PROJECT REPORT No. 252

ADVANCED RADAR FOR MEASURING GREEN AREA INDEX (GAI), BIOMASS AND SHOOT NUMBERS IN WHEAT (RADWHEAT)

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ADVANCED RADAR FOR MEASURING GREEN AREA INDEX (GAI), BIOMASS AND SHOOT NUMBERS IN WHEAT (RADWHEAT)

by

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This is the final report of a two-year project which started in February 1999. The project was funded under the British National Space Centre (BNSC) Earth Observation LINK programme with the following grants: £107,233 (HGCA - project no. 2110), £125,000 (LINK) and £28,000 (Astrium UK plc, formerly Matra Marconi Space UK Ltd).

Contents

ABSTRACT

The RADWHEAT project has developed the potential of radar sensors for the quantitative measurement of key parameters of winter wheat (GAI, shoot numbers and biomass). Measurement of these parameters are important in order to improve nitrogen and PGR decision-making accuracy using canopy management principles. Using sensors would provide potentially cheap but objective crop measurements, and would have great value for conventional ‘uniform’ field management as well as allowing the implementation of appropriate ‘precision farming’ or variable rate inputs management practices.

The two most promising sensing techniques are spectral reflectance (being investigated in the SPARTAN project, MAFF LINK funded with HGCA as the major industry partner) and radar. The development of commercial applications for SAR (Synthetic Aperture Radar) imaging is of considerable interest to the aerospace community with forthcoming SAR satellites planned which will be providing information products to the agricultural market. Compared to reflectance sensors, radar can operate 24 hours a day and is not restricted by cloud cover.

The main conclusions of the project are as follows:-

1. The project studies have broken new ground in understanding the physical features of wheat crops and soil that influence radar backscatter at different wavelengths, polarisations and incidence angles. C- and X-band radar at VV and VH polarisations (VV = vertical transmit, vertical receive; VH = vertical transmit, horizontal receive) and high incidence angles seem to offer the most potential for recovering information on the characteristics of wheat crop canopies. It has been possible to distinguish components of the upper canopy (flag leaf and ears) from the lower canopy and the soil layer. This new information has allowed substantial improvements to be made to the Radiative Transfer RT2 backscatter model.

2. The project has confirmed that wheat crop sensing using radar does have some prospect for measuring crop GAI and biomass, but that considerable further research is needed before robust *quantitative* interpretation of radar backscatter signals is likely to be possible. A reasonable relationship was found between radar backscatter with total above ground crop biomass and Green Area Index (GAI) but not with shoot numbers.

3. Up to GAI 3, the relationship of GAI and biomass to the Normalised Difference Vegetation Index (NDVI) using hyperspectral reflectance measurements was better than with radar.

4. A small study has shown that surface water (e.g. rain, dew) can increase backscatter by 2-4 dB (decibels) for all polarisations. As a result, the HH-VV difference may provide a measure of biomass which is more insensitive to this effect than individual polarisation channels – this requires further study.

5. Coincidental high resolution airborne imagery during the project (but not funded by RADWHEAT) showed interesting visual differences between crop canopies, illustrating the potential value of SAR for *qualitative* if not *quantitative* assessment of crops. Simulations have been made of the potential value of proposed information products from the forthcoming TerraSAR satellite system.

6. An assessment of a possible tractor-mounted radar system concluded that the principles of radar sensing might be developed using Frequency Modulated Continuous Wave (FMCW) radar. Use of SAR is not considered feasible for tractor mounting.

INTRODUCTION AND OBJECTIVES

The RADWHEAT project was developed as a result of the common interests of the agricultural end-user (the farmer), a technology provider (Astrium UK plc, formerly Matra Marconi Space (UK) Ltd) and the academic community (Sheffield University Centre for Earth Observation Science (SCEOS), and BAE SYSTEMS Advanced Technology Centre (BSATC)).

Recent agronomic research by the ADAS/University of Nottingham Centre for Agronomy (largely funded by HGCA) has demonstrated the potential advantages of managing winter wheat according to crop physiological or ‘Canopy Management’ guidelines. The HGCA ‘Wheat Growth Guide’ (1997) represents an important output of this research. The Guide provides benchmark values for a typical wheat crop, providing farmers with a framework against which the management of their own crop can be measured, and input decisions made.

The lack of cost-effective and quantitative methods for the in-field measurement of these wheat crop parameters is a major limitation but remote sensing by optical and/or radar techniques offers a potential solution. A sensing solution providing potentially cheap but objective crop measurements would be valuable for conventional ‘uniform’ field management as well as to allow the implementation of ‘precision farming’ or variable rate inputs management practices. The RADWHEAT project has focused on advanced radar technology and has been complementary to the project ‘Spectral reflectance as a basis for in-field sensing of crop canopies for precision husbandry of winter wheat (SPARTAN)’ project - MAFF LINK funded with HGCA as the major industry partner. In contrast to sensing by spectral reflectance which measures reflectance of sunlight by the crop, sensing by radar involves the active emission of a radar signal which is reflected back to a sensor. The signal can have different characteristics of wavelength, polarisation and incidence angle. The ‘backscattered’ signal contains information on features of the target crop/soil. Because radar does not rely on sunlight, it can operate during both day and night, and in contrast to reflectance sensing, a space-borne radar system can ‘see through’ clouds.

