# Production and validation of BRDF and albedo extracted from airborne and spaceborne data

M. I. Disney and P. Lewis
*Remote Sensing Unit, Dept. of Geog., UCL, UK.*

J.-P. Muller
*Dept. of Photogrammetry & Surveying, UCL, UK*

M. J. Barnsley
*Remote Sensing Unit, Dept. of Geography, Univ. of Wales, Swansea, UK.*

ABSTRACT: Although not an intrinsic surface property, an approximation to albedo can be derived from sparse samples of directional reflectance from remote sensing data by use of models of the Bi-directional Reflectance Distribution Function (BRDF). Directional reflectance of a millet canopy generated from manual measurements and a 3D canopy reflectance model - the Botanical Plant Modelling System (BPMS) - has been simulated to study the factors affecting canopy reflectance. Comparisons have been made between the simulated reflectance and albedo and estimates derived using kernel-driven BRDF models using airborne remotely sensed data. Albedo has been derived at satellite scale through extrapolation of BRDF model parameter information generated at the airborne scale.

## 1. INTRODUCTION

There is a requirement for accurate and rapid global measurement of the characteristics of the Earth's surface which can potentially be fulfilled by remote sensing. The measured reflectance of a point on the Earth's surface depends on the conditions under which that point is both viewed and illuminated. This dependence is described by the bi-directional reflectance distribution function (BRDF) (Nicodemus et al. 1977). One approach to investigating the BRDF has been to exploit the directional element of surface reflectance by designing sensors with the capability of viewing from a number of different angles e.g. the NASA Advanced Solid-state Array Spectrometer (ASAS) (Irons et al. 1991) and the forthcoming Moderate Resolution Imaging Spectrometer (MODIS) instrument on the NASA Earth Observing System (EOS) (Wanner et al. 1997) . There has been a concurrent development of modelling techniques for investigating the reflectance of vegetation canopies (Goel, 1988; Strahler, 1994). Given a model of vegetation canopies, driven by measurable biophysical parameters such as leaf area index (LAI) it is possible to invert such models against measured reflectance data to obtain estimates of these biophysical parameters. Such models typically assume a homogeneous canopy, so alternative strategies must be employed when considering applications to moderate resolution satellite data over heterogeneous areas such as that found in the Sahel. One approach to modelling such situations, outlined below, shows much promise for describing and normalising directional reflectance and deriving albedo, but products derived from such techniques need to be further validated.

### *1.1 3D BRDF modelling*

One technique for canopy reflectance modelling involves creating 3D plant structure and topology information and associated numerical techniques for solving for radiation transport (Monte Carlo ray tracing - MCRT, Lewis & Muller 1992). Using a model such as the Botanical Plant Modelling System (BPMS), (Lewis 1996; Lewis & Boissard 1997) a detailed simulation of canopy reflectance can be made for comparison with measured data, and additional information on components of the radiation (single- and multiple-scattering, direct and diffuse components etc.) can be calculated to aid an understanding of the influence of canopy structure on the simulated reflectance.

### *1.2 Kernel-driven BRDF models*

Whilst such a model is useful for understanding factors affecting canopy reflectance and validation of alternative modelling strategies, it cannot be directly inverted due to the complexity of the model parameterisation. A more practical approach for model inversion has been developed for the description of BRDF, normalisation of directional reflectance effects and the derivation of surface albedo (Roujean et al. 1992; Wanner et al. 1995) from current and forthcoming satellite data. Algorithms based on such a model are being used to process data from the POLDER instrument on ADEOS (Deschamps et al. 1994) and MODIS and MISR instruments on EOS (Wanner et al. 1997). In these ‘kernel -driven’ models, the BRDF is decomposed into a linear combination of BRDF ‘shapes’ or ‘kernels’. These kernels can be derived from approximations to physical theory, such as the RossThin kernel derived from considerations of single scattering in a turbid medium making assumptions of low LAI. Similarly, the RossThick kernel is derived by performing a linearisation assuming a high LAI. A set of kernels are also defined for processing the EOS data based on surface shadowing considerations (geometric optics theory), known as the Li kernels (Wanner et al. 1995). These kernels are formed by considering a distribution of spheroids on a surface. Various approximations to the theory lead to two main kernels: LiSparseModis and LiDenseModis, based on assumptions of sparse and dense distributions of scatterers. In addition, kernels can be formed from purely empirical functions, such as the modified Walthall function (Walthall et al 1985; Nilson & Kuusk 1989).

