Modelling Microwave Interactions with Crops and Comparison with ERS-2 SAR Observations

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I. ABSTRACT
A comprehensive multi-layer second order radiative transfer model, driven entirely by intensive field observations, is used to show that second order terms contribute at most 0.5 dB to the backscattering coefficient at all polarisations from wheat and barley throughout the growing season, and 1 dB to the copolar response of oilseed rape. Under these circumstances, an equivalent integrable first order model, with coefficients derived from full model runs, can be formulated. This allows the role of each of the plant components in attenuating and scattering the radar signal to be clarified, and provides a basis for quantitative comparison of observed ERS-2 backscatter values with model calculations, taking full account of measurement uncertainties. Discrepancies between the two suggest that effective attenuation through mature cereal crops is over-estimated by the model. This appears to be either an intrinsic failure of the radiative transfer formulation or (more likely) due to an inadequate adaptation of the notion of crop coverage to the microwave case. Non-planarity of leaves is an important source of model error for oilseed rape.

II. INTRODUCTION
The interaction of radar with crop canopies depends on scattering and attenuation of the microwave signal, both of which are dependent on the plant architecture and water content as well as on the radar parameters [1,2]. Additionally, if the attenuation in the canopy is low enough, surface scatter from the soil will contribute to, or even dominate, the signal. However, quantitative understanding of the contribution by each crop component to scattering and attenuation and the relative magnitude of the scattering from the soil and the vegetation is still a matter of debate for most crops. This greatly hinders the recovery of crop characteristics, and the resolution of these issues is critical for attempts to monitor crops by radar.

There have been many measurements of radar backscatter from crops, using scatterometry [1,3,4,5], airborne SAR (for example, AirSAR) [6] and satellites [7]. Interpretation of these results necessarily requires the use of some kind of model. Water cloud models, used in [2,3,4,5] for wheat and additionally for barley in [3], proved productive in early studies since they led to broad understanding of the mechanisms operating. However, they require data fitting and are
unable to explain polarimetric effects. More recently, radiative transfer models for scattering from plant canopies have been developed, using theories detailed in [8]. Studies making use of such models include [6,7,9]. Of the crops we consider in this paper, only wheat is discussed in these, and only [7] develops a mechanistic description of the radar interaction through the growing season. In that work, however, the model calculations were not validated directly against backscatter measurements since the crop data used to drive the model was collected in several campaigns over a number of years.

The primary objective of our study is to establish the mechanisms determining the ERS-2 C-band radar backscatter from winter wheat, spring barley and oilseed rape throughout the growing season. The investigation is based on a sophisticated, physically based radiative transfer model (RT2). This model is explicitly driven, with no data fitting, by comprehensive ground data sets describing the crops throughout the growing season. The fieldwork was timed to coincide (to within a day) with ERS-2 overpasses, and field-averaged backscatter values were generated for the same fields from which the crop data were collected.

A crucial element in our analysis is to formulate a mechanistic breakdown of the roles of the various canopy components in the radar response. Comparable treatments have been carried out in [6,7] but we take the process much further, demonstrating that the sensitivity of the signal to variations in certain of the canopy parameters may be tackled in a straightforward way, and that uncertainties in the model predictions may be estimated directly from estimates of the errors in the field measurements. Our model results indicate that the ERS-2 radar signal may be extremely insensitive to changes in the crop condition at certain growth stages, and the sensitivity analysis makes clear why this occurs. By quantifying uncertainties in the model calculations, we ensure that the comparisons with measurements are meaningful; such issues have been ignored in most previous work.

The RT2 model is fully polarimetric and the theory developed in Section III incorporates polarisation dependencies. However, we concentrate here on whether the calculated response, which is completely determined by the input data, adequately reproduces observed ERS-2 measurements. If so, we have some confidence in using the model to interpret how the response arises. If not, we have little justification in extending its results to situations where we have no data.

In the case of oilseed rape, we find that discrepancies between model calculations and observations can be readily accounted for by known deficiencies in how the model represents the leaves. For the cereal crops, particularly wheat, the discrepancies are harder to explain but seem to imply over-estimation of attenuation in the model. Plausible reasons for such over-estimates are developed, but this issue is not fully clarified. This affects our discussion of polarisation effects.

A further aspect of the RT2 model is that it incorporates second-order effects. For the crops studied here, we establish that these become significant only for the cross-polarised term from oil-seed rape. This is in fact central to our analysis,
since it allows us to formulate an integrable water cloud type model that is approximately equivalent to RT2 in most of the cases of interest. This simplified model relies on RT2 to provide quantitative values for its coefficients, but provides much clearer insight into the processes occurring.

III. THE RT2 MODEL OF BACKSCATTER

A. Basic Description

RT2 is a fully polarimetric second-order solution to the radiative transfer equations [8] that treats the vegetation canopy as a plane stratified multi-layer region over a rough surface. The formulation for the vegetation components is sufficiently general to allow calculation of the backscatter from either forests or agricultural crops over at least the X to L band frequency range.