Wavelength	L, S, C and X bands are radar of decreasing wavelength (i.e. X band has a shorter wavelength than C band.
Polarisation	Radar may be transmitted in horizontal or vertical polarisation and then received in either horizontal or vertical polar – e.g. HV is horizontal transmit, vertical receive.
Incidence angle	The angle between the vertical (nadir) and direction that radar is pointing.

A summary of the RADWHEAT project objectives is given below.

1. To identify the potential of advanced radar sensors for measuring *green area index (GAI), ear biomass, total crop biomass and shoot numbers* in winter wheat.

2. To improve the physical understanding of radar backscatter processes and to develop an improved version of the existing Radiative Transfer (RT2) model of radar backscatter.

3. To use a combination of laboratory and field studies to develop a technical specification of the optimal radar configurations (wavelength, polarisation and incidence angle) required to measure the target wheat crop parameters at different growth stages and under different environmental conditions.

4. To assess the potential synergistic benefits that might accrue from integrating radar with spectral reflectance sensor data for the target wheat crop parameters.

5. To carry out simulation studies of specimen satellite, airborne and ground-based radar configurations for retrieving the crop parameter information, assessing likely data quality.

Project Partners

The partners in the RADWHEAT project are given below.

Science partners
ADAS Boxworth, Cambridge (lead partner)
Sheffield Centre for Earth Observation Science (SCEOS), Sheffield University
BAE SYSTEMS Advanced Technology Centre (BSATC), Chelmsford, Essex

Industry partners
HGCA
Astrium (UK) plc, Portsmouth, Hants

British National Space Centre (BNSC) LINK programme

Project Workplan

The project consisted of a series of 6 work packages (WP) intended to improve the crop and soil factors influencing the radar backscatter signal. The title of each WP is given below.

WP1. Interfacing existing radar backscatter and wheat physiology knowledge.

WP2. Laboratory (Anechoic chamber) studies.

WP3. Field experiments using co-ordinated ground-based radar and optical sensors.

WP4. Data analysis, RT2 model improvement and assessment of radar/optical synergy.

WP5. Simulation of potential application products.

WP6. Exploitation, reporting and scientific papers.

KEY RESULTS

(Copies of technical reports produced during the RADWHEAT project, including colour radar and other images, can be obtained on request from HGCA – see Appendix 1 for list of reports and papers)

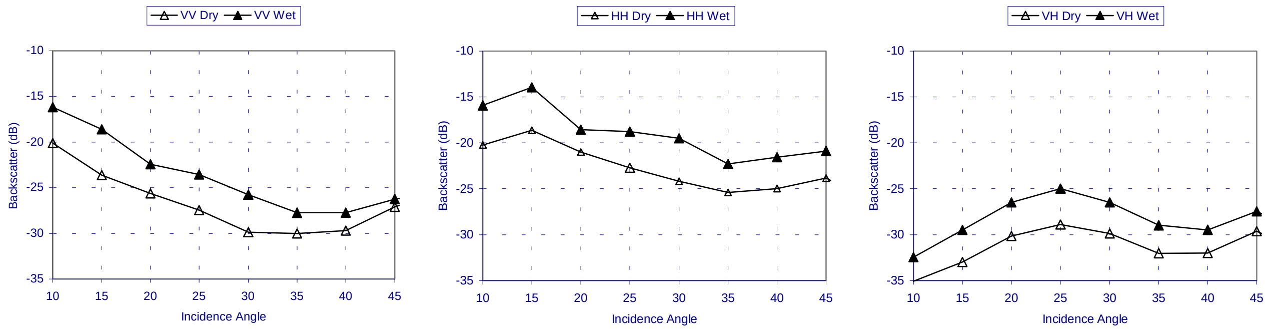
Laboratory (Anechoic Chamber) Studies

In year 1 (1999), two different sowing densities of spring wheat were grown in containers at ADAS Boxworth and transported at intervals to the anechoic chamber facility at Sheffield where they were reconstructed into a 1.6m by 1.7m canopy. High resolution 2-D and 3-D polarimetric radar measurements were carried out at L, S, C and X bands, over a range of incidence angles. Complementary crop and soil measurements were taken. These measurements generated a unique set of high resolution 2-D and 3-D radar images of a number of individual wheat canopies. By so doing, the scattering within the crop canopy was visualised and the radar sensitivity to particular crop components assessed. The significance of factors such as crop surface moisture were considered.

