanasse 1989), a value for the coefficient of variation between 0·08 and 0·1 is expected for the block means used in this study. Values larger than this indicate spatial variability which cannot be attributed to speckle alone. We also consider the separability of different crop types. The methodology is fully described for image 222, and is followed for the other two images.

2.1. *Image 222*

Bivariate plots for image 222 are presented in figure 2(*a–d*), corresponding to each of the two soil types in both range and azimuth directions. On the range plots, far range is at *lower* pixel coordinates, so that incidence angle decreases from 60°–30° as the range coordinate increases. (In scene 322 the corresponding values are from 58°–30°, and from 65°–50° in scene 422. These differences occur because of varying flight-lines for the different scenes, causing different overlaps with the area where crop data were available). For the azimuth plot, pixel coordinate increases from west to east.

For each crop on each soil type, we fitted regressions of the form

$$x = b_0 + b_R R + b_A A \tag{3}$$

to the observations x, where b_0 is the estimated intercept and b_R and b_A are the estimated slope coefficients in range (R) and azimuth (A), giving five regressions for each image. A slope coefficient can be regarded as significant if its corresponding t-ratio, t_R or t_A, has absolute value exceeding 2 (the t-ratio is the estimated coefficient divided by its estimated standard deviation). The spread of the data is best described using the estimated standard deviation from the regression ($\hat{\sigma}$), which makes allowance for the variation of the mean value which occurs if either of the slope coefficients is significant. It will be smaller than the actual standard deviation, s. For similar reasons, we use $\hat{\sigma}/m$ instead of s/m (where m is the sample mean), as an estimate of the coefficient of variation. These estimated coefficients are given in tables 1 and 2, which also give the sample size (n) of the sample means.

2.1.1. *Soil type 1*

The results for this portion of image 222 are summarised in figure 2(*a–b*) and table 1. An obvious feature of the range plot (figure 2(*a*)) is the difference in slope of the regression lines for winter wheat and sugar beet. In Quegan *et al.* (1991) it was argued that for the corrected data the mean values from a given crop type would be proportional to $\sqrt{\gamma}$. Since the slope of the regression line for the winter wheat is not significant, it can be seen that the range correction applied seems to be equivalent to assuming that the cereals have constant γ across the swath. However, the range correction for antenna pattern has not produced a constant mean for sugar beet, probably because the scene contains a smaller area of sugar beet than cereals, and thus the correction is dominated by the cereals. These plots seem inconsistent with both cereals and sugar beet having constant γ, though this conclusion could be affected by system noise. This is discussed more fully in Quegan and Yanasse (1989).

Figure 2(*b*) gives an azimuth plot for the same region. We note that the mean values for sugar beet decline significantly from west to east; the cereal crop gives a

Table 1. Summary statistics for data from image 222, soil type 1.

	b_0	b_R	t_R	b_A	t_A	$\hat{\sigma}$	m	s	$\hat{\sigma}/m$	n
SU	1228	−0·172	−7·09	−0·056	−4·04	113·1	877	141	0·13	118
WW	560	0·030	1·73	−0·027	−3·16	64·0	575	66	0·11	127

SU = sugar beet; WW = winter wheat.

Table 2. Summary statistics for data from image 222, soil type 2.

	b_0	b_R	t_R	b_A	t_A	$\hat{\sigma}$	m	s	$\hat{\sigma}/m$	n
SU	1040	−0·133	−3·66	0·026	1·11	112·3	899	124	0·13	59
WW	311	−0·013	−0·29	0·067	2·41	72·5	484	79	0·15	29
SP	443	−0·005	−0·16	0·022	1·13	87·6	508	87	0·17	49

SU = sugar beet; WW = winter wheat.

flatter linear fit, but the slope coefficient is highly significant. The reason for this is unclear, since azimuthal corrections were particularly small for this image.

