COMPARISON OF MODELLED BACKSCATTER RESPONSE AND ERS-1 SAR DATA FOR DESERT SURFACES, THE EASTERN BADIA OF JORDAN

Kevin Tansey[1] — [1] Department of Geography, University of Leicester,

Leicester, LE1 7RH, UK.

e-mail: kjt7 le.ac.uk

Kevin White[2] — [2] Department of Geography, University of Reading,

Reading, RG6 2AB, UK.

e-mail: k.h.white geography.rdg.ac.uk

Andrew Millington[1] — e-mail: acm4 le.ac.uk

Anwar Battikhi[3] — [3] Dean, Faculty of Graduate Studies, University of Jordan,

Amman, Jordan.

ABSTRACT

The objective of this paper is to investigate the use of theoretical surface scattering models to simulate the backscatter coefficient for a range of dryland surfaces. *In-situ* measurements of soil moisture, surface roughness and soil texture have been used in the Kirchoff and Small Perturbation models. Comparison of the results of this modelling with ERS-1 SAR data indicate good agreement between the predicted and observed backscatter coefficient ($R^2 > 0.8$). An analysis of the suitability of the Integral Equation Model is also presented. The modelling has demonstrated the need for accurate and representative surface roughness parameterisation for the retrieval of soil moisture. Further research is aimed at increasing the sample dataset, deriving surface roughness characteristics and to develop a greater understanding of the interactions between microwaves and desert surfaces.

Keywords: ERS SAR, soil moisture, surface roughness, desert, modelling.

1. INTRODUCTION

The retrieval of information related to physical surface parameters is a major objective of many studies in remote sensing investigations. With the deployment of ERS-1 Synthetic Aperture Radar (SAR) and more recently ERS-2 SAR (C-band, VV polarisation with an incidence angle of 23°) estimates of soil moisture have been extensively exploited in such disciplines as agriculture and hydrology. Other satellite radar systems such as JERS-1 and RADARSAT complement and increase our knowledge of interactions between radar and natural surfaces. The optimal configuration, as stated by Ulaby *et al*. (1978), for maximum soil moisture sensitivity was a C-band system operating at an incidence angle between 10 and 20° , but compared with the configuration of ERS SAR, consideration must be made of other surface parameters notably surface roughness and soil texture which influence backscatter.

One approach to understanding interactions between radar and natural surfaces is through modelling. In this paper, theoretical models of surface scattering, described in section 2, are validated using *in-situ* measurements of surface parameters for an arid climatic region of the Jordanian Badia, described in sections 3 and 4. Using backscatter values derived from ERS-1 SAR PRI imagery, described in section 5, at overpass times contemporous with field data collection, comparison with modelled values are made. The results, displayed in section 6, are encouraging but are interpreted to indicate where problems in using the models as predictive tools may occur. These problems are addressed with respect to the retrieval of soil moisture parameters. Conclusions and recommendations for future research are described in section 7.

2. THEORETICAL MODELS

Simple models of rough surface scattering help us to understand and interpret the nature of wave scattering and to extract information from radar images. The models used in this study are the Small Perturbation Method (SPM), the Kirchoff Method (comprising the Geometrical Optics (GO) and the Physical Optics (PO) models) and the Integral Equation Model (IEM). For a full description of the SPM, GO and PO models see Ulaby *et al*. (1982). In simple terms, the SPM assumes that variations in surface height, parameterised as root mean square (RMS) height (σ), are small compared to the wavelength (λ) of the radar signal ($\lambda \cong$ 5.66cm for ERS-SAR). Also, that the surface slope parameter, m, is small (where $m = \sigma / l$ where l, the correlation length, can be considered as the horizontal distance beyond which two points are approximately statistically independent), (Ulaby *et al*., 1982). The GO solution is valid when RMS height is large compared to the wavelength. The PO solution is valid when RMS height is small compared to the wavelength.

The IEM developed by Fung *et al*. (1992), is less restrictive in its validation domain. The complex version of the model accounts for a wide range of roughness and frequencies. For the purpose of this study an approximate solution is used, the only limitation being for surfaces with large RMS heights compared to the wavelength. Two further assumptions are made; firstly, only the real part of the dielectric constant (ε) is used, a reasonable approach for soil moisture retrieval (Sreenivas *et al.*, 1995); and secondly, the autocorrelation function, a descriptor of the correlation between two points over a horizontal scale as the distance between the points change, is assumed isotropic and represented by a Gaussian or exponential distribution function (Altese *et al*., 1995; Su and Troch, 1996).