The scattering properties of all plant components are derived from their depictions as simple geometric forms: for example, plant stems are represented as finite length cylinders [10] while leaves are modeled as plane circular or elliptical discs [11,12]. The orientation of each of the components is described using one of a number of distribution functions: for example, as a Gaussian with a specified average value (with respect to the vertical) and a variance about this direction. The dielectric properties of each component are calculated from its gravimetric water content using the empirical dual-dispersion model of [13].

The soil dielectric properties are derived from its volumetric water content using the empirical model of [14]. Forward scatter from the soil surface is calculated using specular coefficients alone, but direct backscatter from the soil surface may use various surface scattering models, including the Michigan Empirical Model (MEM) [15] or the Integral Equation Method (IEM) [16].

B. Conceptual Approach

Fig.1 illustrates the geometry of the configuration for the following treatment.

Embedded in radiative transfer models such as RT2 is the concept that a scattering component of type $i$ distributed uniformly within a horizontal layer of thickness $d$ contributes a direct backscatter signal given to first order by an expression of the form:

$$B_{(i, pq)} = \int_{0}^{d} S_{(i, pq)} \exp[-2 \cdot \alpha_{(i, pq)} \cdot x] \cdot dx \quad (1)$$

Here

$B$ is the mean backscattered power,
pq signifies the polarisation configuration (VV, HH, HV or VH),

\[ B \] in the subscript to \( B \) indicates that only direct backscatter is considered (see below),

\( S_i \) expresses the backscattered power from component type \( i \), averaged over orientation, which is directly proportional to its number density,

\( \alpha_i \) is the one-way attenuation coefficient per unit layer thickness caused by component type \( i \) alone; it incorporates a \( \sec(\theta) \) term, where \( \theta \) is the incidence angle.

When there is a scattering surface below the layer a second term arises (indicated by a 2), which for the co-polarised terms is given by:

\[
B_{(i,2,\,pp)} = \int_0^d L_{(i,\,pp)} \cdot \exp[-2 \cdot \alpha_{(i,\,pp)} \cdot d] \cdot dx \tag{2}
\]

Here \( L \) is an interaction term incorporating the scattering properties of the component type (averaged over all orientations) and forward scattering from the surface. As Fig. 1 illustrates, two sets of scattering events have been absorbed into (2): scatter at depth \( x \) as the wave descends, followed by specular reflection at the surface and the reverse process.

The cross-polarised terms are more complex, having the form:

\[
B_{(i,2,\,pq)} = \int_0^d L_{(i,\,pq)} \cdot \left\{ \exp[-2 \cdot \alpha_{pp} \cdot d] \cdot \exp[\alpha_{pp} - \alpha_{pq}] \cdot x \right\} \\
\quad \quad \quad + \exp[-2 \cdot \alpha_{pq} \cdot d] \cdot \exp[\alpha_{pq} - \alpha_{pp}] \cdot x \right\} \cdot dx \tag{3}
\]

because a signal with polarisation \( pq \) may arise either by forward scatter from the component, which brings about the change in polarisation, followed by propagation to the surface and reflection back to the receiver or by scattering at the component after reflection at the surface. Thus, there are two additive attenuating terms in (3); the overall symmetry of the scattering component means that the same term \( L \) is appropriate in both cases.

To first order, the net backscatter from a single component type is the incoherent sum of the values in (1) and (2), or, in the case of cross-polarised terms, (1) and (3).

These expressions can be extended to a layered composite medium by noting that, when several component types are present in a single layer, the backscatter contributed by a single component type is calculated simply by replacing \( \alpha_i \) in (1), (2) and (3) by \( \alpha_T \), the total attenuation coefficient arising from all the scatterers present:

\[
\alpha_{T,\,pq} = \sum_{i=1}^{N} \alpha_{(i,\,pq)} \tag{4}
\]
The total backscatter from the layer is then given by the sum of all the individual contributions. For instance, the direct term is given by:

\[ B_{T, pq} = \sum_{i=1}^{N} \left[ \int_{0}^{d} S_{i, pq} \cdot \exp[-2 \cdot \alpha_{T, pq} \cdot x] \, dx \right] \]  

(5)

and a similar modification to (2) or (3) accounts for the surface interaction term. Where several layers are present, the contributions of each term from each layer must be adjusted by the attenuation experienced in passing through the other layers. Finally, it is necessary to include the direct ground backscatter, which includes both attenuated and unattenuated components, depending on the crop coverage, \( \eta \) (which is defined relative to the SAR geometry and is discussed further in Section VI). The overall predicted backscattering coefficient of the field is then given by the incoherent summation:

\[ \sigma^0 = \eta \cdot \left[ B_{T, pq} + \exp[-2 \cdot A_{T, pq}] \cdot G_{pq} \right] + (1 - \eta) \cdot G_{pq} \]  

(6)

Here

\( B_T \) is the total backscatter from the vegetation, as derived above,
\( \exp[-2 \cdot A_T] \) is the total two way attenuation,
\( G \) is the direct ground backscatter term.