*1.3 Reflectance and albedo in HAPEX Sahel*

The purpose of this paper is to present a number of methods for modelling BRDF and deriving estimates of albedo from remote sensing data. A 3D model of a plant canopy is used to help understand factors affecting canopy reflectance and to compare with remote sensing data. Airborne remote sensing data is used as the main data source in the experimentation. Aspects of the algorithm proposed for the EOS MODIS and MISR BRDF/Albedo product are tested on these data and spatial maps of albedo produced.

Data on the 3D geometry of millet plants were measured during the HAPEX Sahel field campaign in Niger in September 1992. The use of these data in simulating canopy reflectance and albedo and understanding the factors affecting these is described in this paper. Airborne directional reflectance measurements were collected by the NASA ASAS instrument. A comparison was made of the simulated and measured millet reflectance data, which is presented below. The ASAS data were also inverted against the kernel-driven models and used to produce spatial maps of the model parameters over the extent of the ASAS data. The model parameters were used to derive estimates of albedo from the airborne data, which are also compared with simulations using the 3D models.

Finally, as the ASAS data have a rather limited spatial extent (around 1.5 km by 1.5 km), a technique for the spatial extrapolation of the BRDF information derived from these data was developed, making use of TM data over a larger spatial extent.

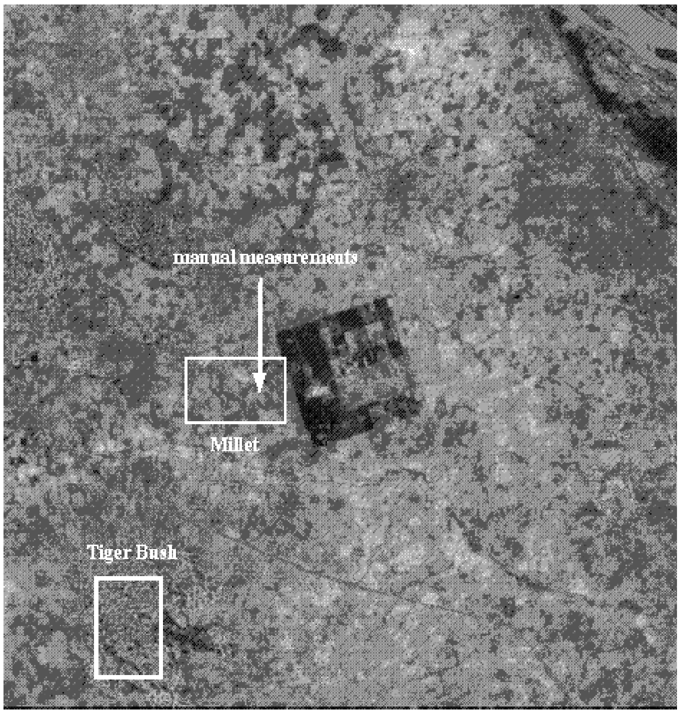



Figure 1. TM Southern supersite subscene - ASAS coverage of millet and tiger bush areas are marked, as is the area where 3D geometric measurements of millet were made

Figure 1 shows TM coverage (in the visible red band) of the HAPEX Sahel Southern Super Site, with ASAS Tiger Bush and millet coverage marked. Also marked is the area within the ASAS images where the 3D measurements of individual millet plants used in the BPMS simulations were made.

## 2. METHODOLOGY AND RESULTS

Directional reflectance simulations generated from 3D modelling are described and discussed, followed by experiments at the scale of airborne data. Finally, results of extrapolations of BRDF model parameter information from the airborne scale through to satellite resolution are presented and discussed.

### *2.1 BPMS modelling of a millet canopy*

Detailed manual geometric measurements were made of five millet plants in the HAPEX Sahel Southern Super Site during September 1992. Topological descriptions of the plants along with characterisations of features such as stem and leaf lengths, inclination and leaf curvature were recorded.

These data have been used within the BPMS to construct accurate 3D models of the millet plants.

The BPMS is a model designed to interpret data from as wide a variety of sources as possible (e.g., 3D photogrammetric data, manual measurements etc.) and construct 3D representations of plant models (Lewis & Boissard, 1997). A 'field' of plants is constructed according to some planting pattern and planting density. The defined (measured) plant models are distributed over the field (cloned) according to some probability of occurrence of each individual model. All elements within the scene are assigned material properties, describing, for instance, leaf reflectance and transmittance properties. Radiometric simulations of the canopy are carried out using MCRT (Lewis & Muller, 1992). A major advantage of the BPMS is the ability it gives the user to easily derive detailed information regarding the behaviour of reflected radiation (contributions to reflectance as a function of scattering order, proportions of sunlit and shaded scene components, contributions from direct and diffuse illumination, detailed characterisation of leaf angle distribution and leaf area density etc.).