The validation domains of these models can be identified in the ksigma-kl feature space (figure 1) where k is the free space wavenumber ($k = 2\pi / \lambda \cong 1.11$ for ERS SAR). Plotted within this feature space are measured roughness values from field sites. It can be seen that there are sites for which none of the models are valid (especially for the SPM, GO and PO model domains). The output from the models, the backscattering coefficient (σ^0 or Sigma 0) measured in decibels (dB), is expressed as a function of the radar frequency, polarisation, incidence angle; surface RMS height, correlation length, autocorrelation function and the dielectric constant, the latter calculated from volumetric soil moisture and soil texture using an empirical relationship given by Hallikainen *et al*. (1985).

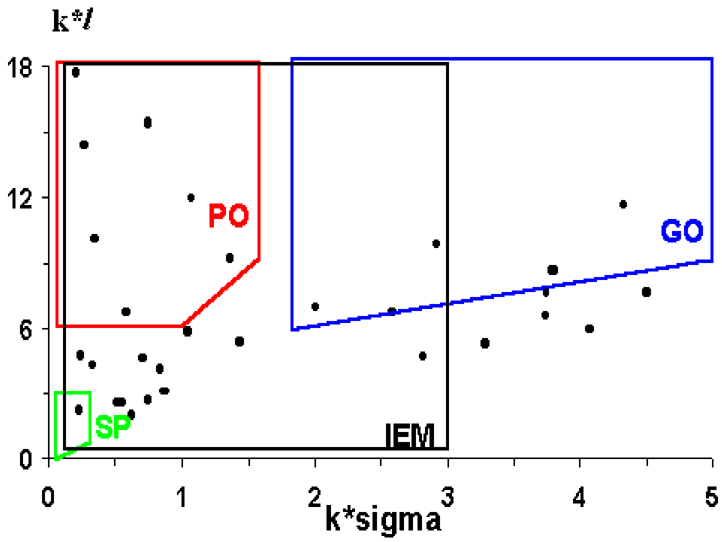

Figure 1 - Validity domains of the Small Perturbation Method (SP), Geometrical Optics (GO), Physical Optics (PO) and Integral Equation Models (IEM), shown against measured roughness values for desert surfaces. k ≅ 1.11, l is the correlation length and sigma is the RMS height

3. STUDY AREA

The majority of soil moisture experiments using radar remote sensing have focused on systems where human activity has altered the land surface. This study looks at a wide range of natural and non-natural desert surfaces characteristic of the eastern Badia of Jordan (figure 2). The Jordan Badia Research and Development Programme area, bounded by Syria to the north and Saudi Arabia to the south, covers a total of 11,210 km^2. The eastern and western margins follow a perimeter of Tertiary-Quaternary basalt flows and tuffs, known locally as *harrat*, comprising parts of the Harrat Ash-Shaam Basaltic Super-group (Ibrahim, 1993). The land surface towards the south of the programme area comprises of mainly sedimentary rocks and cherts, known locally as *hammad*. Thin layers of sand cover the *hammad* in the far south and south-eastern reaches of the area, termed sand veils in this paper. Within these major geomorphic units are drainage systems, forming what are known locally as *qaa* and *marab*. *Qaas* are characteristically flat, silt-clay loam surfaces that act as sinks for sediment and water fluxes. Desiccation cracking is also a feature of these surfaces. *Marabs* are areas of natural vegetation usually associated with channel systems and outwash plains. Vegetation covers are low, primarily due to limited rainfall and also grazing in the programme area with almost all areas having less than 10% cover (Edwards *et al*., 1996). Some cultivation is practised within the programme area.

An arid desert climate exists within the Badia. Mean annual rainfall totals vary from 200mm in the north to less than 50mm in the south. Annual equivalent evaporation rates range from 1500mm to 2000mm along a gradient from north to south (Al-Homoud *et al*., 1995).