It should be emphasised that the formulation given above only incorporates first-order interactions in the vegetation. In fact, we have established that the differences between this formulation and normal runs of RT2 incorporating second order scattering terms are less than 0.5dB for all polarisations for the cereal crops and less than 1dB for the oilseed rape co-polar terms. The second order terms are needed only in cross-polarised calculations for the dense canopy of oilseed rape, where the difference is as much as 8dB. Consequently, all the results presented in this paper derive from (6).

C. Relation To Measurements

The approach outlined above expresses the overall backscatter in terms of average scattering and attenuation properties of the individual plant components. It is very useful to note that the scattering strengths \( S_i \) and \( L_i \) and attenuation constants \( \alpha_i \) of the plant component types can, to first order, be related to gross canopy characteristics by

\[ S_{i, pq} \propto N \cdot V \cdot f_{i, pq}(\psi) \cdot \epsilon' \]  

(7)
\[ L(i, pq) \propto N \cdot V \cdot g(i, pq) \cdot \epsilon' \quad (8) \]

\[ \alpha(i, pq) \propto N \cdot V \cdot \epsilon'' \quad (9) \]

where

- \( N \) is the number density of the component type,
- \( V \) is its volume,
- \( f(\psi), g(\psi) \) are polarisation dependent functions of the orientation of the component type: the overall scattering strengths of the component types are weighted sums of the contributions from the sub-populations at all orientations,
- \( \epsilon' \) and \( \epsilon'' \) are the real and imaginary parts, respectively, of the dielectric properties of the component type.

Functions \( f \) and \( g \) differ because of the different interaction mechanisms for \( S \) and \( L \), as expressed in (1) and (2). The attenuation constant is also weakly dependent on the orientation distribution of the component type, but this will only have an influence if there are gross changes in the orientation of the plant component. Hence (9) is a viable approximation for most crops.

Expressions (7) – (9) provide a direct link to field measurements, and are also important because:

i) They allow a straightforward estimation of the uncertainties in the predicted signal arising from measurement errors in the quantities on their right-hand sides; this is exploited in Section VB. Note that in some cases for cylindrical components, the dependence on the volume term set out in (7) - (9) is not strictly valid. The estimation nevertheless then provides an upper bound for the magnitude of the signal uncertainty.

ii) The sensitivity of the backscatter signal to small changes in number density or water content can be calculated by direct differentiation using these expressions.

Integration of (1) & (2) gives (10) & (11) respectively:

\[ B(i,1, pq) = \frac{S(i, pq) \cdot [1 - \exp[-2 \cdot \alpha(i, pq) \cdot d]]}{2 \cdot \alpha(i, pq)} \quad (10) \]

\[ B(i,2, pp) = L(i, pp) \cdot \exp[-2 \cdot \alpha(i, pp) \cdot d] \cdot d \quad (11) \]

and reveals two interesting phenomena. The first occurs when the attenuation due to one type of plant component is very high and it is the principal contributor to direct backscatter. Then (10) shows that backscatter is no longer
dependent on the number density or the moisture content (since results in [13] indicate that $\varepsilon'$ and $\varepsilon''$ are approximately linearly related). In other words the signal effectively saturates. Secondly, differentiation of (11) shows that the double bounce backscatter increases with number density until $N = \left(2Vd\varepsilon''''\right)^{-1}$, after which the exponential attenuation dominates.

Equations (10) & (11) (and the integration of (3) to give a similar result) also allow $S$, $L$ and $\alpha$ to be derived directly from RT2 runs considering each component type (leaf, stem, branch, ear/pod) in turn as the only type present in each model layer. This approach has been used to calculate the contributions from each of the plant components. It should be emphasised that the same procedure can be carried out for any comparable radiative transfer model. In addition, it is possible to substitute empirically derived values (e.g. from laboratory measurements) for any of $S$, $L$ and $\alpha$, if their values calculated in the theoretical model are found to be erroneous.

IV. EXPERIMENTAL CAMPAIGN

A. Field Measurements

We made intensive ground measurements on winter wheat, spring barley and oilseed rape throughout the growing season of 1997 in the Great Driffield area of the UK. Most of the measurements reported in this paper were made within 4 hours of the descending passes of ERS-2; the remainder were made either on the morning after or the morning before. Table 1 summarises the field campaign dates, the crops measured and their phenology and the days of the corresponding ERS-2 overpasses. For each crop three widely separated fields were selected, and complete sets of measurements were collected at two sites in each field on each visit. The field measurements were designed to provide all the raw data needed to drive RT2 simulations for the crops on all of the site visits and followed recommendations in [17].