Marked polarisation and waveband effects were found. At X band, the canopy scattering was found to arise principally from the flag leaves at VV polarisation, but there were contributions from the lower leaves later in the season at HH polarisation. The magnitude of the ground (soil) return relative to the canopy was much stronger at HH polarisation, because of the preferential attenuation (interaction and loss of energy of the radar wave) of vertically polarised radiation by the near vertical stalks of the wheat. At VV, canopy scattering dominated for incidence angles greater than 30°, but for HH it was competitive with the ground return only at large incidence angles. For both polarisations, the ground return diminished with incidence angle, because of the longer path length (and associated attenuation) through the vegetation. The VH images showed a dominant return at soil level. This is likely to be a double bounce effect, from the vegetation to the ground (or vice versa) and then back to the sensor. The conventional view that the cross-polarised return is dominated by volume scattering in the canopy was not supported by these measurements. At C band, the longer wavelength allows greater penetration of the radar waves, resulting in a ground scatter which dominates the canopy return at all incidence angles for HH. For VV and VH, competitive canopy return does not occur until the incidence angle exceeds 35° - 40°.

These results have key implications for the recovery of canopy properties from radar data. The most useful appear to be VV and VH polarisations and large incidence angles where there is little contamination from the ground returns. At HH polarisation (especially C band), the ground return dominates, preventing extraction of direct information for the canopy. At large incidence angles the signal mainly contains information on the upper canopy, where most scattering occurs.

To investigate the effect of surface moisture from rain or dew, a specific experiment involved measuring a 1.6m $\times$ 1.7m canopy before and after applying 21 litres of water. The water was sprayed over the canopy using a watering can fitted with a rose to simulate the effect of rain. At C band, the effect was to increase the backscatter at all polarisations as shown in Figure 1. The increase was fairly uniform and 3-4 dB in magnitude for all polarisations and incidence angles (the exception is at the higher incidence angles for VV, where the wet-dry difference is less). Examination of the 3-D scattering images revealed that there was little variation in the upper canopy region between the wet and dry crops, with most variation originating in the lower canopy or ground regions. These data are significant in demonstrating that radar is highly sensitive to the moisture content of a canopy and the underlying ground. However, it is important to note that changes at VV and HH are comparable, except at the higher incidence angles, so that the VV-HH difference is much less sensitive to moisture variations than the HH or VV individually.



VV HH VH

Figure 1. Backscatter from Wet and Dry Wheat Canopy

Field Experiment

In year 2 (2000), a field experiment at ADAS Boxworth was established. Twelve plots of winter wheat, each measuring 24m by 50m, were grown to give a range of crop densities and treatments (Figure 1).