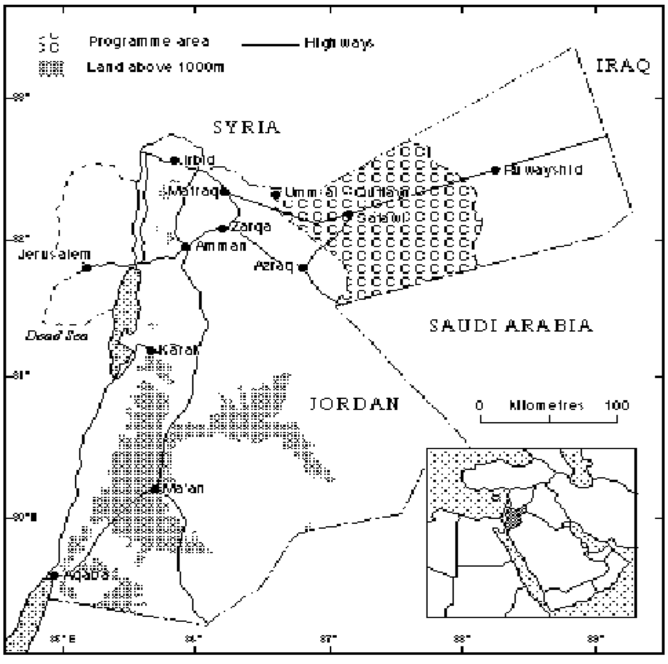

Figure 2 - Location of the Jordan Badia Research and Development Programme Area

4. METHODOLOGY

Study sites were chosen within each major landcover unit that were considered homogeneous over approximately a square kilometre. Two field campaigns were completed in November-December 1995 and April-May 1996. Soil moisture data were collected using a dielectric probe that produced an estimate of the volumetric soil moisture content from the upper 6cm of surface material. 30 samples were taken at random locations within a 30 by 30m area and the average value derived. Surface roughness data were collected with a profilometer recording height measurements along transects between 1.5 and 3m in length at a sampling resolution of 5mm. The profiles were digitised and statistical descriptors of the surface properties derived. The RMS height (σ) and the correlation length (*l*) were calculated following the recommendations of Ulaby *et al*. (1982) and Cox (1983). Analysis of the surface height distributions showed that the majority of sites were characterised by approximate Gaussian distributions. Calculation of the surface slope parameter, *m*, defined in section 2, was made for either exponential or Gaussian autocorrelation functions based on goodness-of-fit observations of these theoretical distributions to actual distributions (see Oh *et al*., 1992). Soil texture information were partially derived from comprehensive soil maps of the programme area and from analysis of field samples.

5. ERS-1 SAR IMAGERY

Backscatter coefficients were derived from ERS-1 SAR PRI imagery, acquired in conjunction with collection of field data, using the comprehensive equation by Laur *et al*. (1996). The dates of image acquisition were (day-month-year); 23-11-95, 09-12-95, 12-12-95, 11-04-96, 01-05-96 and 16-05-96. The raw images were transformed to geographic co-ordinates using ground control points, identifiable both on imagery and in the field. Nearest neighbour resampling was used with an RMS transformation error of approximately one pixel. This enabled accurate identification and location of sites within the SAR image. As no algorithm for speckle reduction was applied to the images, thus maintaining original pixel DN, the backscatter coefficient was derived from an average of 25 by 20 pixel DN, approximately equivalent to 300 by 250m on the ground. Original site selection criteria assumed homogeneity for at least a square kilometre.

6. RESULTS AND DISCUSSION

Estimates of the backscatter coefficient were calculated using sites that satisfied the validation domains of the models shown in figure 1. From a total of 30 sites, only 13 lie within the criteria set by the SPM, GO and PO models whereas 23 sites lie within the criteria of the IEM. Predicted backscatter values are plotted against observed backscatter values, using the SPM, GO and PO models (figure 3), giving a correlation coefficient of 0.82. Some points are very well predicted by the models (e.g. *harrat*) while other sites (e.g. sand veil) show that the models are not representative of the scattering processes. For example, in figure 3, sites indicated by red symbols are *harrat* surfaces and green symbols, sand veil surfaces.