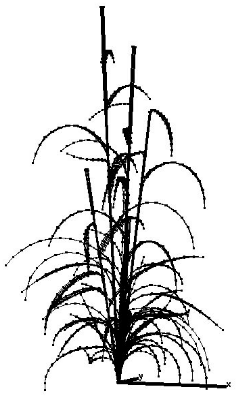


Figure 2. Wireframe view of millet plant generated by the BPMS.

One of the measured millet plants is shown as a wireframe model in figure 2. A millet canopy was constructed by randomly distributing 'clones' of the five plants on a rectangular grid. The row and plant spacing was 2m. The PROSPECT model (Jacquemoud & Baret 1990) was used to generate leaf and stem spectral reflectance and transmittances. A set of soil spectral directional reflectance measurements made in the Sahel were also included.

MCRT simulations were carried out using a diffuse sky radiance function, at 4 wavelengths, 498nm, 535nm, 666nm and 800nm (corresponding to four wavebands of the ASAS instrument). Using the BPMS, any number of sampling regimes can be approximated. In this case, reflectance was simulated at a dense set of view and solar zenith angles. An orthographic camera projection was used, which allows the same area on the surface to be viewed despite the changing camera position.

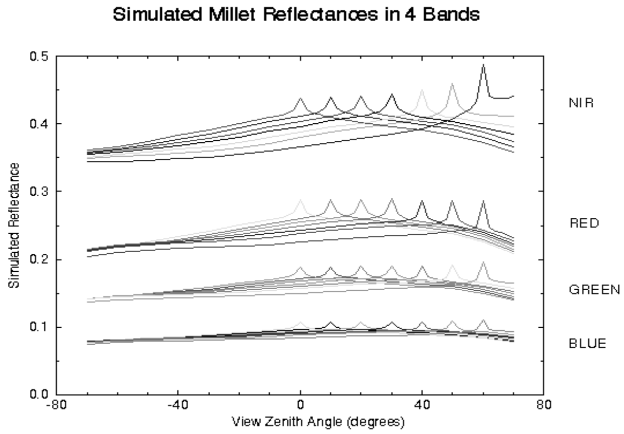



Figure 3 - Dense sampling simulation with solar zenith varying from 0 to 70 degrees in 10 degree steps.

Densely sampled directional reflectances of the simulated millet canopy are shown in figure 3. View zenith varies from -70$^{o}$ (forward scattering direction) to 70$^{o}$ (back scattering direction) in steps of 10$^{o}$, and solar zenith varying from 0 to 70$^{o}$. View zenith sampling is increased to every 2$^{o}$ in the 10$^{o}$ either side of the hot-spot direction to allow the fine structure of the hot-spot feature to be fully explored.

The simulated millet reflectances display the expected trends for such a vegetation canopy: a gradual rise in reflectance with increasing view zenith angle up to a pronounced, relatively narrow hot-spot feature, followed by a reduction in reflectance as view zenith increases beyond the hot-spot point. The strong reflectance in the red band is due to the high contribution of the soil component within the sparse canopy (Lewis & Boissard 1997).

In the BPMS approach, the single and multiple scattering components of the diffuse and direct radiation can all be separated. In addition, the degree of attenuation at each scattering interaction can be calculated, as can the sunlit and shadowed proportions of each of the canopy primitives (soil, leaf, stem etc.). This is a powerful way of exploring how BRDF models can describe a surface.

Figure 4 shows the total diffuse and direct components contributing to the simulated reflectance. The diffuse component of reflectance is the directional hemispherical reflectance, and is thus part of the albedo equation in the case of isotropic illumination (Lewis & Barnsley, 1994). The single scattered component dominates (see Lewis & Boissard, 1997), with the multiple scattered component contributing very little to the resultant reflectance (around 15% in the near infrared and less than 4% for other wavebands - see Lewis and Boissard figure 12).