On each visit the following procedure was followed. Any obvious stratification in the crop canopy was noted, the thickness of each layer was measured, and generic plant components were identified and assigned to one of the model layers. At most two layers seemed necessary for the crops under consideration. Number densities of all components were counted over a randomly selected 1 m$^2$ area at each site. A hierarchical approach was used so that (for instance) the number of oilseed rape pods was calculated by multiplying the number of pods per branch by the number of branches per plant and by the number of plants per m$^2$. This has implications in the error analysis, as noted below. A representative sample – typically 20 at each site – of each of the plant components was measured and average dimensions were calculated so that a suitable geometric form could be used to represent the component type in the model. Thus for stems, branches, cereal ears and oilseed rape pods, length and thickness were measured, allowing them
to be represented as finite-length cylinders of circular cross section. The thickness value used was intermediate between the measured maximum and minimum, so that the average actual volume of the component and its model representation were in close correspondence. Leaves were represented as elliptical disks, based on their maximum length, maximum width and thickness; measurement of the latter was made carefully to avoid any veins. The model again closely preserves the average volume of the leaves. In all cases, only these regular forms were employed, so no allowance was made for bending, tapering or curvature; a consequence in the case of oilseed rape is raised in the Section VI. Samples of each of the component types were collected in sealed containers and analysed in the lab to determine their gravimetric water content.

Orientation was characterised by measuring with a protractor the inclination with respect to the vertical of a large number of each of the component types, and selecting the best approximation to the observed distribution from the functions available in the model. Generally, both the spread and the mean orientation are important, but for vertical plant stems and wheat ears only the spread need be assessed. For instance, on day 199 the orientation of wheat ears was found to be well modeled by a uniform distribution centred on the vertical and of 20 degrees half width, while the observed stem orientation was closely matched by a Gaussian about the vertical with a standard deviation of 6 degrees. However, barley ears characteristically droop in late season, and the angle of droop must be measured. On day 199, for example, the ear orientation was modeled by a Gaussian distribution of 20 degrees standard deviation, centred at 75 degrees to the vertical; the distribution for the barley stems at this time had a similar distribution to that for wheat.

Azimuthal symmetry was assumed for all components. There was no discernible bias due to phototropism or wind direction, except for the drooping barley ears, which were clearly driven by the wind.

For the soil surface, the early-season roughness was measured using a pin-board profilometer. This comprised a set of 101 metal rods of equal length, spaced at 1cm intervals over a 1m long panel, which are allowed to come to rest freely on the soil surface. A photograph was used to record the levels of the tops of the rods, allowing the vertical rms height (following linear detrending) and the lateral autocorrelation length to be derived. When possible, we assessed the surface roughness at the two sampling sites in each field parallel to and perpendicular to drill-lines in the fields. Coincidentally, for all the fields, one or other of these orientations was very closely aligned with the ERS-2 ground range direction, so that data from a single orientation could be used directly for the prediction of the surface scatter for ERS-2.

In order to measure soil moisture, samples from the top 5cm of the soil were collected on all site visits from all fields, using a can of known volume. The sampling density varied between 2 and 12 samples per field through the season: the higher densities were introduced when the soil was drying, where greater accuracy is needed for accurate prediction of the dielectric properties.
Finally, (6) requires an estimate of the crop coverage. This was based on visual estimation of the fraction of ground surface that could be seen through the canopy at a look angle close to the radar incidence angle (approximately 23 degrees).

Satellite Data

Only ERS-2 images for descending orbits covering the Great Driffield area were used in this study, giving 11 images within the duration of the field campaign. These were all standard ESA PRI products (3-look images with nominal 12.5 metre ground-range pixels), and Table 2 summarises their dates and geometries. Data were corrected for local incidence angle using a DEM and calibrated using the National Remote Sensing Centre Ltd. software package TSAR. Field-averaged $\sigma^0$ values were then extracted using a digitised map of field boundaries for the area, which had been verified on the ground. The minimum number of pixels used to derive these values was 778 (for the spring barley field discussed later in this paper); more than 1500 pixels were used for the other fields. We have also verified that there is a high degree of linearity (for pooled results, $R^2 = 0.95$) between the standard deviations and the means of measured values within each field. Consequently the $\sigma^0$ values are expected to be far more precise than the model predictions, and there is no evidence of any bias to them.

Meteorological Data

Records, which included midday wind speed values and rain data and covered the entire growing season, were obtained from a nearby weather station. An extremely wet spell of weather preceded the ERS-2 overpass at day 181, and rain fell heavily throughout that day. Rain also fell in the area at the time of the overpass on day 41, and some hours prior to that on day 111.