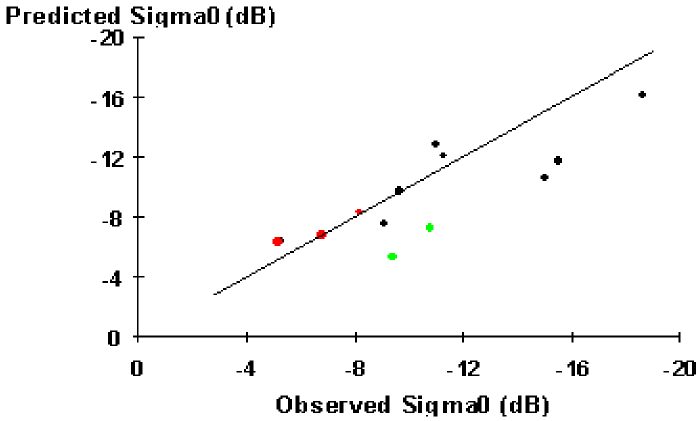

Figure 3 - Modelled backscatter values (predicted Sigma 0) plotted against ERS-1 SAR derived values (observed Sigma 0) for sites satisfying SPM, GO and PO model criteria for all surfaces. Basalt or harrat surfaces are displayed as red circles, sand veil surfaces are shown as green circles, R^2 *= 0.82*

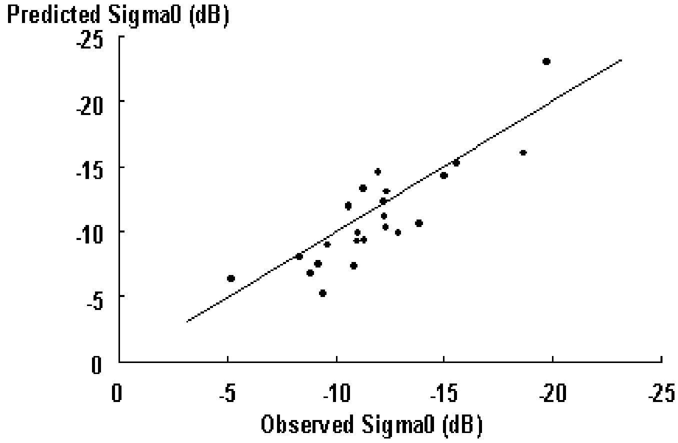

Figure 4 - Modelled backscatter values (predicted Sigma 0) plotted against ERS-1 SAR derived values (observed Sigma 0) for sites satisfying the IEM criteria, R^2 *= 0.87*

The results of the IEM validation are similar (figure 4). The correlation coefficient between the predicted and observed backscatter values is improved to 0.87 using the 23 sites that satisfy the model validation criteria. This is an encouraging result given that the model is predicting the backscatter response for a variety of natural surfaces and is based on field measurements. Further analysis of the scatterplot shows that the model overpredicts (indicated by the fact that the model predicts a greater backscatter coefficient should be detected (lower negative dB value) than that indicated by the SAR data) the backscatter response for quite a number of sites. This was further indicated in figure 3 where some surfaces were not well predicted by the models, the sand veil sites for example. The inaccuracies of the models can be explained in a variety of ways based on an understanding of model theory and may be attributable to the following:

(i) The models are derived from surface scattering principles. Volume scattering especially in dry, sandy areas, such as those existing towards the south-east of the programme area may be a significant process.

(ii) Vegetation in the *marabs* could possibly influence the radar signal even though present in low amounts. Therefore observations of the change in backscatter response over the year will be crucial in understanding the contribution of vegetation to the backscatter signal.

(iii) Natural surfaces are not entirely homogeneous over the spatial scales observed by ERS-SAR. Distribution of moisture and hence dielectric properties are likely to vary. Sarabandi *et al*. (1996) investigate these problems by modelling the surface as a inhomogeneous random layer comprising two-dimensional humps of varying size, shape and dielectric constant overlying a smooth, uniform impedance layer. The same approach could be adopted to derive an average dielectric constant for the *harrat* and *hammad* surfaces where basaltic and sedimentary rocks overlie a soil surface. The models, as they are, assume only a soil surface when calculating the dielectric constant.

(iv) Natural surfaces rarely have autocorrelation functions that fit either Gaussian or exponential theoretical functions.