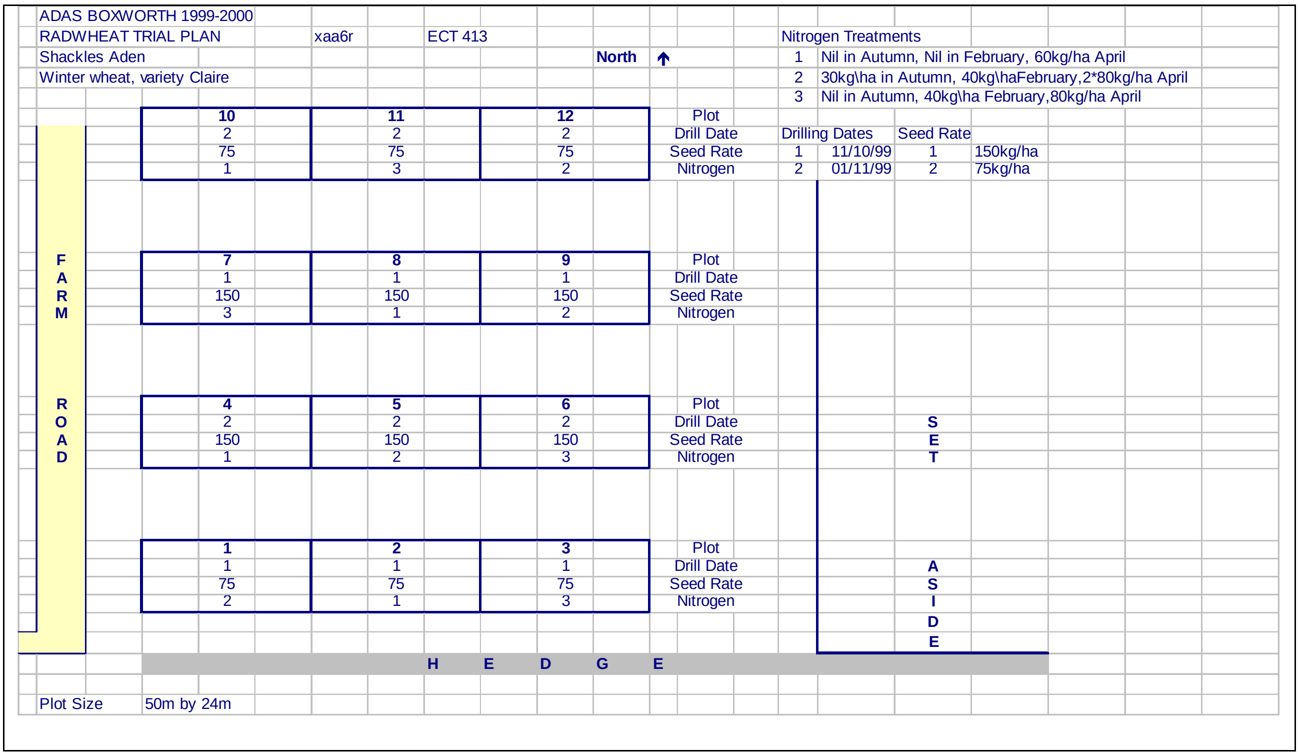


Figure 2. Treatments and layout of wheat plots at ADAS Boxworth (2000)

Radar data were collected using the NERC Ground-based Synthetic Aperture Radar (GB-SAR) facility, operated by Sheffield University. This mimics a satellite based radar system. GB-SAR consists of a radar scanner at the top of a mobile hydraulic hoist at about 10m above ground level. The 4 wheel drive towing vehicle contains all the support electronics. Power is provided by a mobile generator, making the system completely autonomous and capable of being deployed at any suitable field site. GB-SAR imaging is a time-consuming process but information is collected for crop area of about 2000m^2.

Despite some of the worst weather since records began, the GB-SAR data collected (Table 1) covered incidence angles from 30° to 70° at L, S, C and X bands. Most measurements were fully polarimetric. For each set of radar measurements, detailed agronomic and crop architecture data were also collected.

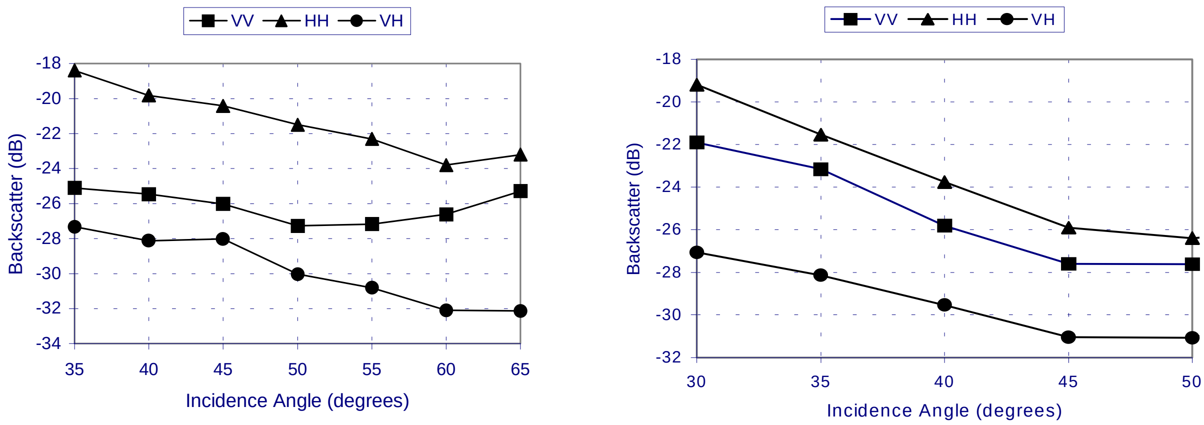
Date (2000)	Plot 4	Plot 5	Plot 12
15 March	C-Band (VV & HH only)		
16 March	C-Band X-Band		
17 March	X-Band (VV & HH only)		
10 April		C-Band	
10 May		C-Band	
15 May			C-Band X-Band
16 May		C-Band C-Band (parallel to row direction) X-Band	
30 May		X-Band L&S-Bands	
31 May	C-Band X-Band X-Band (parallel to row direction) X-Band (wet crop – VV only)	C-Band	
13 June			L&S-Bands L&S-Bands (parallel to row direction) L&S-Bands (wet crop)
14 June			L&S-Bands

Table 1. Summary of GB-SAR radar measurements

In March, there were clear differences between the backscatter at different polarisations, with the highest backscatter levels generated at HH polarisation (due to strong backscatter from the soil). Significant differences in backscatter levels between identical polarisations on different dates were also visible. The canopy measured in March showed higher levels of backscatter at all polarisations than canopies in May. This would be due to the increased canopy coverage and reduced ground backscatter in May.

For C and X band on 31 May, backscatter usually decreased with increasing incidence angle at all polarisations. However, at C band VV, an increase was observed for incidence angles over 50°. This was due to the strong interaction with the upper canopy region at large incidence angles. Simulations with the RT2 model indicate that this is caused by increased returns from the flag leaves and ears. However, it is not clear whether this selective sensing of a particular layer and set of plant components in that layer is the most effective way to measure parameters such as biomass and GAI. That depends on the strength of the correlation between the upper canopy structure and these parameters.