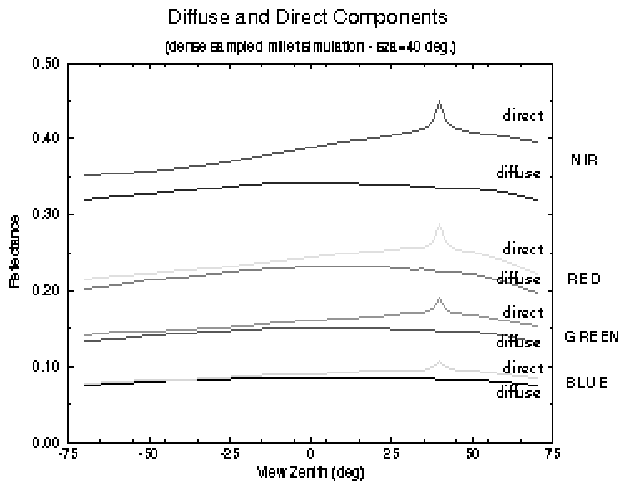



Figure 4 - total diffuse and direct components of reflectance for the millet simulations.

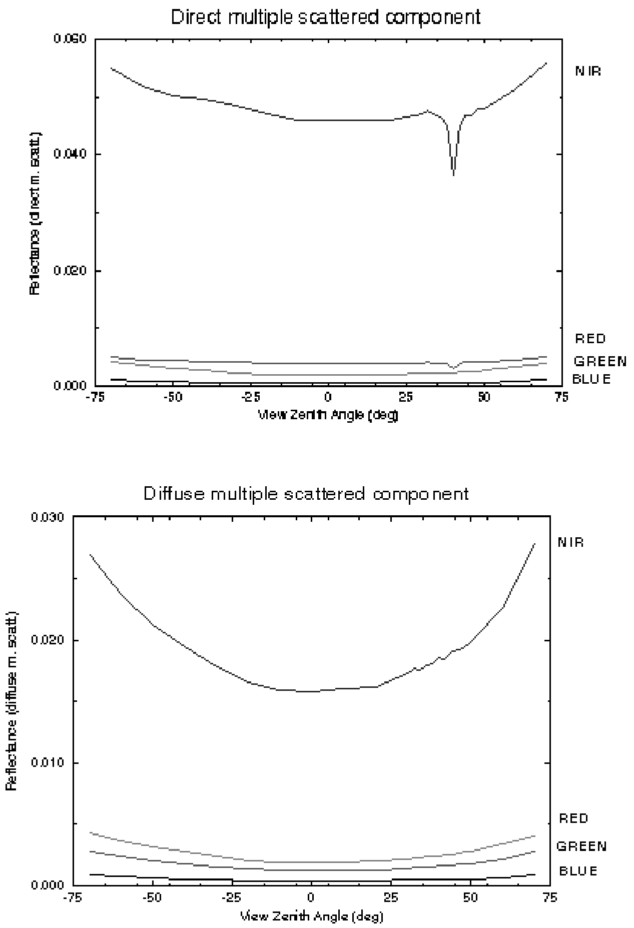
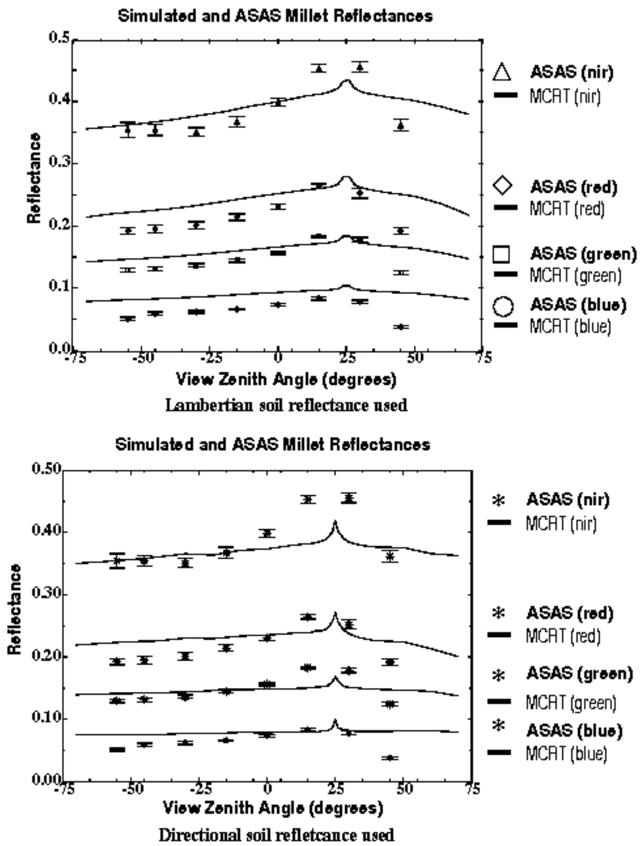



Figure 5 a (top) and b (bottom) - direct and diffuse elements of the multiple scattered component of soil reflectance.

