ISBN 0 86076 150 9

PRIFYSGOL CYMRU ABERTAWE
UNIVERSITY OF WALES SWANSEA

"Reflections on a changing planet: observing the Earth from space"

by

Professor Michael J Barnsley

20th October 1997

First published 1997 by University of Wales Swansea

Obtainable from:

The Department of Planning and Marketing
University of Wales Swansea
Singleton Park
Swansea
SA2 8PP

ISBN 0 86076 150 9

University of Wales Swansea

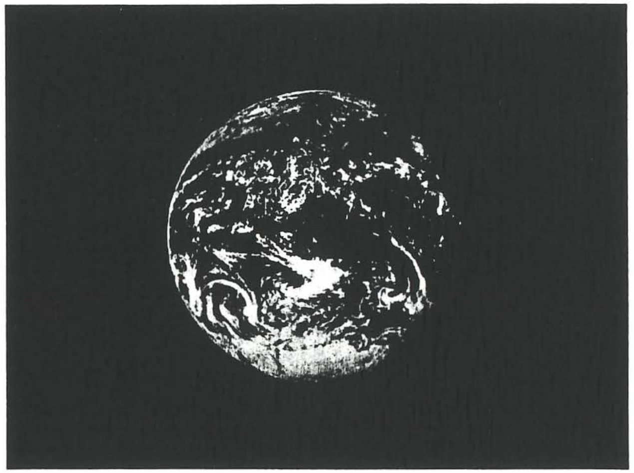
20th October 1997

"Reflections on a changing planet: observing the Earth from space"

by

Professor Michael J Barnsley
Research Professor in Physical Geography

Reflections on a changing planet: observing the Earth from space



Michael John Barnsley
Research Professor of Remote Sensing and Geographical Information Systems

Department of Geography,
University of Wales Swansea,
Singleton Park,
Swansea SA2 8PP, U.K.
m.barnsley@swan.ac.uk
http://www.swan.ac.uk/geog/mjb/mikeb.htm

Contents

List of Figures

1 Observing the Earth from space

The frontispiece shows a photograph of the Earth that was taken in December 1972 by an astronaut on board Apollo-17. Set amid the deep black of space, it shows with great clarity the intricate pattern of clouds encircling the Earth — a function of the complex circulation of water vapour, as well as other gases and particulate matter, within the atmosphere. Beneath the clouds we can see the land masses of Africa, the Arabian peninsula and, far to the south, ice-covered Antarctica. Elsewhere, it is just possible to make out the patterns of vegetation and soils on the land surface. It is an extraordinary view of our ever-changing planet — one that seems not to have become hackneyed despite the numerous times that it has been reproduced. It doesn't really matter that it was not the first such image to be acquired from space, or even that the technology used to capture it has long-since been superceded by digital devices: it, and others like it, have helped to provide us with a new perspective on our planet. By viewing the Earth from space, we distance ourselves — both physically and metaphorically — from the complex environmental systems that represent our natural laboratory and begin to train an objective 'microscope' upon them.

In this presentation I intend to explore the broad subject matter of observing the Earth from space — or 'remote sensing' as it is also known — as well as my personal research in this field. The impetus for both derives in large measure from the growing public and, hence, political concern about environmental issues at local, regional and global scales. I will attempt to show that Earth Observation has a key role to play in providing timely, consistent and objective data sets that may be used to study many environmental processes. For example, Figure 1 presents a satellite sensor image of the Mississippi River during a recent, extensive flooding event. The image, which covers an area of many hundreds of square kilometres, clearly shows the extent of flooding and, if we were to examine it in greater detail, the depth of flooding. As a second example, Figure 2 shows the use of satellite remote sensing to observe the oil-well fires started towards the end of the recent Gulf war. The image shows the individual well-head fires and the large plume of dense black smoke that extends for over a hundred kilometres to the south.

The scientific response to these environmental issues, in terms of the development and application of Earth Observation techniques, has been widespread and involves a host of different nations. The magnitude of the investment in this technology is perhaps best exemplified by NASA's "Mission to Planet Earth" programme and its associated suite of satellite-based sensors — known as the Earth Observing System — a programme in which I and my colleagues are very closely involved. "Mission to Planet Earth" is a multi-billion dollar project intended to increase our understanding of the Earth as a set of dynamic, interacting environmental systems. It aims to provide the technical means by which we can monitor the state of these systems and to measure the exchange of energy, mass and momentum between their component elements. Ultimately, the goal is to understand the impact of mankind on a range of natural systems: to determine our contribution to recent trends in, for example, atmospheric carbon dioxide.

Having established the broad credentials for Earth Observation, it is now appropriate to examine the science and technology that underpin it. It is, I believe, an exciting and dynamic subject one that brings geographers, like myself, together with engineers, physicists, computer scientists, mathematicians and many others.