Figure 3 shows the large difference (about 7 dB) between the C-band HH and VV returns, except at the higher incidence angles. This is a consequence of the differential attenuation noted in the indoor chamber measurements. A difference of around 2 dB between HH and VV polarisations is also clear at X-band.



C-band X-band

Figure 3. Relationship of C and X-Band backscatter with Incidence Angle (31 May)

Sensitivity to Wheat Crop Parameters - Radar

Figure 4 shows the relationship of C-band average backscatter, at an incidence angle of 40°, with crop biomass, GAI and shoot numbers.

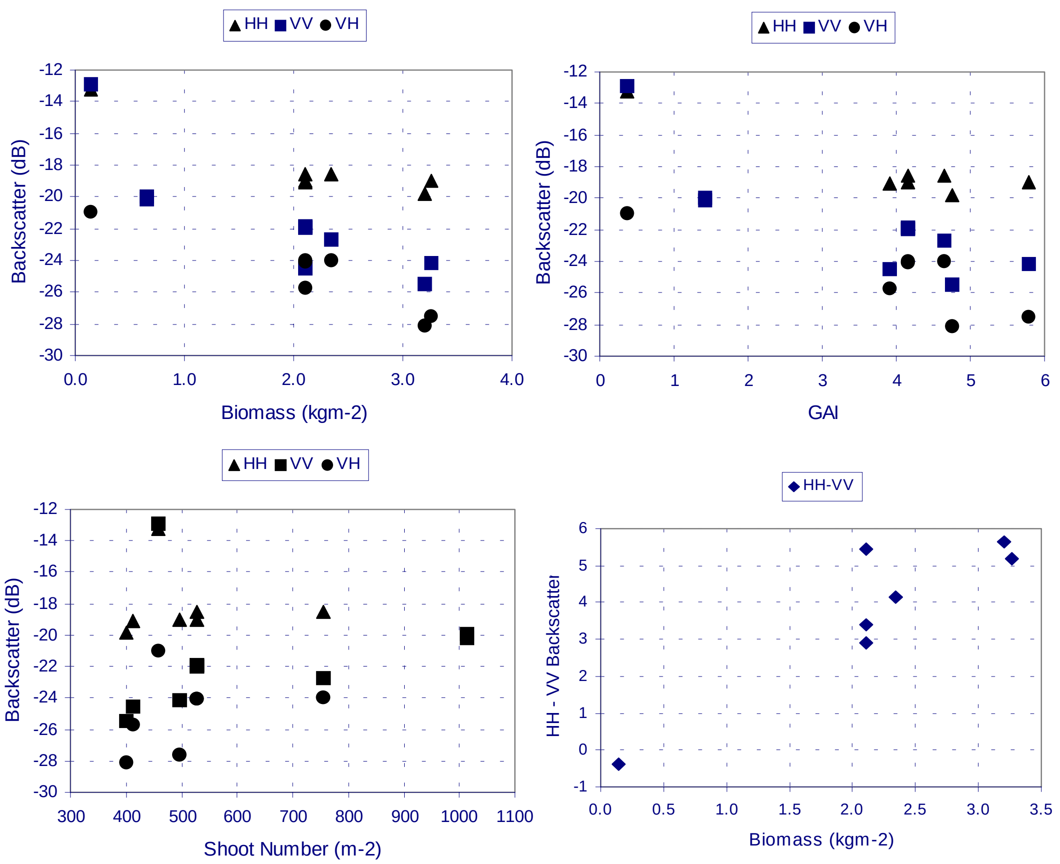


Figure 4. Comparison of Radar Backscatter with Agronomic Parameters

Although there are insufficient data points at each polarisation for statistical analysis, some relationship can be seen between the average radar backscatter at VV and VH polarisations with wet biomass and GAI. The radar backscatter decreased as wet biomass and GAI increased. In contrast, there appeared to be little relationship between wet biomass or GAI and the radar backscatter at HH polarisation. This is readily understood from the chamber studies. Both the VV and VH returns are strongly affected by attenuation (in the vertical channel), while HH is only weakly attenuated. The difference between the VV and HH measurements was found to be a useful biomass indicator and a clear linear trend is observed in Figure 4 between biomass and the difference between HH and VV. This difference will to some extent be resilient to soil moisture variations, because of the similar response of VV and HH to soil moisture. The graph showing radar backscatter against shoot number shows no obvious relationship between the two parameters at HH or VH polarisation. However, with the exception of one data point, there is an increasing trend of backscatter with shoot number at VV polarisation. This trend is not predicted by the RT2 simulations and it is unlikely that there is any strong relationship between backscatter and shoot number early in the season. Later in the season there may be some relationship, but probably due to changing biomass or GAI rather than shoot number.