Investigating the separability of the two crops is not straightforward because the separability depends on position in the image. The following procedure was adopted. We find the 95, 99 and 99·9 per cent confidence intervals for the difference in predicted mean amplitude values of the two crops (referred to as 1 and 2) at the four corners of the rectangle defined as the intersection of the two rectangles T_1 and T_2, where T_i ($i = 1, 2$) is the smallest rectangle with edges parallel to range and azimuth directions that contains all the sampled points for crop i. These four cases include the widest possible confidence interval over the chosen rectangle. We say that the two crops are separable at a given corner and confidence level if the confidence interval there does not include zero. We also find the 95, 99 and 99·9 per cent tolerance intervals for differences between two new observations at these four corners. These tolerance intervals show the extent to which we expect observations for the two crops to overlap. We say that the two crops overlap at a corner and at a given level if the tolerance interval includes zero. Since the tolerance intervals are always considerably wider than the confidence intervals for a given percentage level, the tolerance interval will always include zero whenever the confidence interval does.

This procedure indicates that sugar beet and winter wheat are separable at each of the four corners of the test rectangle at the 99·9 per cent level. These two crops do not overlap at far range at the 99·9 per cent level, but do overlap at near range at the 95 per cent level.

Note that the observed values of the coefficient of variation are greater than those expected on the basis of speckle alone for both crop types.

2.1.2. *Soil type 2*

Consider now figures 2 (*c*) and (*d*) and table 2, which refer to soil type 2. Sugar beet observations again exhibit a significant trend with range, but the west–east trend noted in soil type 1 is no longer present. The average amplitude from the wheat seems lower for this soil type. Both cereal crops appear to show similar behaviour, but b_A is only significant for winter wheat. These crops are not separable at any corner of the test rectangle at the 95 per cent level. Sugar beet and the cereal crops are separable at all four corners of the test rectangle at the 99·9 per cent level. Sugar beet and the cereal crops do not overlap at far range at the 99 per cent level; at near range they do not overlap at the 95 per cent level. For all crops, the coefficient of variation is larger than expected from speckle.

2.1.3. *General comments on image 222*

For this image, ground data suggest that many of the sugar beet fields exhibited only partial cover. Hence some of the pixel values used to form the sugar beet block averages may be due to return from the soil; this would be particularly true at near range, where steeper look angles occur. Hence the unexpectedly large coefficient of variation for sugar beet fields may be due to spatial variations in the backscatter within these fields, but not necessarily in the backscatter from the plant itself. For wheat, which exhibited 100 per cent cover, the larger coefficient of variation appears to indicate real spatial variability.

A test for equality of the regressions in the two soils for sugar beet and winter wheat was performed. For each crop type, the two data sets were merged and a regression on range and azimuth with an indicator variable for soil type and interaction terms was fitted. The coefficients corresponding to these latter variables were then tested to see if they could be taken as zero. This showed that the range slope can be assumed to be the same on the two soil types, but that the intercepts and the azimuth slopes differ. For winter wheat, mean amplitude significantly decreases with azimuth on soil type 1, but significantly increases with azimuth on soil type 2. This is unlikely to be due to direct backscatter from the soil, since the wheat exhibited nearly 100 per cent cover, and at X-band we would therefore expect most of the return to be from the crop rather than radiation penetrating to the surface. It could be due to different wheat varieties or different growth stages on the two soil types, but we do not have sufficient ground data to corroborate any such hypothesis.

2.2. *Images 322*

The plots for image 322 are shown in figure 3 (*a–d*), and the summary statistics are given in tables 3 and 4. In many respects the results are similar to those for image 222. For sugar beet there is a significant decrease in the mean as range decreases, and for soil type 2 there is no dependence on azimuth. The two cereal crops again do not significantly vary with range.

In the azimuth direction there are some differences from image 222. The regressions for sugar beet and wheat no longer exhibit a significant slope in azimuth, while the corresponding slope for spring barley is now significant.

The separability results are also very similar to those of image 222. The important difference is that spring barley and winter wheat are now separable at the 95 per cent level at far range, and at the 99 per cent level at near range and high azimuth. On soil type 1, sugar beet and winter wheat now overlap at low azimuth at the 95 per cent level; for high azimuth there is overlap at the 99 per cent level at near range and at the 99·9 per cent level at far range. Sugar beet and spring barley now overlap at high azimuth at the 95 per cent level.