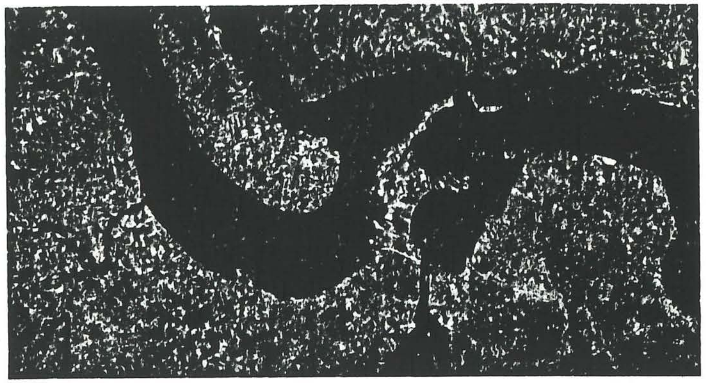


Figure 1: A Landsat-TM image of part of the Mississippi River during a recent flooding event (original in colour).

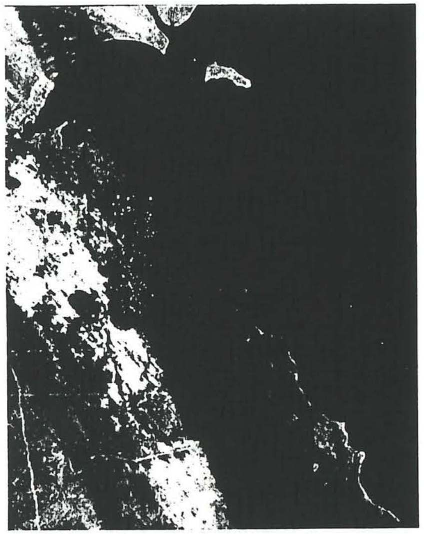


Figure 2: A Landsat-TM image over Kuwait, showing the oil-well fires started towards the end of the Gulf war in 1992 (original in colour).

2 Introduction to Satellite Remote Sensing

Broadly speaking, remote sensing encompasses the set of instruments and techniques used to obtain information about the Earth surface — including its atmosphere and oceans — without being in direct with them (hence, 'remote' sensing). This is achieved by measuring the energy, propagated in the form of electromagnetic radiation, emanating from the observed surface. Depending on its wavelength, the radiation might be manifested in the form of reflected 'light', emitted thermal energy, or scattered microwave radiation.

In practice, however, remote sensing is rarely straightforward. Few of the physical, chemical or biological properties that are of interest to environmental scientists can be measured directly by remote sensing. Instead, they must be inferred from observations of radiation reflected, emitted or scattered from the surface, together with the variation in these measurements as a function of wavelength, direction, polarization, phase, space and time. As a result, the values derived from remotely-sensed data are almost always *estimates* of the true quantities. The processes of *inference* and *estimation* therefore lie at the heart of remote sensing: it is, after all, the science of detection and, like all good detective stories, it involves the analysis of a limited number of clues to solve a specific problem. Instead of asking "whodunnit?", however, the questions that we pose are "what is it?" and "what are its properties?"

The image presented in Figure 3 can perhaps be used to illustrate, albeit somewhat facetiously, the process of inference. Thus, a detailed examination of the image suggests that it may have been acquired on a warm Sunday afternoon at some point during the summer. We can infer that the image was acquired in the summer because of the healthy appearance of the green vegetation and the relatively short shadows cast by the University buildings. We can deduce that it was probably a Sunday afternoon due to the fact that the University car parks are empty, while that of the "Pub on the Pond" is full. On the other hand, it could have been an ordinary weekday lunchtime!

Although remote sensing — particularly that involving spaceborne sensors — is still a relatively young science, the technology continues to develop rapidly. In this presentation, I will focus exclusively on digital sensors — that is, instruments that record the detected radiation directly in numerical, as opposed to analogue, form. Digital sensors have many advantages over their analogue counterparts, such as photographic systems. They can be designed to operate throughout the electromagnetic spectrum — that is to record visible light, as well as thermal and microwave radiation. They also permit prolonged operation on board Earth-orbiting satellites. In this context, the data recorded by spaceborne systems can be transmitted directly to Earth when the satellite is within range of a ground receiving station, or they can be relayed via a telecommunications satellite in a much higher Earth-orbit. One further advantage of spaceborne sensors is that they can provide data coverage for the entire globe.

Most satellite sensors currently in operation are what are known as 'multispectral' devices — that is, they record data in the form of images in more than one part of the electromagnetic spectrum. By judicious choice of the wavelengths at which these data are sampled, it often possible to generate images that allow one to distinguish different types of surface material — for example, different land cover types — or to estimate their physical and chemical properties. Figure 4 (right) shows the fraction of energy from the Sun that is reflected by two broad land-

Figure 3: Airborne scanner image of the main campus at the University of Wales Swansea (original in colour). Image data courtesy of the Natural Environment Research Council.