Sensitivity to Wheat Crop Parameters – Spectral reflectance

On four dates (17 April, 15 May, 30 June and 11 July) the reflectance of each plot was measured using the ADAS Licor LI-1800 spectro-radiometer which measures reflectance at 1nm intervals between 350 and 850nm. Four replicate spectra were recorded for each plot with the sensor held about 0.5m above the crop. The measurements were carried out during periods of stable incoming solar radiation, checked by measuring incoming radiation before and after the four replicate measurements. Mean reflectance on each plot was calculated separately for each reflected radiation measurement and the results averaged. Throughout the season, there were a total of 48 coincident measurements of reflectance and ground truth crop measurement. Because of the treatment design, there was a wide range of crop growth on all assessment dates. This provided a good dataset for the study.

A simple Normalised Difference Vegetation Ratio (NDVI) was calculated based on the mean reflectances at each wavelength for each plot.

$$NDVI = \frac{NIR - R}{NIR + R}$$

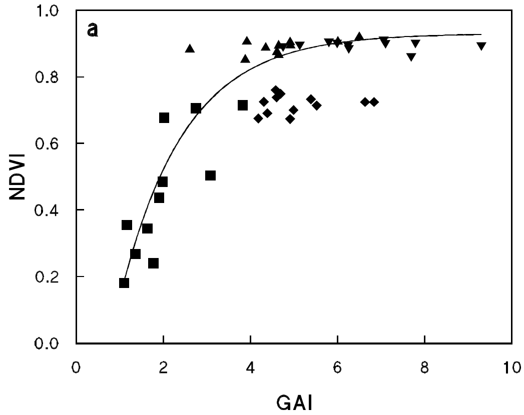
where:
NIR = the sum of reflectance between 790 and 850nm
R = the sum of reflectance between 600 and 690nm.

When expressed as the NDVI, the canopy reflectance was strongly related to GAI on 17 April when GAI ranged from 1 to 4 (Figure 5a). However because of the asymptotic nature of the relationship little further change in NDVI occurred once canopy closure was complete at about GAI 3.5. By 11 July, there was a distinct fall in NDVI as GAI was reduced by canopy senescence - these results are excluded from the fitted relationship. Excluding the July dataset, there was a statistically significant relationship between NDVI and GAI (r=0.935).

The dynamics of shoot number are more complex than those of GAI and the relationship of NDVI with shoot numbers is much more variable (Figure 5b). The positive relationship with shoot numbers was just significant (at p=0.05) on 17 April. The lower proportion of the variance accounted for by the regression probably reflects the large variation in shoot size (in terms of factors affecting reflectance per shoot – e.g. fresh or dry weight, leaf number or leaf area) for crops with the wide range of treatments used here. There was no useful relationship later in the season.

Crop biomass (total above ground dry weight) was particularly well related to NDVI on 17 April (Figure 5c, r=0.948). However, as for the other target parameters, no relationship was evident later in the life of the crop.

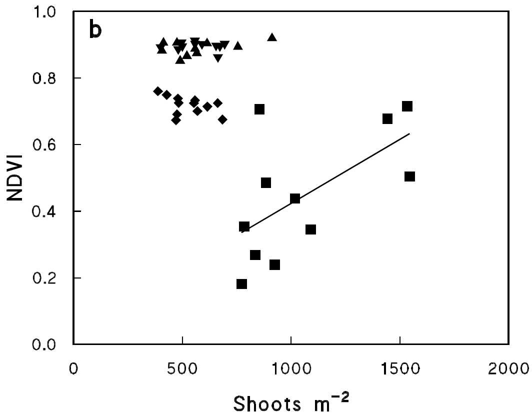
These relationships can be compared with those of C-band radar backscatter. Comparison of the datasets shows that reflectance sensing offers a good prospect for the quantitative estimation of GAI and biomass at early stages of crop growth up to around GAI 3. Radar would appear to offer potential for measuring GAI and biomass at later stages of crop development.



(a) Crop GAI

$y = -1.56\ e^{(-0.6673\ x)} + 0.931$, r=0.935

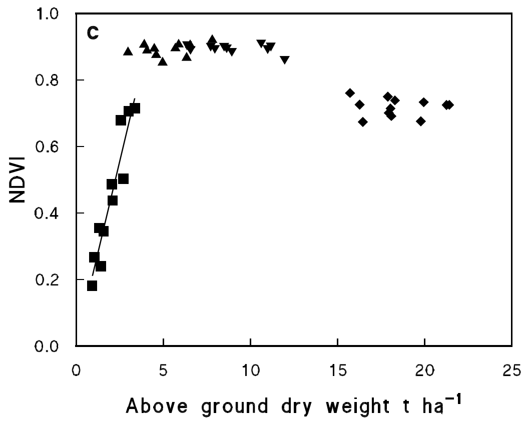
(fitted to points except 11 July)



(b) Crop shoot number

y = 0.000385x + 0.03816, r= 0.611

(fitted to 17 April data only)



(c) Crop biomass

y = 0.22x + 0.0069 , r= 0.948

(fitted to 17 April data only)

Figure 5. Relationship between NDVI and (a) GAI, (b) shoot number and (c) crop dry weight across all RADWHEAT field plots on 17 April (■), 15 May(▲) 30 May (▼) and 11 July (◆). Correlation coefficients (r) are given.