The regressions appear to be the same over the two soil types for both sugar beet and winter wheat. In all cases the magnitude of the coefficient of variation is larger than expected, with sugar beet having the lowest coefficient of variation.

2.3. *Image 422*

The plots and summary statistics for image 422 are shown in figure 4 (*a–d*), and in tables 5 and 6. We again observe the significant slope of the sugar beet regression line with range. For winter wheat on soil type 1 the slope with azimuth is now highly significant, and for spring barley the slope with azimuth is again significant but is now negative.

The results for separability are similar to those for image 222. The two cereals are only separable at the 95 per cent level at near range and high azimuth, and are not separable at the other corners of the test rectangle at the 95 per cent level. At near range, sugar beet and winter wheat are separable on soil type 2 at the 95 per cent level at low azimuth, and at the 99 per cent level at high azimuth. There is considerable overlap (at most 95 per cent) between the three crops at near range, except for sugar beet and winter wheat on soil type 1 at low azimuth, which only overlap at the 99 per cent level. At far range sugar beet and the cereal crops overlap at the 99 per cent level in four out of the six cases. In the remaining two cases, sugar beet and spring barley overlap at the 95 per cent level at far range and low azimuth, and sugar beet and winter wheat overlap at the 99·9 per cent level at far range and low azimuth on soil type 1. The two cereal crops overlap considerably.

The sugar beet regression appears to be the same on the two soil types, but the winter wheat regression differs in all three parameters. Sugar beet again has the lowest coefficient of variation, and all coefficients are larger than expected.