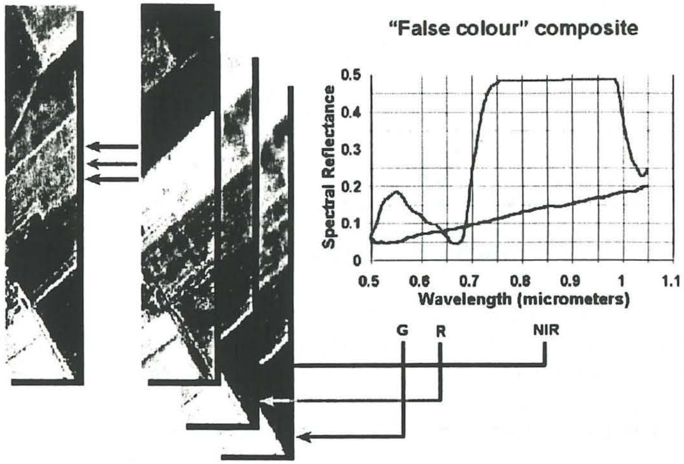


Figure 4: Spectral reflectance curves for green leaves and soil at visible and infrared wavelengths (original in colour). Image data courtesy of the Natural Environment Research Council.

cover types, namely vegetation and soil, and its variation through part of the electromagnetic spectrum. For example, vegetation reflects less than one tenth of the incident sunlight at those wavelengths corresponding to what the human eye perceives as blue and red light. Most of the radiation that is not reflected at these wavelengths is used by plant pigments, such as chlorophyll, for photosynthesis. One the other hand, vegetation reflects up to one fifth of the incident sunlight at green wavelengths, which is why the human eye perceives vegetation as being green. At still longer wavelengths, in a part of the electromagnetic spectrum known as the 'near infrared' (or 'NIR'), vegetation reflects almost half of the incident solar energy. This illustrates the relationship between the physical and chemical properties of a surface material and its reflectance characteristics — a relationship that remote sensing seeks to exploit, by measuring reflectance and attempting to estimate the driving biophysical properties.

Unfortunately, space does not permit an explanation of the factors controlling the reflectance of soil surfaces, but one should be able to see from the graph in Figure 4 that there are parts of the spectrum in which the reflectance of vegetation and soil differ markedly. If digital image data are recorded at some of these wavelengths — for example, at green, red and near-infrared wavelengths — it is possible to display these data separately through the red, green and blue colour guns of a computer monitor to produce what is commonly known as a "false-colour" image (Figure 4; left). These are so-called because the colours in the image differ from those that would be seen by the unassisted human eye. In Figure 4, for example, it is possible to identify a number of different crop types, and to distinguish these from areas of bare soil.

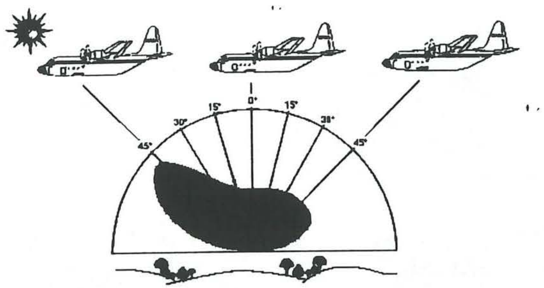


Figure 5: Schematic representation of the Bidirectional Reflectance Distribution Function (BRDF), which describes how surface materials reflect radiation according to the angles at which they are illuminated by the Sun and viewed by the sensor.

3 Estimating Land-Surface Biophysical Properties

Having provided a brief introduction to some of the principles of Earth Observation, I would now like to discuss several areas of my own research. The first of these concerns my involvement in a number of future satellite sensor missions that are intended to provide global data-sets on a range of biophysical properties of the Earth surface, such as maps of vegetation biomass, land-cover type and surface albedo. These and other parameters will be routinely monitored from space using comparatively coarse spatial resolution sensors — that is, instruments that map features on the Earth surface in terms of 1km square cells: these are rather perversely known as 'moderate' resolution instruments. The intention is that resultant 'data products' will be made available to the relevant user-communities, such as global climate modellers, so that they can be assimilated within their own studies and models.

The focus of my attention, and that of my colleagues Prof. Peter Muller and Dr. Philip Lewis at University College London and Prof. Alan Strahler of Boston University in the USA, has been an investigation of the directional reflectance characteristics of Earth surface materials — or, more properly, the Bidirectional Reflectance Distribution Function (BRDF). The function behind this particularly indigestible acronym describes how the apparent reflectance of a surface varies according to the angles at which it is illuminated by the Sun and viewed by the sensor. The BRDF, which is represented schematically in Figure 5, is of interest for two reasons. First, it provides the means by which we can accurately estimate the albedo of Earth surface materials. Albedo is a parameter that is of considerable importance to climate modellers and, broadly speaking, refers to the ratio of the amount of radiation reflected from a surface (over all possible angles of reflection) to the amount of radiation incident on that surface. This is shown diagrammatically in Figure 6.