(v) The measurement of surface roughness may be a potential limitation of the data. For example, Engman and Wang (1987) found correlation coefficients between the backscatter coefficient ($\sigma°$), and RMS height, and $\sigma°$ and correlation length to be 0.59 and 0.04 respectively. This indicates there is little relationship between backscatter and the correlation length for the large number of bare, dry fields the authors' studied. The general theory behind derivations of roughness parameters that adequately describe topographic variation appears unclear especially for remote sensing applications. Other methods seem more suitable, although data collection and analysis are time consuming. In a unifying approach, Greenwood (1984) stated that a complete description of a random surface's topography can be derived in terms of the PDF and the power spectrum of the surface profile. However, for power spectrum analysis, profiles of different sampling resolutions are required and a large number of independent profiles are desirable to reduce noise (Farr, 1992). The uncertainty of the roughness parameters used in the models can be argued through interpretation of the work by Sayles and Thomas (1978), who show through Gaussian statistics that the variance of the height distribution of a random structure is linearly related to the length of the sample involved. This implies that the RMS height increases as profile length increases and, through fractal analysis the function describing this relationship cannot be described and varies significantly with observation frequency (Brown and Scholtz, 1985). This invokes an uncertainty over what profile length should be used for radar studies and demonstrates the need for more accurate and representative measures of surface roughness.

(vii) Errors in determining the soil dielectric constant for very dry, structureless desert soils.

(viii) Calibration errors deriving $\sigma°$ from ERS-SAR imagery.

The outcome of the model depends on field parameters that may be unrepresentative of the surface conditions. Another approach, less demanding of data than an empirical approach, would be to use the models to derive a roughness parameter through model inversion, simulate soil moisture and RMS height variation, and subsequently monitor the sensitivity of the backscatter coefficient to these variations. Correlation lengths (the roughness parameter) were derived for different land cover types using the SPM, GO and PO models that yielded values of backscatter corresponding most closely to those observed from the imagery. Using actual values of RMS height, the sensitivity of the radar backscatter to changes in volumetric soil moisture from 0.0 to 0.4 m^3 (water)/ m^3 (soil) were simulated (figure 5).

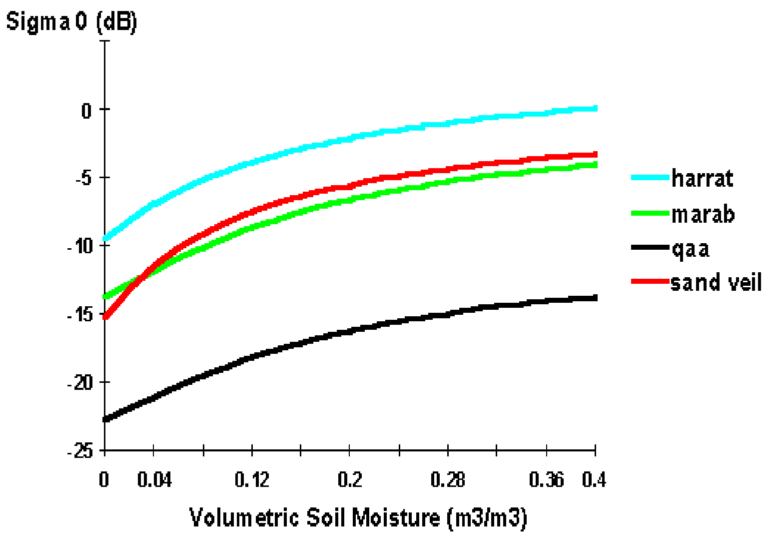

Figure 5 - Backscatter response to changes in soil moisture for various land cover types simulated with the SPM, GO and PO models. RMS heights (cm) are 3.9 (harrat), 1.23 (marab), 0.18 (qaa) and 0.94 (sand veil)

The simulation indicates that surface roughness has little effect on the sensitivity of the backscatter coefficient to changes in soil moisture i.e. the curves all have a similar form. What is also important is a greater sensitivity to changes in soil moisture from very dry to small volumes of water, which is the most likely range of values found in desert areas. The influence of soil type can also be seen especially at low values of soil moisture by examining the curve for a *qaa* surface dominated by clay-sized particles. The slope of the backscatter response is seen to be approximately constant over the range of soil moistures with only a small increase in sensitivity as the soil becomes dryer. Comparing this to the curve for a coarse-textured sandy site (sand veil) it can be seen in the latter that backscatter reaches an asymptote more quickly as the soil gets drier. The difference can be explained by the fact that, for a given low value of volumetric soil moisture, there is generally more water available in a sand to influence the dielectric constant than a clay.