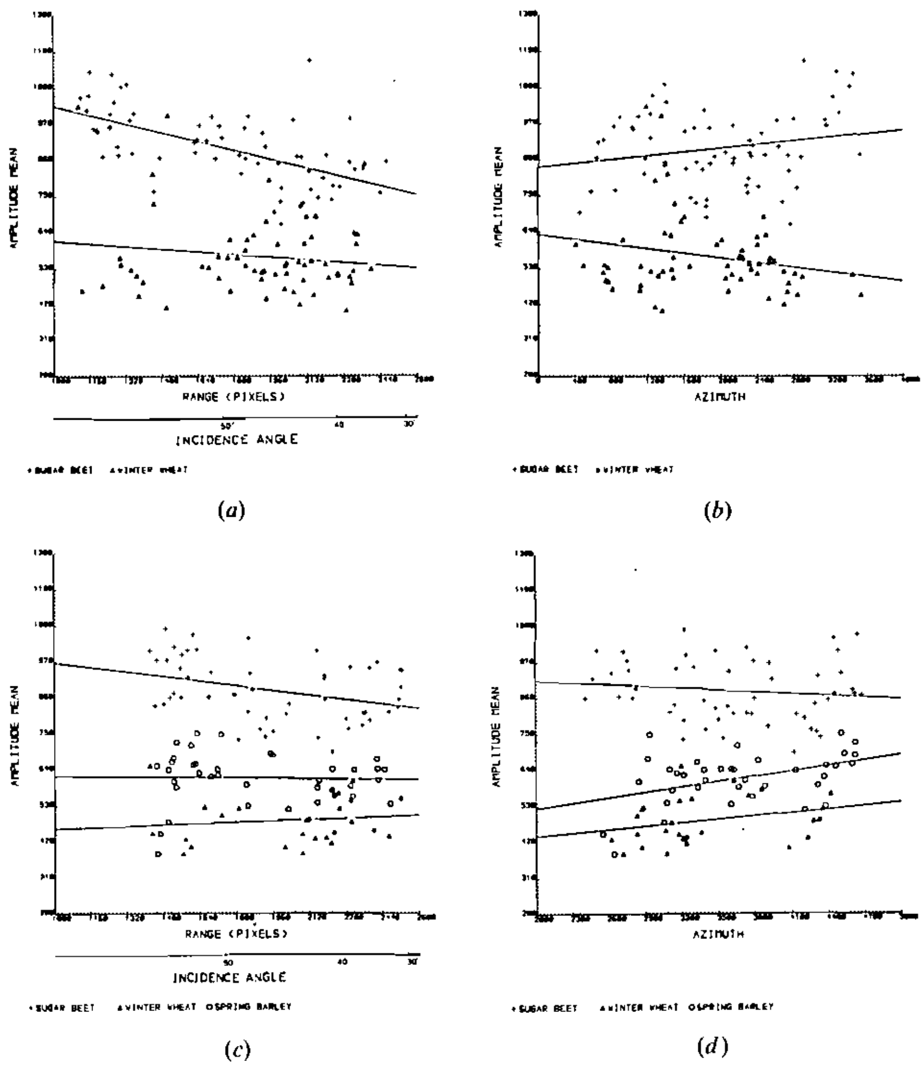

Figure 3. As for figure 2, but for scene 322.

Table 3. Summary statistics for data from image 322, soil type 1.

	b_0	b_R	t_R	b_A	t_A	$\hat{\sigma}$	m	s	$\hat{\sigma}/m$	n
SU	1141	−0·170	−6·13	0·026	1·89	90·3	895	115	0·10	65
WW	703	−0·040	−0·88	−0·033	−1·55	120·8	571	125	0·21	62

SU = sugar beet; WW = winter wheat.

2.4. *Summary for the three images*

The most obvious feature from the regressions is that for all images the mean amplitude for sugar beet falls significantly from far range to near range, and the decrease is at the same rate in the two soil types. For images 322 and 422, only range affects mean sugar beet amplitude, and the relationship with range appears to be the same for both images. However, for image 222 sugar beet also exhibits a significant decrease in mean amplitude with azimuth on soil type 1 (see below).

For the cereal crops, range has no significant effect on mean amplitude, but azimuth sometimes does. There is no obvious pattern in the effect of azimuth; when it is significant, it is sometimes positive and sometimes negative. In most cases, the presence of a significant azimuthal slope cannot be attributed to system effects, since only a single crop exhibits significant slope with azimuth (see the values of t_A in tables 1 to 6). The exception is image 222 on soil type 1, where both winter wheat and sugar beet have significant negative slopes. This may be due to real spatial variation in the crops, but could also be caused by a systematic decline in synthetic antenna gain, such as would occur if the antenna was yawing.

With three exceptions out of 24, sugar beet is always well separated (99.9 per cent level) from the two cereals. The three exceptions are all with winter wheat, and still suggest good separation (two at 99 per cent, one at 95 per cent). The two cereals are poorly separated from each other in images 222 and 422, but their separability improves in image 322.

The results on overlap between sugar beet and cereals are less clear. The two cereals always overlap to a considerable degree. The overlap between sugar beet and the cereals is considerably greater for image 422 than for the others. For images 222 and 322 there was less overlap between sugar beet and winter wheat on soil type 2 than on soil type 1, with the exception of the near range values for image 222 on soil type 1. For image 422, however, the overlap between the sugar beet and winter wheat was less on soil type 1.

In all cases, the coefficient of variation is larger than we would expect from speckle alone. This could indicate real spatial variability; it could also indicate that we expect

Table 4. Summary statistics for data from image 322, soil type 2.

	b_0	b_R	t_R	b_A	t_A	$\hat{\sigma}$	m	s	$\hat{\sigma}/m$	n
SU	1104	−0·086	−2·54	−0·015	−0·81	88·3	833	93	0·10	53
WW	374	−0·005	−0·09	0·036	1·25	71·7	486	72	0·15	27
SP	440	−0·014	−0·42	0·055	2·74	73·3	615	79	0·12	37

SU = sugar beet; WW = winter wheat; SP = spring barley.