B. Measurement Errors

Equations (7) – (9) allow the uncertainties in the model predictions to be estimated in terms of the errors in the measured quantities. For the number densities, the errors are compounded for the plant component number densities. As an example, the uncertainty in the number density of the oilseed rape pods is the product of the uncertainties in crop density, the average number of branches per plant and the average number of pods per branch, leading to errors which may exceed 40%. The standard deviations in the measured dimensions of the plant components typically lead to volume errors of around 10%. A constant uncertainty of 20% was assumed for the dielectric constant (see [13]).
Errors due to uncertainties in orientation are more difficult to quantify, but can be very significant. For example, for large leaves, the sub-population aligned to give specular reflection mainly determines the direct backscatter from the whole population of leaves. The co-polarised stem-ground interaction, (2), is also very sensitive to the number of near-vertical stems, while the stems furthest away from the vertical give rise to the largest cross-polarised signal. Sensitivity runs were carried out to establish the dependence on the mean and/or spread in orientation of the scatter terms in (7) and (8). These covered all plant component types for all of the crops throughout the growing season. As an example, Table 3 shows the sub-population of wheat leaves that dominate the direct scatter terms (7). Early in the season a broad range of orientation angles is important, since the leaves are small. For the co-polarised terms this range becomes narrower as the leaves become larger, while the cross-polarised sensitivity remains broad. Uncertainties in orientation were estimated from the numbers counted for each of these critical ranges: the larger the number counted the smaller the uncertainty. Where the dependence is on the spread-width, as in the stem-ground interaction, the uncertainty is estimated from photographs and direct orientation measurements.

Errors in crop coverage, \( \eta \), were assumed to be negligible for zero or full coverage, with a maximum uncertainty of 0.15 (in absolute terms) when coverage has been estimated at about 0.5 (but see Section VI).

Finally, the uncertainties in the surface roughness parameters were estimated from measurements on the first two site visits. The variance in the measured data from each field suggested measurement errors of as much as 24% in the rms height and 35% or more in the correlation length. These large values arise because of the small profile length, as explained in [18].

V. MODEL CALCULATIONS AND ERS-2 COMPARISON

A. Surface Scattering Model

The measured \( \sigma^0 \) values from nearly bare soils early in the season were compared with calculated values from the IEM and MEM models, using the measured surface roughness parameters as inputs. Much better agreement was found for the MEM, with very large discrepancies between the IEM and observed values. This could be because of inaccuracies in estimating the correlation length for use in the IEM. As explained in [18], a profile length of about 200 times the correlation length is needed to determine the latter to 10% accuracy; the pinboard used in our measurements fell far short of this requirement. In addition, recent studies suggest that soil surfaces are fractal in nature, so that a description which uses a single correlation length may be inadequate [19].
Fig. 2 compares ERS-2 data and MEM calculations. Reasonable correlation between them is observed, but the MEM systematically over-estimates the data. This is probably because of differences between the correlation properties of the soils studied here and the surfaces used in the laboratory measurements from which the MEM was formed [14]. This tendency should be borne in mind when viewing results later in this paper. The calculated values are also associated with large uncertainties, which arise because of measurement errors in the rms height.

B. Results For Crops

The calculated mean backscattering coefficients given below result from Monte Carlo simulations for 1000 sets of input parameters whose uncertainties are as described in Section IV. The uncertainty in the mean is measured by the standard deviation for the whole set of calculations.

Fig. 3 exhibits a typical example of the calculated multitemporal $\sigma^0$ for winter wheat, broken down into contributions from each of the component types. It should be viewed in conjunction with the two-way attenuation through the crop canopy shown in Fig. 4. Clearly, components that make little contribution to the backscatter can nevertheless play an important part in the overall interaction; for example, the stems at day 181, which are primarily responsible for attenuating the ground return.

The early season values (to day 111, at least) are dominated by direct backscatter from the ground. Since there is such a large uncertainty in this term - resulting from imprecise knowledge of surface moisture and roughness conditions - little information about the crop may be derived at these times. Beyond these dates, attenuation by the stems suppresses the direct ground term. The signal is then governed by the scattering properties of the leaves and stems at day 146 and by the ears alone from day 181. In addition, the signal at day 199 is effectively saturated in terms of the bulk properties of the ears, as discussed in Section III, and so is insensitive to small changes in their moisture content or number density.

The corresponding calculations for HH, shown as Fig. 5, exhibit substantial differences from VV. These differences arise principally from the much lower attenuation by the canopy, leading to a large stem-ground contribution. Such effects suggest the likely utility of Envisat data in investigating the crop canopy for cereals, but the calculated differences are much greater than those observed in scatterometer and AirSAR measurements.

Further light on the source of these large copolarised differences is shed by Fig. 6, which superimposes the observed VV field-averaged $\sigma^0$ on the calculated value. Although the model reproduces well the signal reduction through the early season, which arises from the drying of the soil together with the attenuation of the direct soil term by the growing crop, there are discrepancies in the mid-to-late season that far exceed the estimated uncertainties in the calculations. Note that the values predicted by the model are also far below results for wheat $\sigma^0$ from any previous measurement campaign.
(e.g. [20], [21]), which are generally in line with the ERS-2 values derived here. These discrepancies appear to arise from over-estimation of the effective attenuation in the VV calculations, as discussed in Section VI.