The sensitivity of the backscatter to small variations in topographic roughness are displayed in figure 6 for the same surface types. For flat surfaces (*qaa* surfaces and some of the smoother *marabs* present in the study area) very small changes in surface roughness have a large effect on the backscatter. This sensitivity is reduced significantly for surfaces with a RMS height in excess of approximately 1cm and for the *harrat* rock surfaces, changes in roughness over similar scales has a negligible effect on the backscatter response.

The implications for soil moisture monitoring and retrieval using ERS SAR imagery, based on the model simulation, are that the radar backscatter is sensitive to changes in soil moisture for a wide range of surfaces if surface roughness is assumed constant. Le Toan *et al*. (1993) suggest this may be the case for many natural surfaces. For example, if surface roughness remained constant over a year in a vegetated marab, then any changes in backscatter would most probably be due to soil moisture and vegetation fluctuations. However, processes such as wind erosion causing deflation and deposition of surface sediments; and surface swelling and desiccation of smectitie clay-rich surfaces, that each operate over relatively short timescales, need to be accounted for by taking roughness measurements during different seasons. An absence of saline soils within the programme area reduces the effect that salt crystal growth has on backscatter (Wadge *et al*., 1994).

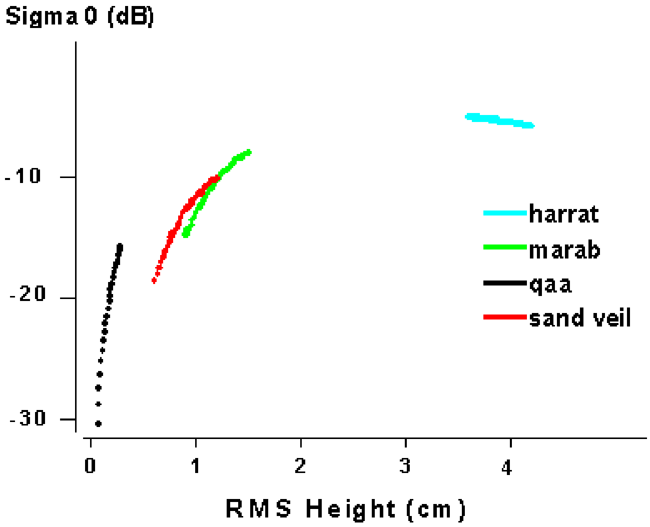

Figure 6 - Backscatter response to changes in RMS height for various land cover types simulated with the SPM, GO and PO models. Soil moisture values are approximately constant

7. CONCLUSION AND FUTURE RESEARCH

Surface scattering models have been validated using field data acquired during two field campaigns in late 1995 and early 1996. The backscatter coefficients have been compared to values derived from ERS-1 SAR PRI imagery collected at similar times. Good agreement was found; the correlation coefficients were 0.82 when validated with the SPM, GO and PO models and 0.87 when validated with the IEM. Further field campaigns will increase the number of sites that can be used for validation. The experiment also highlights the limitations of using the models to monitor and retrieve soil moisture information for a wide range of desert surfaces, unless certain assumptions are made. If it is assumed, that surface roughness is constant over an annual timescale, then retrieval of soil moisture should be possible. Model simulation shows that this is relatively independent of RMS height. If surface roughness does change over the year then soil moisture information will be erroneous; greatest for the smooth surfaces (*qaas*, smooth *marabs*) and negligible for rough surfaces (*harrat*, rough *marabs*) unless the magnitude of the variations are known. This problem is being approached by making roughness measurements during different climatic seasons and using the range of backscatter coefficients derived from multi-temporal ERS SAR imagery as a guide to indicate what surface processes may be occurring. Future research will be focused on:

(i) Increasing the sample dataset for model validation using ERS-2 SAR data.

(ii) Investigate alternative and complimentary measures that characterise surface roughness such as power spectrum analysis.

(iii) Investigate the influence of arid dryland vegetation on the backscatter response both qualitatively, by comparing image texture with field observations, and quantitatively with field measurements of vegetation parameters.

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