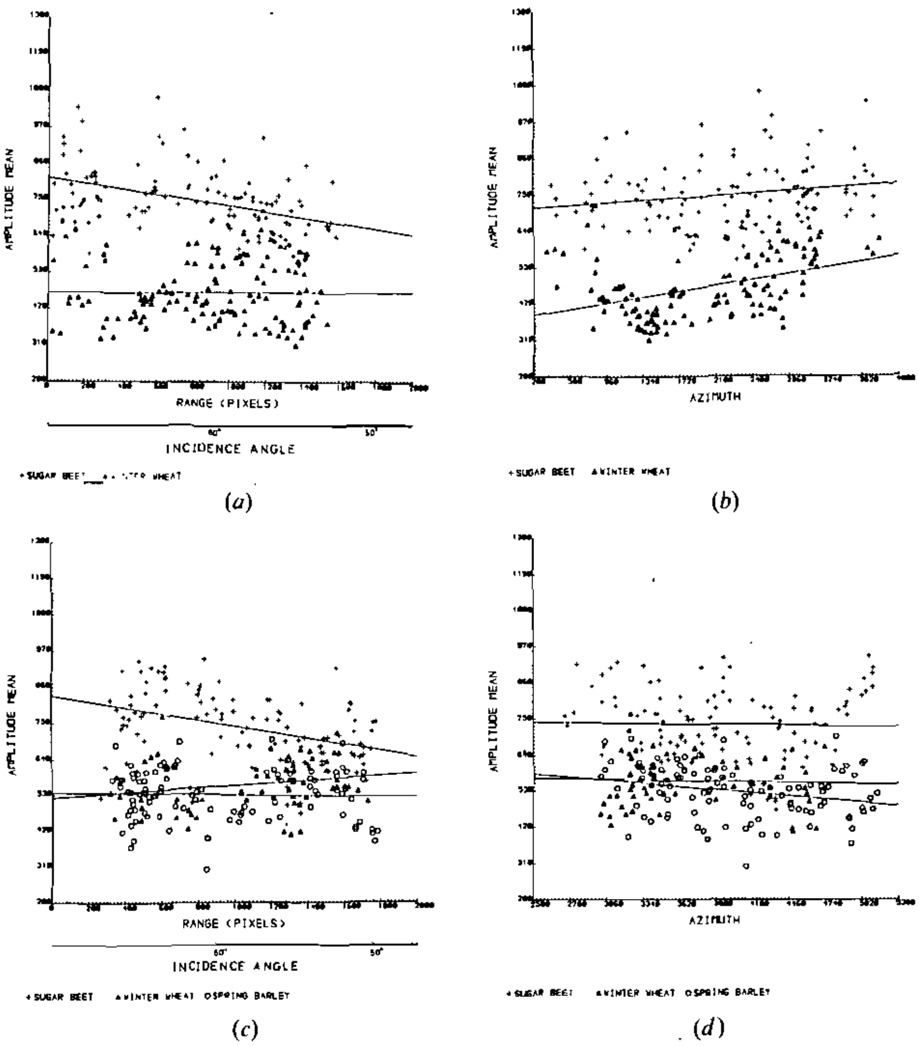

Figure 4. As for figure 2, but for scene 422.

too low a value, as would occur if the distribution is not sufficiently close to a Rayleigh, or the correlation between the amplitude values is underestimated (see (2) and the related discussion). At present, we are unable to distinguish between these three alternatives. However, there does seem to be evidence from tables 1–6 that sugar beet shows less spatial variation than the cereal crops. The single occasion where

Table 5. Summary statistics for data from image 422, soil type 1.

	b_0	b_R	t_R	b_A	t_A	$\hat{\sigma}$	m	s	$\hat{\sigma}/m$	n
SU	778	−0·085	−4·94	0·018	1·97	86·3	749	96	0·12	117
WW	392	−0·023	−1·21	0·049	5·11	85·6	471	93	0·18	128

SU = sugar beet; WW = winter wheat.

Table 6. Summary statistics for data from image 422, soil type 2.

	b_0	b_R	t_R	b_A	t_A	$\hat{\sigma}$	m	s	$\hat{\sigma}/m$	n
SU	871	−0·094	−4·55	−0·009	−0·61	98·4	734	106	0·13	110
WW	598	0·051	1·94	−0·026	−1·21	75·8	561	77	0·14	61
SP	679	−0·011	−0·67	−0·034	−2·70	76·3	532	85	0·14	100

SU = sugar beet; WW = winter wheat; SP = spring barley.

sugar beet gave a greater coefficient of variation than the cereal crops could be attributed to the expected variability in cover type, as discussed in §2.1.3.