Figures 5(a) and 5(b) show the direct and diffuse elements of the multiple scattered component of canopy reflectance. The NIR contribution is far higher than that from the visible region, as expected, due to the high NIR reflectance of the vegetation and soil.

Analysis of the separate shadowed and sunlit components of the simulated millet canopy reflectance (Lewis & Boissard 1997 figures 13 and 14) show clearly that the shape of the BRDF is controlled by the amount of sunlit material (mainly soil) which is visible. The ability to analyse the prorportions of sunlit and shadowed components within the canopy in this manner also aids understanding of BRDF models. The behaviour of the geometric optics (Li) kernels describe the scattering of geometric shapes arranged on a reflecting surface, and so are controlled by the proportions of sunlit and shaded crown and soil.

A comparison between the simulations and millet reflectances extracted from a relevant area within the ASAS data is shown in figure 6. A Lambertain soil reflectance was assumed for simulations presented in figure 6(a), and measured directional soil reflectance data used in the results of figure 6(b). The agreement is good, particularly in the case where directional soil reflectance has been




used. Differences are likely to be due in large part to (i) uncertainties in the ASAS reflectances caused by atmospheric correction, particularly in the blue band (ii) errors in registration (iii) lack of precision in the accuracy of sensor pointing. The broader hot-spot feature of the ASAS reflectances may be caused by smoothing due to averaging across 5x5 pixels; the plant and row spacing of the modelled plants being underestimated; incorrect modelling of the millet row orientation; or the presence of bushes etc. at the edge of the millet field. If parameters such as LAI are to be derived from such simulations, greater care is needed in determining the cause of these differences.

*2.2 Summary*

The success of the BPMS as a simulation and analysis tool has been demonstrated by the production of directional reflectance from manual measurements of individual millet plants. BRDF can be calculated, and comparisons with ASAS reflectance values show good agreement. Detailed information regarding scattering processes within a canopy, including the direct and diffuse components of singly and multiply scattered reflectance, can be extracted. This information is extremely useful in the analysis of the behaviour of linear BRDF kernels

## 3 BRDF FROM ASAS DATA

Directional radiance data of five sites (including Tiger Bush and millet) recorded by the airborne NASA ASAS instrument during HAPEX Sahel, 1992, have been processed to produce directional reflectance (Barnsley et al. 1997). The data are multi-spectral and obtained at 9 separate view zenith angles (-55$^{o}$ back to 70$^{o}$ forward). Several flight lines covering each site were obtained, both in the principal and cross principal planes, and at a variety of solar zenith angles. The data were accurately co-registered to the nadir images using registration software developed at UCL (Allison et al. 1994). The data were atmospherically corrected using the 6S software (Vermote et al. 1994), to produce at-ground directional reflectances. A continental aerosol model was used, following de Colstoun et al. (1996).

*3.1 BRDF model inversions*

The atmospherically corrected ASAS directional reflectance data were inverted against the AMBRALS model, a collection of linear BRDF kernels designed for processing data from the MODIS instrument. Different kernels are combined to form separate model combinations (along with an isotropic component) and the choice of which set of kernels is best suited to a particular pixel is made by using a weighted function of the rms error in model inversion. The kernels used are the volume scattering (Ross), geometric optics (Li) and an empirical model (Walthall) (see section 1).

ASAS data have been combined from 4 flight lines (2 dates), giving 32 angular samples of the surface. Model parameter information obtained from inversion of the AMBRALS kernels against the reflectance data of the Southern Super Site millet area are shown in figure 7. From top to bottom the images show the Isotropic, RossThick and LiSparseModis parameter information of the red band (666 nm). Using this parameter information generated from the model inversions, albedo is calculated as a linear weighting of the model parameters (Lewis 1995).