Fig. 7 shows VV calculations for spring barley, which follow the same pattern as for wheat. The early season values are dominated by direct ground backscatter, so provide little information on the state of the crop. From day 146 onwards, the plant stems attenuate this ground term, and the late season signal comes predominantly from the barley ears. A notable feature of the calculations is the marked increase in the signal from day 181 to 199. This is principally caused by the droop of the barley ears, which leads to a substantial increase in their radar cross-section. A similar increase occurs in the ERS-2 data shown in Fig. 8, though the magnitude is smaller. The model markedly under-predicts the data at day 181, although by a smaller amount than for winter wheat on the same day.

Figs. 9 and 10 show the corresponding plots for oilseed rape. The calculated signal is dominated by direct scatter from the leaves in the early season, and at day 112 is almost saturated. At day 181 the pods are the dominant scatterers; there is just a small dependence on their bulk properties here, in accordance with the argument developed in Section IIIC. The model consistently over-estimates the signal for the first four dates; a possible reason for this is put forward in Section VI.

VI. DISCUSSION

Deficiencies in the RT2 model and/or field measurements might account for the differences found between the model calculations and ERS-2 observations for wheat. Implicit deficiencies will arise if the theoretical expressions used for the scattering and attenuation by the various plant components do not correctly represent reality. Particularly important, as shown below, will be correct representation of the attenuation by the stems and scattering by the ears. Investigation of these processes needs specific experimental studies.

An explicit model deficiency is the omission of environmental factors such as wind and canopy water (due to rain), both of which could be particularly relevant on the wet, windy day 181. Rain is often (but not always) associated with increases in backscatter from crops [20]. The effect of wind on crop backscatter is unclear. However, large differences between the model and the measurements are present on day 146, and persist throughout the remainder of the season, despite these days being quite calm and with no rain.

In order to help our discussion of other possible sources of the observed differences, some of the measured parameters for wheat are shown in Fig. 11. Canopy coverage is 100% from day 146. The stem gravimetric moisture maximises at day 111 and remains high despite the gradual drying out of the crop; this maintains the high levels of attenuation through the canopy illustrated in Fig. 2. Soil moisture decreases in the early part of the season but increases sharply on day 181 due to heavy rain.
Model and ERS-2 values would become comparable if attenuation were reduced by approximately 20 dB for all days from day 146 onwards. Such a large over-estimate of the effective attenuation is not as unreasonable as it may first appear, since it can arise in two ways. The first is a direct over-estimate of the mean stem diameter by 70% in the field, but this greatly exceeds the expected measurement error. An indirect and more likely explanation lies in over-estimation of the canopy coverage term, η. As Fig. 11 shows, this was set to 100% from day 146 onwards, since in the field no ground was visible through the canopy. However, Fig.4 demonstrates that a major source of the visual opacity of the canopy – the leaves – contributes very little to the microwave attenuation for VV polarisation on the later dates.

A more meaningful measure for attenuation purposes is the effective ground cover by stems alone, which we would expect to be significantly less than that by the leaves. Simulation indeed indicates that the visual ground cover by stems alone would be less than 70% (but this value will not strictly be applicable to the microwave case). The tendency of the stems to clump together (particularly early in the season) further enhances this effect. This suggests that the value of η used in (6) should be reduced. For example, if the effective canopy coverage for all cereal crops does not exceed 90% for the later dates, much closer fits to the ERS-2 data emerge, both for winter wheat and barley. This is illustrated for winter wheat in Fig. 12, which also shows dramatic shifts in the importance of the various contributors to the signal, compared to Fig.3. The direct ground scatter is now always the dominant term, although there are significant contributions from the ears at the end of the season.

Despite the closeness of fit in Fig. 12, there are question marks against this explanation. These are illustrated by the scatterplot of Fig. 13, which shows soil moisture against ERS-2 σ0 values across all wheat fields and for all ground data observation dates. We would expect to see a strong correlation if the direct ground term were as important to the overall signal as suggested above. Indeed R² for this plot is 0.43 with day 181 omitted, which would support the interpretation. However it falls to just 0.17 when day 181 is included. Certainly, though, the sensitivity of the calculations to only small variations of the crop cover term means that this concept needs very careful attention, both theoretically and experimentally.

It should also be noted that Fig.13 agrees qualitatively with results in [23] and with the conclusions of [7], in both of which the wheat canopy simply attenuates the direct ground backscatter. Indeed, from our field measurements, the water content in the canopy is minimal at days 41, 76 and 111, reaches a maximum at day 181, and is intermediate for the remainder. Hence, the general pattern of sensitivity of backscatter to soil moisture in Fig. 13 is correlated with the varying attenuation. However, the results in [23] arise from an empirical fit to a water cloud type model, in which attenuation is determined directly by the vegetation water content. The model in [7] is based on radiative transfer, but it is not possible from the published work to derive all the parameters used in the calculations, such as the crop density.
Hence we have no means of establishing why, for example, the significant direct backscatter we found from the cereal ears does not appear in their calculations.