The second reason that we are interested in the Bidirectional Reflectance Distribution Function is because it is a function of the physical and chemical structure of the reflecting surface. This is shown graphically in Figure 7. The image of the far left of Figure 7 is a standard, false-colour composite produced using data sampled at green, red and near-infrared wavelengths — in fact, it covers the same area of ground as Figure 4. The two images in the centre of Figure 4, on the other hand, have each been constructed using data recorded in a single part of the electromagnetic spectrum (visible green and red wavelengths, respectively), but at three different sensor view angles (two oblique and one looking directly downwards; represented schematically on the far right of Figure 7). Since each of the land cover-types present in this scene has a somewhat different three-dimensional, geometric structure, each reflects different amounts of radiation at any given angle. This is represented in these images as differences in colour, so that we are able to distinguish surfaces that differ in terms of physical structure using multi-angle data and, perhaps, to estimate their biophysical properties. Although the relationship between directional reflectance and surface structure had been known for some time, we were perhaps the first group to demonstrate the relationship so clearly using image data.

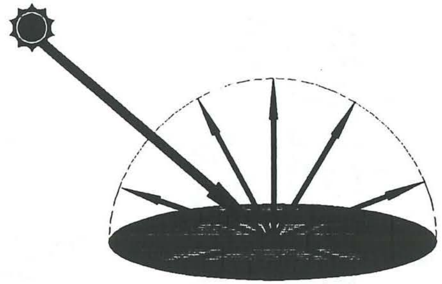


Figure 6: Schematic representation of directional-hemispherical reflectance (albedo).

As I mentioned previously, we are involved in several satellite sensor missions that are being designed, in part at least, with the intention of acquiring image data at different view angles with respect to the Earth surface. These include the joint French and Japanese venture known as POLDER, which was launched almost one year ago. Unfortunately, POLDER recently suffered a severe technical failure and is no longer operational. Other sensor systems in which we are involved include NASA's MISR and MODIS instruments — the first of which is show in Figure 8 — and the French VEGETATION sensor. The MISR instrument is particularly interesting because it consists of nine separate CCD cameras — four pointing forward of the satellite (the telescopes for which can be seen in Figure 8), four pointing aft, and one pointing directly downwards. This will enable MISR to acquire nine images of the Earth surface within the space of a few minutes during a single orbital overpass. By comparison, the other sensors must record data from successive orbits of the satellite over the period of days.

Due to the constraints imposed by the satellite orbit and the design limitations of the sensor, each of these sensors will be able to acquire image data at a comparatively limited number of different angles. In other words, they will only be able to sample the Bidirectional Reflectance Distribution Function. This impacts on our ability to estimate the surface biophysical properties that drive the BRDF. We can visualize this issue more clearly with reference to a polar plot, gen-

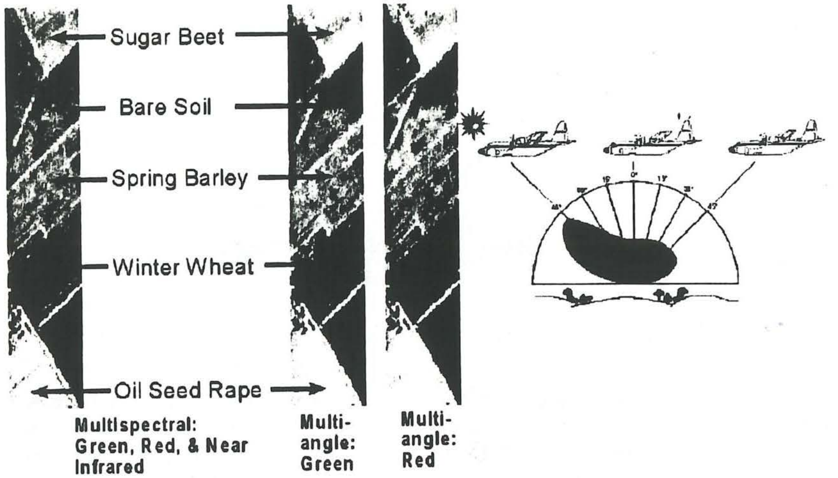


Figure 7: False colour composite images over an area of arable farmland constructed using data acquired at green, red and near-infrared wavelengths (far left) and in single spectral bands but at three different sensor view angles with respect to the Earth surface (centre). Image data courtesy of the Natural Environment Research Council (original in colour).