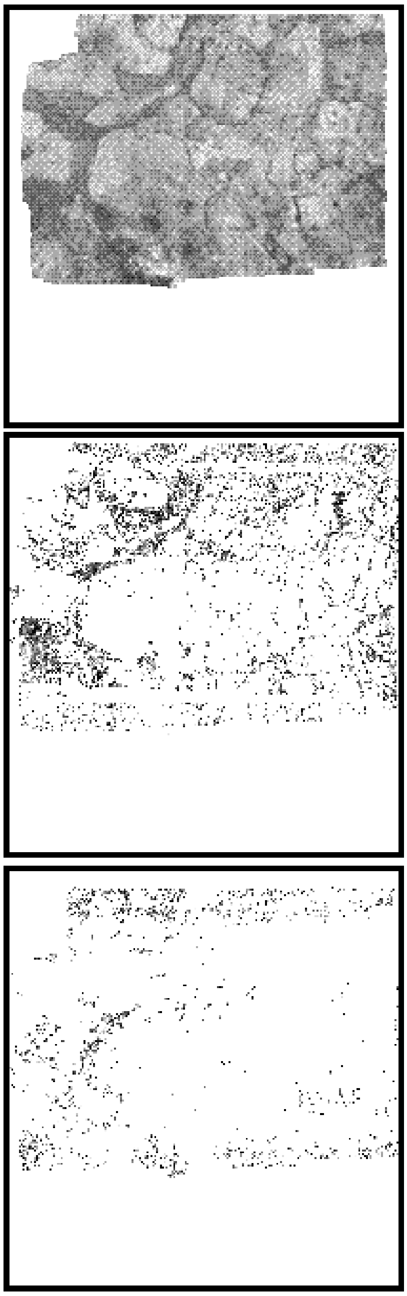
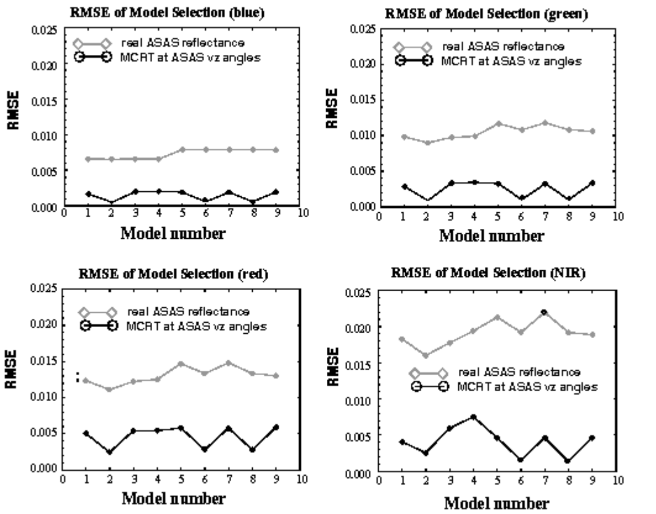


Figure 7 - Isotropic, RossThick and LiSparseModis parameters (top to bottom) for the ASAS Southern supersite millet area. Data are scaled: 0-0.6; 0-0.04; and 0-0.01 respectively for the three parameters.

Figure 7 suggests that the majority of reflectance information is contained within the isotropic parameter, and consequently the albedo will largely be controlled by this. The geometric optics and volume scattering kernels, the directional components of surface reflectance, contain successively lower magnitude information, but the variation described by these is still significant as the surface reflectance is still non-Lambertian. This demonstrates the ability of linear BRDF models to extract information on the spatial variability of directional reflectance, whilst highlighting the difficulty of accurately charaterising the directional component which may be orders of magnitude smaller than the isotropic component.

Figure 8 shows a comparison between the root mean squared error (RMSE) in model inversion for each of the kernel combinations for both the 5x5 pixel ASAS millet area and the simulated millet reflectances described in section 2. Of the 3 parameter cases (model numbers 5, 6, 7, 8 and 9 in figure 8) the same kernel combinations have low RMSE in both the simulation and ASAS cases, confirming that the simulated millet canopy is a good approximation to the real case.




**Model numbers as follows: 1=LiDenseModis; 2=LiSparseModis; 3=RossThick; 4=Ross Thin; 5=RossThick+LiDenseModis; 6=RossThick+LiSparseModis; 7=RossThin+LiDense Modis; 8=RossThin+LiSparseModis; 9=3 parameter Walthall model. All models include the isotropic parameter.**

Figure 8 **-** root mean squared error in model inversion for the simulated and ASAS reflectances.

These results suggest that the simulated millet canopy has a comparable reflectance to that of the millet measured by ASAS. The same models (numbers 6 and 8 in figure 8) are selected on the basis of RMSE in both cases. This represents the combination

Isotropic + Ross(Thick/Thin) + LiSparseModis (1)

Figure 9a shows a comparison between the directional hemispherical reflectance simulated with the BPMS and that generated by a kernel-driven model inverted against the ASAS data. The magnitudes are very similar except in the NIR, whilst there is some divergence of the shapes at more extreme view zenith angles. The reason for the discrepancies may be due to the rather limited solar zenith angle variation encountered in the ASAS data. This is explored in figure 9b. BPMS simulations of millet canopy reflectance were calculated at the same viewing and illumination geometries as the ASAS data. These data were then inverted against the kernel-driven BRDF models to provide model parameters for the Isotropic, RossThick and LiSparseModis kernels. These parameters were then used to derive directional-hemispherical reflectance as a function of solar zenith angle and compared with the values obtained from inverting the measured ASAS data (figure 9b).