Development of the RT2 radiative transfer model

The ability to model radar backscatter from vegetated land surfaces offers a number of useful capabilities. These include:

- Rapid investigation into the usefulness of different frequency and polarisation combinations for studying particular types of vegetation.

- Providing simulated backscatter to test the feasibility and accuracy of algorithms that retrieve vegetation parameters from radar measurements.
- Providing guidelines for the design of radar systems for monitoring vegetation

A variety of different approaches to modelling the backscatter from vegetation have been developed which offer advantages and disadvantages when studying particular radar or vegetation characteristics. The Space Systems Group at BAE SYSTEMS Advanced Technology Centre has continually developed and validated its own second order radiative transfer model, known as RT2. This model has been developed over a number of years and RT2 version 2 has been supplied to a variety of users including the European Space Agency. As part of the RADWHEAT project, a more capable and flexible version of RT2 was required. Consequently, RT2 version 3 was developed which provides

- a greater number of vegetation layers,
- a greater number of scatterer shapes within each layer,
- simple addition of new ground scattering models, new scatterer types, new permittivity models and new orientation distributions,
- a simplified input file format.

A typical use of RT2 was to simulate the backscatter from wheat under different conditions. Such simulations can be used to identify the radar incidence angles and wavelengths which are most sensitive to a particular wheat condition and least sensitive to other factors such as soil moisture.

Results have shown that many characteristics and trends in the backscatter from wheat predicted by RT2 have been confirmed by GB-SAR measurements. However, a number of discrepancies were also found. A sensitivity analysis into the backscatter from early season wheat was carried out using the RT2 model. This examined the influence on radar backscatter of

- different stages of wheat development,
- different levels of soil moisture and roughness,
- different wheat moisture levels and leaf orientations.

Simulation results have indicated that L band is relatively insensitive to wheat condition, whereas there is much greater sensitivity at C band. The analysis also indicated that at early crop growth stages, ground conditions can have a significant effect on backscatter. Techniques to remove the effect of soil from the radar signal are available. These generally rely on using the signal from a radar waveband which is sensitive to the ground conditions to determine the soil moisture which then allows the signal from other wavebands to be corrected.

Satellite information products - simulation studies

Infoterra (part of the Astrium aerospace company) intends to develop a range of satellite image based information products for world-wide sale to commercial customers. These products include crop monitoring based on parameters such as biomass, canopy moisture and surface soil moisture. The products will be based on data obtained from the dual-wavelength and polarimetric SAR system called TerraSAR which will operate at X- and L-band. This satellite system will be available in 2006. It is expected that the information products will be complemented by data from optical, airborne and ground based sources. Prior to launch of the TerraSAR system, Infoterra intends to exploit existing capabilities and techniques, and to advance the techniques using airborne data.

Six agricultural information products relevant to wheat crop management have been considered, namely: Crop Homogeneity, Establishment, Inventory, Yield, Vigour, and Ripeness. High resolution airborne SAR imagery has been used to simulate future satellite SAR imagery and both have been assessed for their ability to provide such information products. The satellite simulation images indicate that a homogeneity product is viable provided that the scale of any inhomogeneity is of the order of tens of meters. Similarly, the simulated images indicate that the wheat crop is easily identifiable in May. However, the viability of inventory production will depend on the accuracy to which the wheat crop can be identified early in the season. This also has an impact on other products, such as yield prediction.

Model simulations indicate that, using radar channels likely on future satellite systems, information can be provided on early season crop establishment, again with the proviso that areas of bare ground are of the order of tens of meters. The modelling results also indicate that the remaining two retrieval products (vigour and ripeness) are potentially possible, given a sophisticated retrieval scheme.

Tractor-mounted

Consideration has been given to the use of a tractor-mounted radar system which must be cost-effective and robust enough to work under practical field conditions. Use of SAR imaging from such a platform is not considered practically feasible in the near or medium term future due to issues of the cost and complexity that would be needed of an operational system. The inevitable platform motion during in-field operation would also create serious problems for data retrieval, processing and interpretation.

A feasible system might be provided using the Frequency Modulated Continuous Wave (FMCW) radar principle. This measures an 'averaged' radar reflectivity of the target. Operationally, an FMCW system might measure the average backscatter of a 0.75 by 7 metre swath of crop close to the position of the radar antenna mounted on the tractor. The FMCW radar would need to be mounted 3-4 metres above ground level and would have dimensions typically 60 by 30 by 15 cm, linked to a ruggedised computer system similar to a laptop. Calibration of the system would be straightforward. The results of the RADWHEAT project would be broadly applicable to an FMCW system.