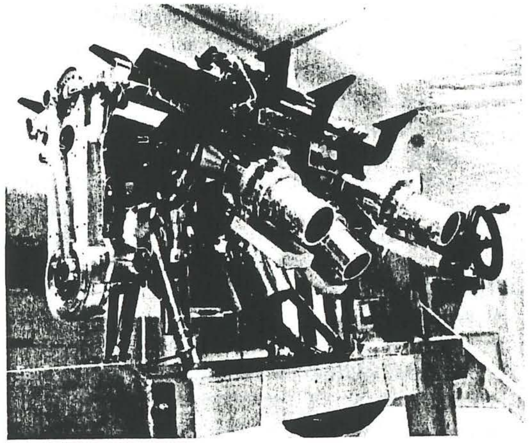


Figure 8: NASA's MISR (Multi-angle Imaging SpectroRadiometer) sensor, which will be capable of obtaining images of the Earth surface at nine different sensor view angles during a single orbital overpass (original in colour).

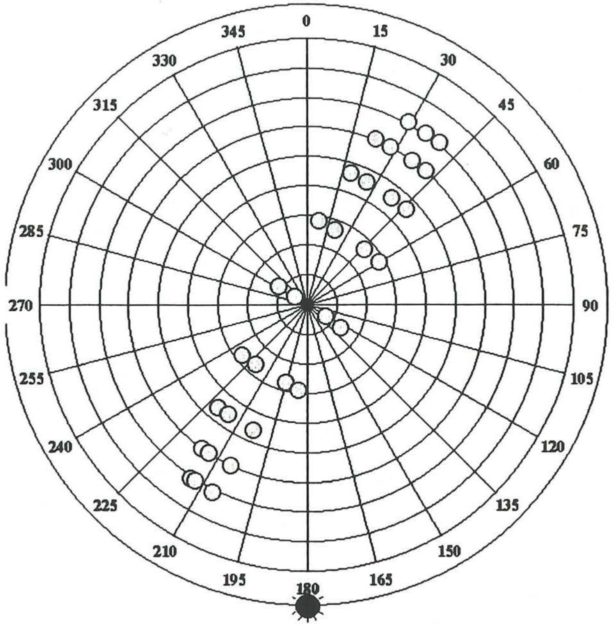


Figure 9: Computer simulation of the angular sampling capabilities of NASA's MISR instrument. The figure shows the number of times that this sensor will be able to observe a fixed point on the Earth surface (50°N) over a given period of time (16 days around the vernal equinox), as well as the Sun and sensor angles at which these data will be acquired.

erated using specialist computer software that we have developed. Figure 9 shows the predicted angular sampling capabilities of the MISR sensor with reference to a fixed point on the Earth surface, located at 50°N, measured over a 16-day period around the vernal equinox. Each dot indicates one occasion on which the sensor is able to see the target area, while the position of the dot indicates the angles at which the target is viewed on that occasion. Points towards the centre of the plot indicate that the sensor is looking vertically downwards, while those towards the edge of the plot indicate that the sensor observes the Earth surface at an oblique angle. The position clockwise around the plot refers to the angle between the Sun and the sensor projected onto the Earth surface. Despite the apparent complexity of this plot, the information that we need to draw from it is comparatively simple — namely, that the number of measurements of directional reflectance obtained by this sensor is small and that these are not distributed evenly across the viewing hemisphere: in fact, some parts of the hemisphere are not sampled at all.

Why is this important? Well, we know that the 'shape' of the BRDF is related to the bio-

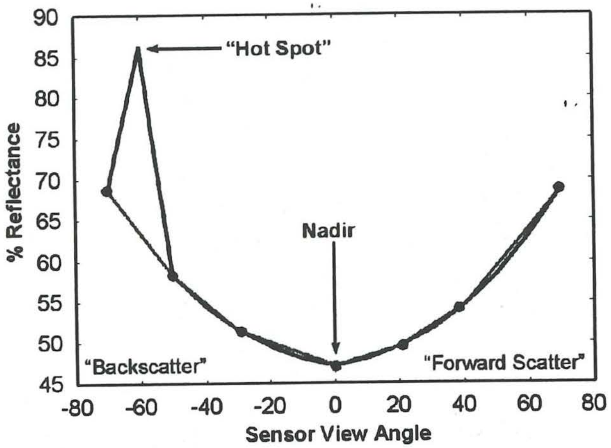


Figure 10: Effect of sparse angular sampling on the ability to characterize the shape of the BRDF and, hence, to retrieve information on the biophysical properties of Earth surface materials.

physical properties of the reflecting surface. For example, there is typically a pronounced peak in the reflectance of vegetation canopies in the direction of the Sun. This is known as the "hot spot" and is theoretically related to the size, shape and arrangement of the leaves in the canopy (Figure 10). If we measure the directional reflectance from a surface such as this at a limited number of different angles and then perform some simple interpolation between the measured values, we may miss the "hot spot" (and other similar) features. This may, in turn, lead us to make an incorrect assessment of the biophysical properties of the observed surface.