3. Measurements from individual fields

The results discussed above have all been concerned with the average behaviour of large numbers of fields. Also of interest is whether individual fields show any consistent pattern through time. The existence of such patterns, their quantification and detection are essential if SAR is to be used to detect local effects such as may be caused by disease, wind damage, etc. Detection requires consideration of local variations and the statistical significance of any measurements.

In what follows, it is essential to remember that the images at different times are not inter-calibrated. Hence the values quoted do not purport to be equivalent to radiometric temporal signatures gathered by, for example, a stable scatterometer. The absolute levels at different dates have no meaning.

Figure 5 shows the average amplitude from four of the largest wheat fields on soil type 1 for the three dates. In each case, several 10 by 20 blocks of pixels were extracted from each field, as indicated in table 7. Note that different numbers of blocks were extracted for each image, because geometric distortion altered the relative sizes and shapes of the images of fields between images.

Performing a two-way analysis of variance using all 50 observations shows that it is reasonable to assume that within each image the mean values are randomly distributed about an overall mean. There is no evidence that different fields show different temporal behaviour. This conclusion is highly dependent on the inclusion of two anomalous values which occur for field 198 in image 322, of which one is very large (996·1) and one is very small (413·6). If these values are excluded, the estimated variance is approximately halved, and now there is evidence that different fields show different temporal behaviour.

Figure 6 is the same as figure 5, except for the addition of three extra observations from individual fields. We can see that one of the observations is relatively large for image 422, but that all other observations are consistent with random variation about an overall mean.

Figure 7 is a similar plot of observations from sugar beet. These observations also appear consistent with the hypothesis of random observations about an overall mean which may depend on the image, apart from the relatively large value for the field marked (1) for image 322.

4. Conclusions

Because of the calibration problems described in Quegan *et al.* (1991), only comparatively weak qualitative statements can be made about spatial and temporal variations of the backscatter from growing crops using the AgriSAR data. We note, however, the following points:

1. Cereals and sugar beet appear to exhibit different backscatter signatures with incidence angle, and the hypothesis that γ is constant for each crop type does not seem supported by the observations reported here.
2. Sugar beet is usually separated from the two cereal crops. In images 222 and 322 the separation is often large enough to ensure little overlap in the sugar beet and cereal 10 by 20 block means, but in image 422 there is an increased amount of overlap. In the latter case, this is a consequence of the reduced dynamic range of the image.
3. Wheat and barley are poorly separated, although there are some differences on image 322.
4. Soil type variations appear to affect winter wheat more than sugar beet. For the range of incidence angles considered, and given that wheat exhibited nearly 100 per cent cover in all images, at X-band we do not expect this to be a direct soil effect, but a secondary effect reflecting some property of the wheat plant itself (perhaps its variety). More detailed ground data would be necessary to clarify this observation.