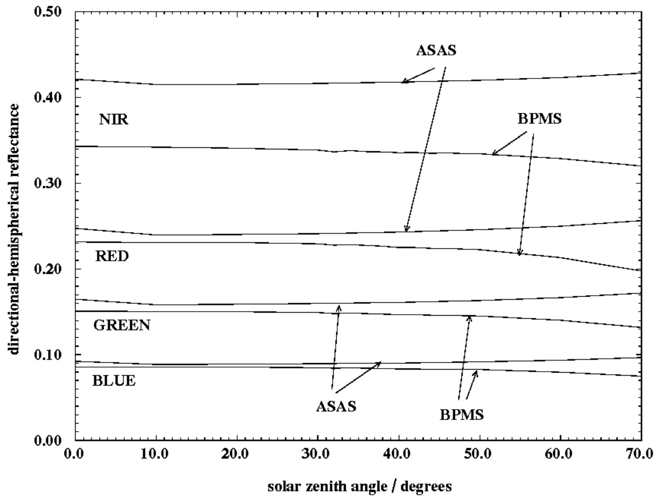



Figure 9a **-** comparison of BPMS modelled directional hemispherical reflectance and that derived from ASAS using the RossThick and LiSparseModis kernels

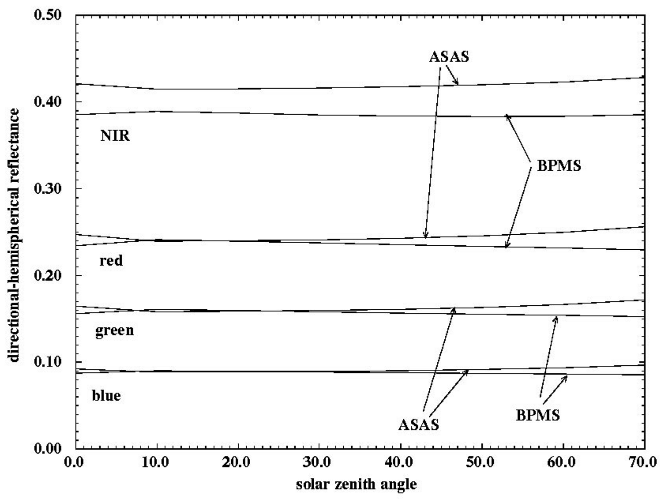



Figure 9b **-** comparison of BPMS directional reflectance modelled at the same viewing/illumination angles as the ASAS data and inverted against the RossThick and LiSparseModis kernels to derive hemispherical reflectance with that derived from ASAS using the same kernels

If we accept the directional-hemispherical reflectance calculated from the BPMS to be representative of the actual values for the millet canopy, figure 9a suggests that there can be a relatively large discrepency between this and that calculated using the linear models.

It is not clear from figure 9a alone whether this is due to discrepencies between the measured (ASAS) data and the simulated (BPMS) data or the inability of the kernels to represent the BRDF shape correctly. Figure 9b supports the view that the error in modelling albedo shown in 9a is due mainly to sampling issues as there is much closer agreement between the modelled albedo values in this case.

*3.2 Summary*

The ability of kernel-driven BRDF models to extract information regarding the spatial distribution of reflectance from angular data has been shown through the generation of linear BRDF parameter information from airborne data of the Sahel. The success of the BPMS approach has been further demonstrated, with BRDF model selection in the simulated and ASAS cases showing very similar trends. The millet reflectance appears to be best characterised as a combination of either one of the Ross kernels, and the LiSparseModis kernel.

Directional hemispherical reflectance was generated for the simulated millet canopy, and compared to ASAS generated albedo. The magnitudes are very similar, except in the NIR, but this may be due to angular sampling issues associated with the ASAS data.