What is required is some form of model that allows us to interpolate between the few measurements of directional reflectance that we do have, and to extrapolate beyond them so that we can predict the 'shape' of the full BRDF. Ideally, the model should be expressed in terms of measurable physical quantities (such as some index of vegetation amount) and should be 'invertible' so that we can estimate values of these quantities from the measurements of directional reflectance. In fact, a large number of such models has been developed over the last twenty years, ranging from purely empirical functions to models with a sound basis in physical principles. Each of these approaches has its attendant problems. The former are generally able to describe the shape of the BRDF, but do not explain it in terms of measurable surface properties — in other words, we can pull the rabbit out of the hat without knowing how or why! The latter place a computational demand that is currently unacceptable in terms of operational application. Consequently, we have developed a suite of models which we refer to as semi-empirical, kernel-driven models. These involve a number of simplifications and approximations to ease the computational load, while retaining sufficient physical realism in terms of the model parameters.

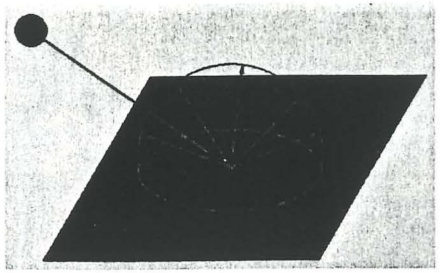


Figure 11: Schematic representation of the isotropic term in the semi-empirical, kernel driven BRDF models (original in colour).

The general format of these models is given by:

$$\rho(\theta_i, \phi_i; \theta_v, \phi_i) = f_{iso} + f_{vol}\, k_{vol} + f_{geo}\, k_{geo} \tag{1}$$

Thus ,the directional reflectance from the surface is modelled as a linear, weighted sum of three components, namely:

(i) a constant term that describes isotropic scattering from the observed surface; that is, equal reflectance in all directions. This is expressed in terms of measurable surface biophysical properties and, in simple terms, accounts for overall differences of brightness between different surfaces (Figure 11;

(ii) a term to account for volume scattering. This is the product of a 'kernel' derived from radiative-transfer theory that describes the 'shape' of the BRDF due to the scattering of radiation within the 'volume' of the surface material and a weighting factor for this kernel that is expressed in terms of measurable biophysical properties. In simple terms, this term is related to the density of scattering elements, such as plant leaves, present on the ground; and

(iii) a term to account for the shadowing and occlusion effects caused by vertical protrusions in the observed scene based on geometrical-optics. In simple terms, this accounts for differences in the three-dimensional structure of the observed surfaces.

We have tested this suite of models using data acquired by an aircraft-mounted sensor, namely NASA's Advanced Solid-state Array Spectrometer (ASAS), as part of an international science programme, known as HAPEX-Sahel, which was carried out in Niger, west Africa during 1992. The airborne sensor is similar in design to the proposed MISR satellite sensor, which was discussed earlier. One of our test sites, an area of Millet cultivation, is shown in Figure 14. The area contains a mixture of cultivated millet, as well as low trees and shrubs that are used as shelter-belts.

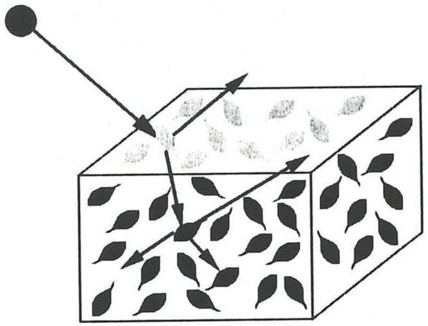


Figure 12: Schematic representation of the volume scattering term in the semi-empirical, kernel driven BRDF models (original in colour).

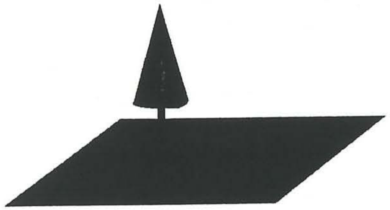


Figure 13: Schematic representation of the geometrical-optic term used in the semi-empirical, kernel-driven BRDF models (original in colour).

Figure 14: Area of millet cultivation in Niger, West Africa observed by NASA's ASAS sensor as part of the international HAPEX-Sahel programme carried out in 1992 (original in colour). Image data courtesy of the US National Aeronautics and Space Administration (NASA).

We have used the image data recorded by ASAS, in conjunction with the BRDF models that have just been described (Eq.1), to demonstrate that it is possible to separate the directional reflectance signal from the Earth surface into its isotropic, volume scattering and geometrical-optic scatting terms (Figure 15), as well as to provide accurate estimates of the surface albedo. Combining the three images together into the false-colour composite shown in the bottom right-hand quadrant of the slide, we are able to distinguish between the different types and levels of vegetation cover based on differences in the physical structure.