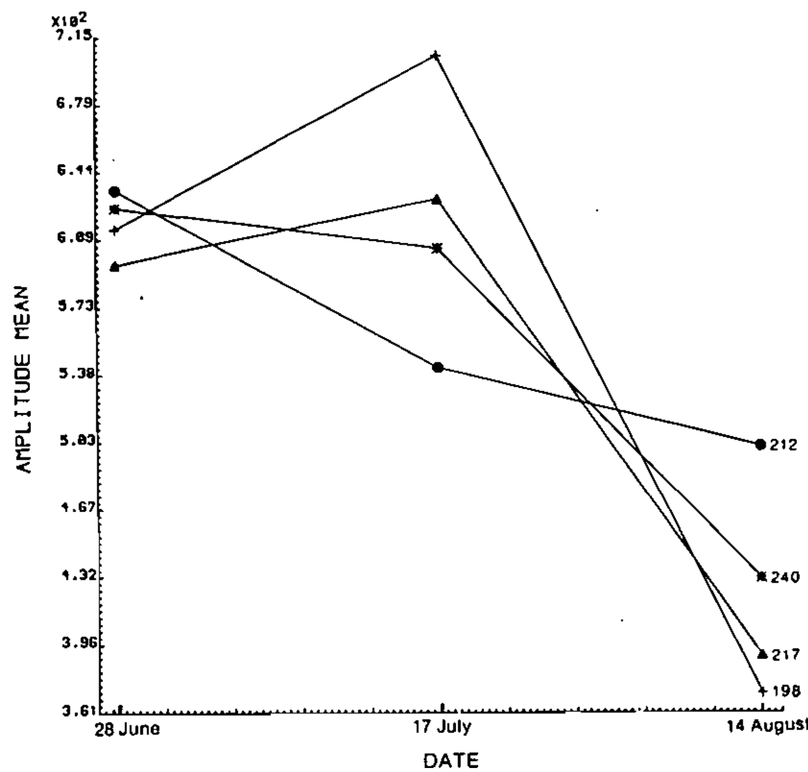

Figure 5. Mean pixel values from four of the largest wheat fields from scenes 222, 322 and 422. Note that the variance of the mean varies between data (different numbers of pixels averaged) and that this variance is not precisely known (because of correlation between pixel values).

Table 7. Number of 200 pixel blocks used to calculate the mean values of figure 5.

	No. of blocks		
Field No.	222	322	422
198	4	2	3
212	4	2	3
217	7	5	5
240	5	4	6

5. Coefficient of variation values indicate that the cereal crops show greater spatial variability than sugar beet.
6. Individual fields show great apparent variation in their multi-temporal behaviour. For the limited sample of observations used in this study, the sugar beet variations may to a large extent be attributed to the effects of speckle. However, there is some evidence that different winter wheat fields may have different temporal behaviour. To make stronger conclusions would require bigger sample sizes.

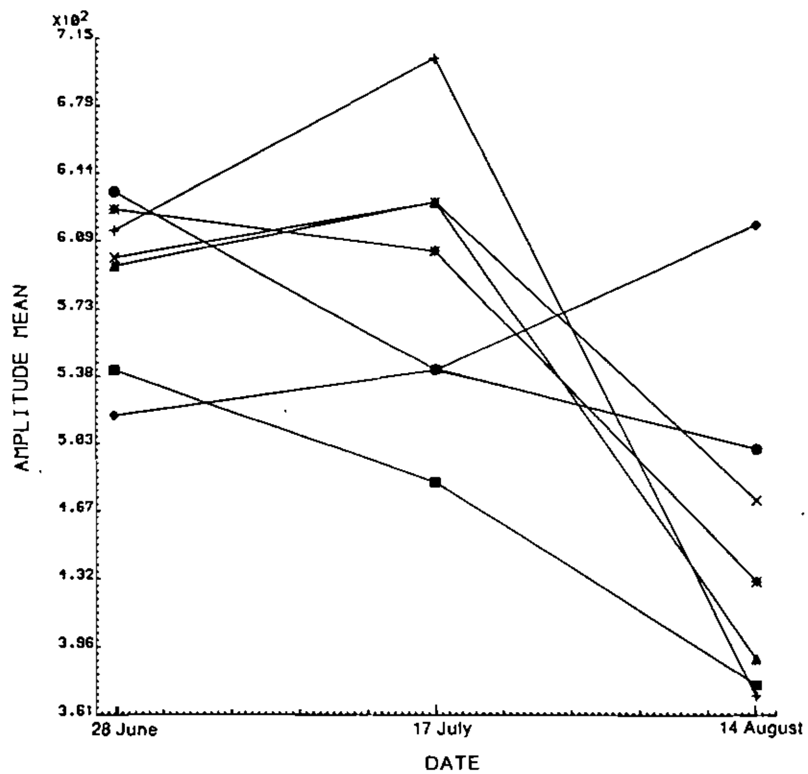

Figure 6. As for figure 5, with the addition of three single samples based on 200 pixels from other smaller wheat fields.