For oilseed rape, the observed over-estimation of the backscatter is likely to result from representation of the leaves as planar objects in the model. In fact, rape leaves have highly irregular surfaces. From [24], a square-shaped leaf of linear dimension 10cm and with a spherical surface of radius of curvature 20cm will have a scattering cross-section 2dB lower than a planar one. The non-planarity across a rape leaf is at least of the same order, and such a correction to the model would yield a good fit to the ERS-2 data. The measurements needed to explore this possibility are outlined in [25].

As concluding remarks, we would like to set the results of this paper in a more general context. Firstly, note that the full power and flexibility of the RT2 model has not been exploited here. We have instead restricted ourselves to the ERS-2 configuration because only thus can we perform backscatter calculations completely driven by measured ground data which can be meaningfully compared with observations. At this stage, particularly given the results and discussion above, a model study unsupported by appropriate comprehensive datasets seems of little value. Nonetheless, the full model and the methodology based on an equivalent integrable first order model are available when such datasets become available. In addition, several of the questions raised above can be explored experimentally by laboratory and ground-based measurements; we have an ongoing programme extending through the year 2000 growing season to carry out these measurements. If, as a result, the extant difficulties can be resolved, we will be much more confident in extending the model to other situations. Secondly, the methodology and problems we have discussed are not specific to RT2 but are implicit in the formulation of radiative transfer models for crops. For example, while checking the possibility of a coding error, we established that the MIMICS model [22] replicates the attenuation levels in RT2 when using the same field data for wheat stems. The apparent particularity of this paper is only forced by the need for suitable data to investigate these general issues.

VII. CONCLUSION

The methodology outlined in Section III clarifies the essential features of radiative transfer models of radar backscatter in situations where first-order effects are dominant. The advantages it conveys are:

i) The predicted backscatter is explained in terms of the properties of plant components and their changes as the plants develop.

ii) Uncertainties in the predicted signal may be related directly to uncertainties in the measured parameters.

iii) The sensitivity of the predicted signal to small variations in the number density and water content of the crop components may be derived directly from differentiable equations.
iv) Although not treated here, the points of comparison between different models become obvious, since the fundamental scattering properties of the components present are addressed directly.

v) Experimental studies to examine reasons for discrepancies between modeled and real behaviour can be defined. Our results suggest that currently the Michigan Empirical Model provides the most useful available model for direct ground backscatter, principally because of the difficulty in determining with sufficient accuracy the surface autocorrelation function that drives the alternative models. Nevertheless, there is sizeable random error in these predictions of scatter from agricultural soils, along with a clear systematic bias of between 1 and 2dB.

For crops, the application of (1) – (6) alongside full runs of RT2 incorporating second-order scatter demonstrates that, for C band, the latter are important only for the case of cross-polarised backscatter from dense canopies such as oilseed rape.

Our predictions of VV backscatter from oilseed rape compare reasonably well with the ERS-2 measurements; overpredictions in mid-season most probably result from modelling the rape leaves as planar objects. However, the mid-season predictions for cereal crops differ significantly from the ERS-2 measurements, and for the remainder of the season in the case of winter wheat. It seems likely that the attenuation through the canopy has been greatly overestimated in the model. This could be due to inaccuracies in our field measurements but it seems more likely to result from misrepresentation of the effective ground cover by the attenuating elements, the cereal stems. It is vital to clarify this issue so that the radar interaction with the crops can be understood with confidence at the plant component level.

We are currently engaged in laboratory-based studies, including direct measurements of the canopy attenuation, to elucidate the matter.
VIII. REFERENCES


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4 National Remote Sensing Centre Ltd., Delta House, Southwood Crescent, Southwood, Farnborough, Hants, GU14 ONL
5 Synoptics Geo Applications Limited, Alexander House, 50 Station Road, Aldershot, Hampshire, GU11 1BG

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Shaun Quegan received the B.A. (1970) and M.Sc. (1972) degrees in mathematics from the University of Warwick. His Ph.D., awarded by the University of Sheffield in 1982, was concerned with atmospheric modelling. Between 1982 and 1986 he worked at Marconi Research Centre, for the last two years of which he led the Remote Sensing Applications Group. He established the SAR Research Group at the University of Sheffield in 1986, whose success led to his Professorship awarded in 1993. In the same year he helped to inaugurate the Sheffield Centre for Earth Observation Science, of which he remains the Director. He has broad interests in the physics, systems and data analysis aspects of radar remote sensing, but more particularly in the exploitation of this technology in environmental science and land applications.

Ralph Cordey was awarded a Ph.D. in Radioastronomy by the University of Cambridge in 1986 for his work on radio sources in nearby galaxies. Since 1985 he has been with the Marconi Research Centre, working principally on synthetic-aperture radar and its applications. His interests have included the retrieval of ocean wave spectra from radar images, the development of physically-based scattering models for vegetation sensing, and the promotion of techniques in radar polarimetry. Since 1994 he has been head of the MRC's Space Division, and he is currently active in the definition of future operational European SAR missions.