Within the next year, we will begin to apply these techniques to produce maps of vegetation type and amount and its change over time on a global basis. These should improve our understanding of various aspects of global environmental change.

4 Mapping Land-Use in Urban Areas

I turn now to a very different application of remote sensing, using data acquired at a very different spatial scale, namely land-use monitoring in urban areas. Much of the impetus for this work — not to mention some of the funds! — has come from Eurostat (the statistical office of the European Communities) who wish to assess on a frequent and regular basis the area of land within the European Union that might be classified as being 'urban'. Their interest stems from the fact that the criteria currently used to define what is meant by 'urban' land differ between

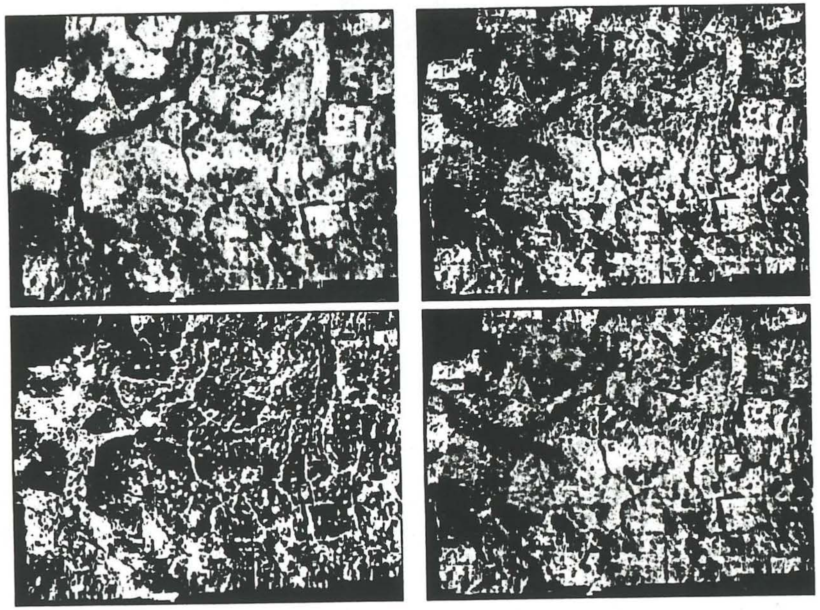


Figure 15: Images generated by inverting the semi-empirical, kernel-driven BRDF models against the directional reflectance data recorded by NASA's ASAS instrument over the Millet test site in HAPEX-Sahel. Top left: isotropic term; top right: volume scattering term; bottom left: geometrical-optic term; bottom right: false colour composite of the isotropic (red), volume scattering (green) and geometrical-optic (blue) terms (original in colour).

each of the member states. Moreover, the conventional surveys carried out by each member state use different measurement techniques, are based on different sampling strategies, and are carried out at different intervals of time. Remote sensing, by contrast, offers the potential to acquire a consistent and timely source of data on land use on a European-wide basis.

Until now, civilian satellite sensors have not be able to provide data of sufficiently high spatial resolution — that is, large mapping scale — to identify the features of interest in urban areas, such as individual buildings, roads and areas of open space. This situation is, however, about to change with the advent of a number of commercial satellite sensors that will provide image data with a spatial resolution as fine as 1m: that is, roughly speaking, they will be able to detect objects approximately 1m by 1m in size. The advent of these sensors owes much to 'glasnost', but still more to the desire of the former Soviet Union states to earn hard currency by selling data from their military satellite sensors. This has, in turn, forced the hand of their counterparts in the USA.

The problem is that while the sensor technology available for civilian use has effectively 'advanced' overnight, this has not been mirrored by an equivalent improvement in the techniques used to process the resultant data. One option is to employ standard photo-interpretation skills to analyze the new sources of image data. The human interpreter uses various 'cues' to deduce the nature of the land use, such as the colour, texture, shape, size and context of the objects visible in the image. Thus, she or he might distinguish between the various districts in the 1m-resolution image of Orpington in Kent shown in Figure 16 based on the size, shape and arrangement of the buildings and the residual 'open space'. Manual interpretation is, however, time-consuming, labourious and, hence, expensive. Ideally, we would like to be able emulate this process in an automated (or at least a semi-automated) data-processing environment.

My colleague Stuart Barr and I have begun to develop such a data processing system. This examines the spatial pattern (or structure) of discrete regions of different land-cover types identified in a remotely-sensed image, with the aim of inferring the dominant land use in different parts of the corresponding scene. Conceptually, at least, the system represents the structural relations between these land-cover regions in the form of a 'graph' (in the discrete mathematics sense of the word, rather than the popular meaning of an X-Y plot). Thus, each land-cover region is represented by a node in the graph, while the existence of some spatial relation between two such regions is represented by an edge (or arc) connecting them. Figure 17 shows the graph visualization of a simple urban scene, based on an examination of the spatial relation adjacency: that is, nodes (represented by the circles) that are connected by an edge (the black lines) represent land-cover regions that are adjacent to one another in the scene. For instance, node 2 represents the road region and is connected to (adjacent to) nodes 1, 3, 18, 19 and 26 which represent areas of open space. Thus, we have captured something of the spatial pattern of land cover regions that make up this urban district.