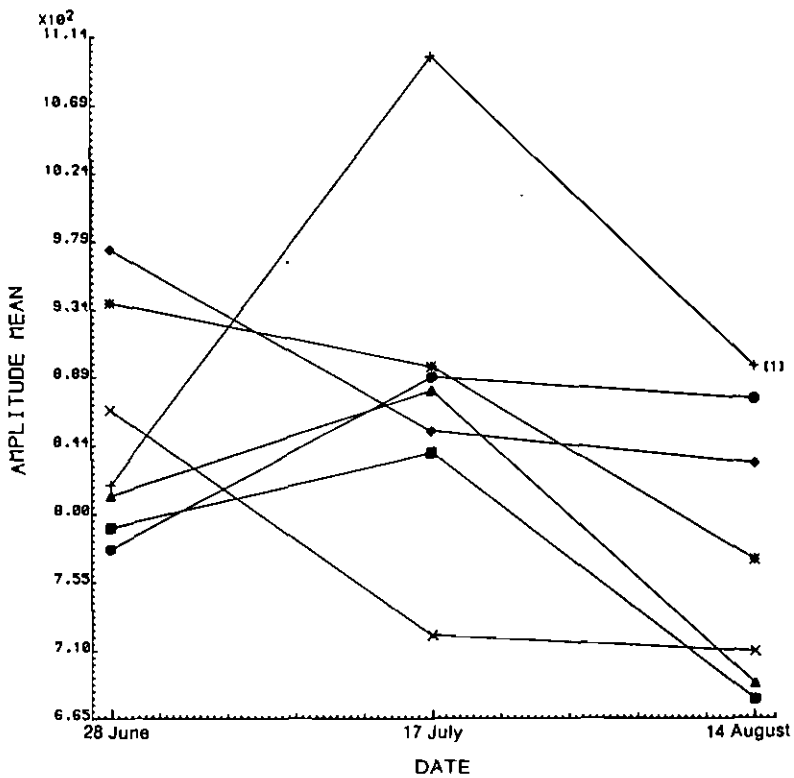

Figure 7. As for figure 6, using single samples of 200 pixels from sugar-beet fields.

7. The results of measurements from individual fields discussed in § 3 call into question the viability of space-borne SAR as a diagnostic of local conditions. Because the range of mean backscatter from growing crops is only of the order of 10 dB (Krul 1988, de Nooren *et al.* 1985), detection of spatial or temporal changes of the order of 1 dB is required. If we take n independent samples from two homogeneous regions of one-look intensity (and hence exponentially-distributed) data, with means μ_1 and μ_2, and form the sample means $\bar{x}_1$ and $\bar{x}_2$, then the difference $\bar{x}_1-\bar{x}_2$ is approximately normally distributed with mean $\mu_1-\mu_2$ and variance $(\mu_1^2+\mu_2^2)/n$. Hence, with approximate probability $1-\alpha$,

$$|(\bar{x}_1-\bar{x}_2)-(\mu_1-\mu_2)| \leqslant \frac{z_{\alpha/2}}{\sqrt{n}}\sqrt{(\mu_1^2+\mu_2^2)} \quad (4)$$

where $z_{\alpha/2}$ is the upper $\alpha/2$ point of the standard normal distribution. If we want to estimate $\mu_1-\mu_2$ with a maximum absolute error e and with probability at most $1-\alpha$, n must be chosen so that

$$\frac{z_{\alpha/2}}{\sqrt{n}}\sqrt{(\mu_1^2+\mu_2^2)} \leqslant e.$$

Setting $e=|\mu_1-\mu_2|e'/100$, we obtain the condition

$$n \geqslant \left|\frac{100}{e'} z_{\alpha/2}\right|^2 \frac{r^2+1}{(r-1)^2} \quad (5)$$

where $r=\mu_1/\mu_2$. The choice of e' requires discussion, but a not unreasonable value would be $e'=50$. Detecting a difference of 1 dB (i.e. $r=1{\cdot}26$) with 95 per cent probability (i.e. $z_{a/2}=1{\cdot}96$) therefore requires at least 588 independent samples. At the spatial resolution of planned space-based SAR systems this quantity of independent samples would be available only for the largest fields in the U.K., for example. This suggests that currently planned spaceborne SARs will not be suitable for local monitoring of agricultural crops.

Acknowledgments

The authors would like to thank P. N. Churchill, H. de Groof and A. Sieber of JRC, Ispra for useful discussions and for permission to use material developed while working on Contract No. 3312-87-12 ED ISP GB. We would also like to thank M. Wooding, Hunting Technical Services and GEC Marconi Research Centre for supplying ground data measurements.

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