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Acknowledgements

This work was supported by funding from BNSC/LINK project R2/005. We thank ESA for the use of the ERS-2 images in the project, and Peter Meadows of GEC-Marconi for advice on their calibration. We also thank the many assistants to the fieldwork. We are most grateful for the many helpful comments of the reviewers of the original version of this paper.
Table 1: Schedule of intensive field measurements.
[Key: W = winter wheat, B = spring barley, O = oilseed rape]
Crop phenology is reported in accordance with [25], [26] for oilseed rape, and with [27] for the cereal crops.
<table>
<thead>
<tr>
<th>Ground data observation dates</th>
<th>ERS-2: DOY</th>
<th>Crops measured</th>
<th>Crop phenology</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOY 41 (10/2/97) 41</td>
<td>41 W</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>O</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>(B not sown)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>76 (17/3/97) 76</td>
<td>76 W</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>O</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>(B now drilled)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>111 (21/4/97) 111</td>
<td>111 W</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>112</td>
<td>O</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>B</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>146 (26/5/97) 146</td>
<td>146 W</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>146</td>
<td>O</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>146</td>
<td>B</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>181 (30/6/97) 181</td>
<td>181 W</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>181</td>
<td>O</td>
<td>6.2</td>
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<tr>
<td>181</td>
<td>B</td>
<td>59</td>
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<td>200 W</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>199</td>
<td>B</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>215 (3/8/97) 216</td>
<td>216 W</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>215</td>
<td>B</td>
<td>92</td>
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Table 2: Schedule of ERS-2 overpasses used in this study and associated field measurements. All overpasses used were descending orbits.
<table>
<thead>
<tr>
<th>Date</th>
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<th>Orbit Family</th>
<th>Orbit</th>
<th>Frame</th>
<th>Ground measurements</th>
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<td>9238</td>
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<tr>
<td>10/2/97</td>
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<td>94</td>
<td>11972</td>
<td>2511</td>
<td>3/8/97</td>
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Table 3: Orientation angle ranges that specify which of the winter wheat leaves will dominate the direct scatter term in (1) for ERS-2. The values are given in degrees between the normal to the leaf and the vertical.
<table>
<thead>
<tr>
<th>Day of Year</th>
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<td>199</td>
<td>20 - 30</td>
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<tr>
<td>215</td>
<td>20 - 30</td>
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Fig. 1: Schematic diagram of a single scatterer component type distributed with uniform density but random orientation in a horizontal layer. The numbered contributions to backscatter, 1 & 2, arising from events at depth $x$ correspond to the components considered in (1) and (2) respectively.
Fig. 1: Schematic diagram of a single scatterer component type distributed with uniform density but random orientation in a horizontal layer. The numbered contributions to backscatter, 1 & 2, arising from events at depth $x$ correspond to the components considered in (1) and (2) respectively.
Fig. 2: Comparison of ERS-2 near-bare soil backscatter values with predictions of Michigan Empirical Model.
Fig. 3: Breakdown of scatter contributions leading to the VV prediction of $\sigma^0$ for Field 2, winter wheat. (Numbers in brackets in the legend refer to the model layer where the component type is located: 1=lower; 2=upper).
Predicted VV  ○ Leaf(1)  △ Stem(1)  ▲ Ear(2)  - - - - Ground
Fig.4: Breakdown of 2-way attenuation through canopy for Field 2, winter wheat.
Fig.5: Breakdown of scatter contributions leading to the HH prediction of $\sigma^0$ for Field 2, winter wheat.
Fig.6: Comparison of the prediction of Field 2, winter wheat, with ERS-2 field-averaged $\sigma^0$. 
Predicted VV - - ERS-2
Fig.7: Breakdown of scatter contributions leading to the prediction of $\sigma^0$ for Field 6, spring barley.
Fig. 8: Comparison of the prediction of Field 6, spring barley, with ERS-2 field-averaged $\sigma^0$. 
Predicted VV

ERS-2

\( \sigma^o (dB) \)

DOY
Fig. 9: Breakdown of scatter contributions leading to the prediction of $\sigma^0$ for Field 4, oilseed rape.
DOY

\( \sigma^0 \) (dB)

- Predicted VV
- Leaf(1)
- Branch/Petiole(1)
- Branch(2)
- Stem(1)
- Pod(2)
- Ground
Fig.10: Comparison of the prediction of Field 4, oilseed rape, with ERS-2 field-averaged $\sigma^0$. 
Fig. 11: The variation of measured soil moisture, canopy coverage and stem moisture through the growing season for winter wheat, Field 2.
Fig. 12: Predicted $\sigma^0$ for VV, Field 2, winter wheat, and breakdown of scatter contributions. The crop coverage has been limited empirically to a maximum of 90% and this gives a closer fit to the ERS-2 data.
Fig. 13: Scatter plot of volumetric soil moisture against ERS-2 values; all wheat fields, on all observation dates.
Volumetric soil moisture $\sigma_0$ (dB)

- Days 41, 76 & 111
- Days 146, 199 & 215
- Day 181