CONCLUSIONS

The potential of radar for recognising differences in crop GAI and biomass is encouraging though the capability for retrieving quantitative crop information from radar backscatter data is several years behind that for retrieving such information from reflectance data. Results from the RADWHEAT project show that differences between crops of different canopy structure can be detected using radar. Such *qualitative* or *relative* differences between different cropped areas (different fields or different parts of fields) can be useful information to help farmers target ground inspections and for defining boundaries between field areas which might benefit from different treatments. This can provide the opportunity to create treatment maps for fertiliser and/or agro-chemicals. Radar images indicate that X-band radar images can distinguish qualitatively between crops of different 'vigour'.

The perfect solution, however, would be for a sensor technique to provide a *quantitative* estimate of key crop parameters. The model simulations indicate relationships between GAI, biomass and backscatter, which means that quantitative measures of these agronomic parameters can potentially be derived from radar backscatter. Although the RADWHEAT project has indicated some promise from radar, much more research is needed before robust relationships are likely to be developed that take account, where necessary, of factors such as crop variety, soil type and condition, topography and environmental factors such as wind and surface moisture. More research is needed if the potential of transforming absolute values of radar backscatter into absolute values of GAI or biomass is to be realised.

The work comparing the effectiveness of reflectance sensing with radar sensing has indicated that, on current knowledge, reflectance sensing is more sensitive to GAI than radar. Thus, currently, reflectance sensing seems to offer the best potential for quantitative measurement of this crop parameter. A tractor-mounted system is currently seen as the most promising option combining reflectance sensor technology with a platform that is less influenced by cloud cover than airborne or satellite platforms.

The potential for radar in crop management applications is thus most likely to come from satellite or airborne operational systems which can reliably provide a birds eye view of large areas of land to help farmers target crop inspections and/or prioritise field operations. Cloud cover greatly restricts the potential and reliability of airborne/satellite optical imaging for this purpose. Reliability of supply of images is of key importance if they are to be utilised by farmers in practice. If a planned information supply chain should fail, alternatives may not be readily available at short notice. Thus, radar images may help to 'gap fill' sequences of reflectance images with integration of images from different sources providing products to the farmer which have added value.

The impact of surface moisture (rain, dew) on the radar backscatter signal is a serious concern and one which needs further research to identify its practical significance as a source of error and to identify if there are robust ways of correcting the backscatter signal to account for it. The project has shown that backscatter from a wet crop can be 3 dB higher than from a crop with no surface moisture. Surface moisture from rain or dew is a common occurrence, especially in the UK and Northern Europe. Some means must therefore be developed to estimate surface moisture content at the time of sensing.

APPENDIX 1. PROJECT REPORTS, PUBLICITY AND SCIENTIFIC PAPERS

Project technical reports

1. Interface between Existing Wheat Physiology data and the Radiative Transfer Model known as RT2 (issued October 1999)

2. Chamber Studies and RT2 Enhancements (issued March 2000)

3. Methodology and Preliminary Results of Field Experiment (issued July 2000)

4. Final Report on Chamber Studies (issued February 2001)

5. Field Experiments (issued February 2001)

6. Comparison of Radar and Spectral Reflectance (issued February 2001)

7. Simulation of Potential Application Products (issued February 2001)

8. RADWHEAT Final Report (issued March 2001)

Publicity

Entry in BNSC website
Entry in HGCA website
Entry in EC EWSE database (May 1999)
Article in MAFF LINK Newsletter (July 1999)

Planned article for NERC Newsletter (May 2001 issue).

Scientific papers (published)

BROWN, S.C.M., MORRISON, K., COOKMARTIN. G., BENNETT, J.C., QUEGAN, S., ANDERSON, C., CORDEY, R.C. AND DAMPNEY, P.M.R. *Using radar for the management of wheat canopies.* Aspects of Applied Biology 60, Remote Sensing in Agriculture, 11-20.

BROWN, S.C.M., COOKMARTIN. G., MORRISON, K., McDONALD, A.J., QUEGAN, S., ANDERSON, C., CORDEY, R.C. AND DAMPNEY, P.M.R. *Wheat Scattering Mechanisms Observed in Near-Field Radar Imagery Compared with Results from a Radiative Transfer Model.* International Geoscience and Remote Sensing Symposium, July 2000 pp. 2933-2935.

BENNETT, J.C., MORRISON, K., COOKMARTIN, G. and QUEGAN, S. *The UK NERC Fully Portable Polarimetric Ground-Based Synthetic Aperture Radar (GB-SAR).* International Geoscience and Remote Sensing Symposium, July 2000 pp. 2313-2315.

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Scientific papers (planned or in preparation)

Using very high resolution three dimensional radar images to resolve the polarimetric scattering mechanisms in wheat canopies. To be submitted to the IEEE Transactions in Geoscience and Remote Sensing.

Inferring the biomass of wheat canopies from radar measurements. To be submitted to the IEEE Transactions in Geoscience and Remote Sensing.

Evaluation of SHAC and BB-SAR data at ADAS Boxworth. To be submitted to the IGARSS conference (Sydney, summer 2001).

Paper(s) to the meeting on retrieval of Bio- and Geophysical Parameters from SAR for Land Applications, University of Sheffield, September 2001.