## 4. MAPPING TO TM SCALE

In order to generate albedo over a wider spatial area than covered in the relatively small ASAS areas, a method was developed for extrapolating model parameter information generated from the ASAS data through to the scale of Landsat TM. The ASAS millet and Tiger Bush areas were located within the TM coverage (see figure 1). The TM data were then radiometrically shifted to match the ASAS data. The ASAS data were spatially degraded to match the resolution of the TM data, and the TM scene 'classified' with a minimum distance classification algorithm. In the classification process, each ASAS pixel is defined as a separate class. This allows model parameter information generated from the ASAS BRDF model inversions to be mapped to the correspondingly classified pixels within the TM scene. In this way the TM scene can be described in terms of the ASAS data. The extrapolated parameter information was then used to calculate albedo at TM scale in the manner described in equation (1) i.e.

$$\alpha = \text{Isotropic} + W_1 * (\text{RossThick}) + W_2 * (\text{LiSparseModis}) \quad (2)$$

where $\alpha$ is albedo; Isotropic is the isotropic parameter, and $W_1$ and $W_2$ are the angular integrals of the respective kernels.

Figure 10 shows the resulting 'albedo' (directional-hemispherical reflectance at a solar zenith angle of 40°) of the Southern Super Site at TM scale in the visible red band. Albedo was generated using the isotropic, RossThin and LiSparseModis kernels. Not surprisingly, it appears very similar to the TM reflectance of figure 1 as it is dominated by the isotropic component.

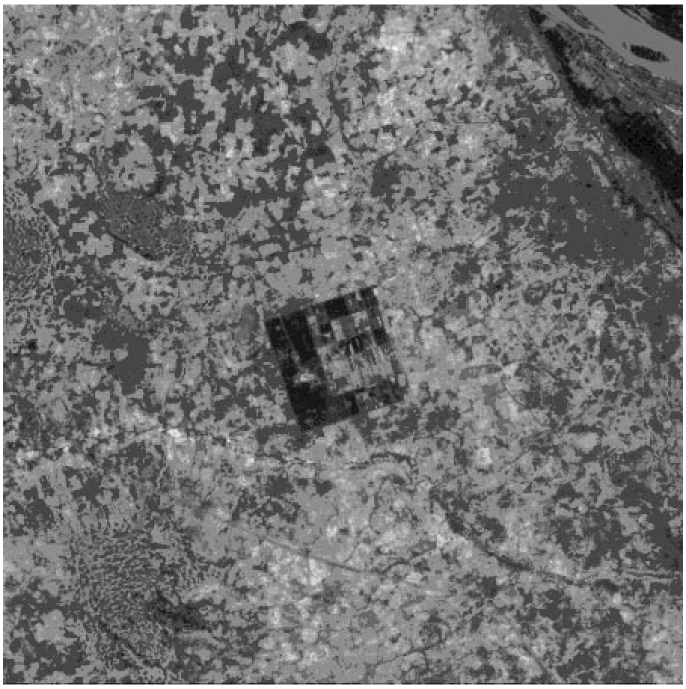


Figure 10 - Albedo at 666nm at TM scale.

If this technique can be successfully validated by comparison of the generated albedo with ground-based measurement or coarser-resolution satellite data then it seems a fast and flexible way to generate albedo at a variety of scales from a single directional data set. A significant difficulty in this case, however, has proved to be the lack of availability of relevant ground-based albedo data and uncertainty associated with the calibration of coarser resolution datasets.

*4.1 Summary*

A method has been developed which allows the extrapolation of BRDF model parameter information from derived from airborne ASAS data (3m resolution) to the scale of Landsat TM (30m resolution). Using BRDF parameters generated from the ASAS data, albedo has been calculated for the

HAPEX Sahel Southern Super Site at 30m resolution. Whilst the technique looks interesting and potentially very useful, it has yet to be validated.

## 5. CONCLUSION

Using the BPMS, a 3D millet canopy has been constructed, and MCRT simulations of this canopy have been performed. The results agree well with ASAS millet directional reflectances.

Using linear BRDF modelling techniques, model parameter information has been generated from a set of airborne directional reflectance.

The millet area within the ASAS data appears best characterised by a combination of the isotropic RossThick and LiSparseModis kernels. The trends in the RMSE of model selection are common between the simulated and ASAS reflectances suggesting the modelled canopy is an accurate representation of a real canopy. Albedo was generated from the millet simulations, and compared with that from ASAS. The magnitudes were very similar except in the NIR band. This was shown to be mainly a sampling issue associated with the data available from the ASAS instrument.

A method was developed for extrapolating BRDF parameter information from the ASAS to TM resolution. In this way, albedo was calculated at TM resolution for the HAPEX Sahel Southern super site at TM (30m) resolution. This method could be used to extrapolate to coarser resolution such as AVHRR.

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