The data processing system that we are developing, known as XRAG (eXtended Relational Attribute Graph), is actually considerably more flexible than the preceding example implies. It is able to represent and to analyze the morphological properties of the individual regions (such as their size and shape), as well as various structural relations between them (such as adjacency, containment, distance and direction) (Figure 18).

Recently, we have tested the system using simulated remotely-sensed images generated from

Figure 16: False-colour composite image (1m spatial resolution) covering part of the town of Orpington in the London Borough of Bromley (original in colour). Image data courtesy of the Natural Environment Research Council.

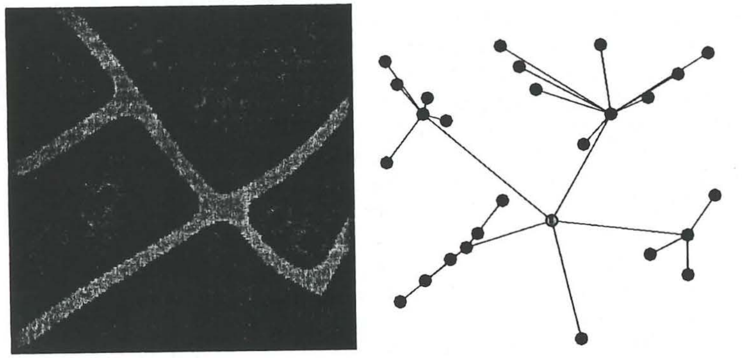


Figure 17: Left: simulated urban scene (original in colour), showing buildings (red), roads (grey) and open space (green); right: graph visualization of the same urban scene, showing the spatial relation adjacency between the discrete land-cover regions. Note that the coloured circles (nodes) in the righthand image represent individual regions, while the lines (edges) joining two such nodes indicate that the corresponding regions are adjacent to one another in the urban scene. Source data courtesy of the Ordnance Survey.

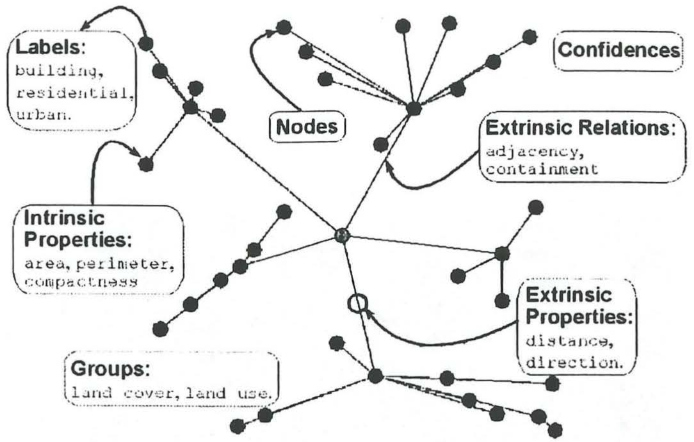


Figure 18: Graphical representation of the structural properties and relations that can be encoded within XRAG.

Ordnance Survey 1:1,250 scale digital map data. The area that we selected was, again, centred on the town of Orpington (Figure 19). The map data have been topologically structured, labelled and converted into a 1m-resolution image. The areas in red represent tiled-roof buildings, those in yellow represent buildings with concrete roofs, while those in grey indicate the roads. The areas shown in dark green are woods, while those in light green represent all other areas of 'open space'. If we now focus in on two areas of contrasting residential land, one built during the 1930s (Figure 20a) and the other in the 1990s (Figure 20b), we can clearly see that there are visible differences in the spatial pattern of buildings, roads and open space evident in these two sub-scenes. What we wish to know is can these differences be captured and quantified by XRAG? Turning to the graph visualizations of the spatial relation adjacency for these two sub-scenes (Figure 21), we can see that the differences are captured in terms of the number of nodes and the pattern of their inter-connectivity. The latter can be quantified using quite simple measures, such as 'node degree', which describes the number of other nodes to which each node in the graph is connected.

We are currently working to extend XRAG so that it is not only able to quantify differences in the spatial structure of distinct land-use categories, but can also be used to infer the dominant land use in an area from an analysis of its spatial structure. This requires us to develop techniques that can determine the similarity between the sub-graph for an area of known land use and those for which the land use is unknown. This, in turn, requires techniques to search the graphs for the image as a whole — each of which may contain tens of thousands of nodes — to find potential candidates for such a match. We are investigating both deterministic and artificial neural network approaches to this problem. The eventual aim is to be able to use these techniques to

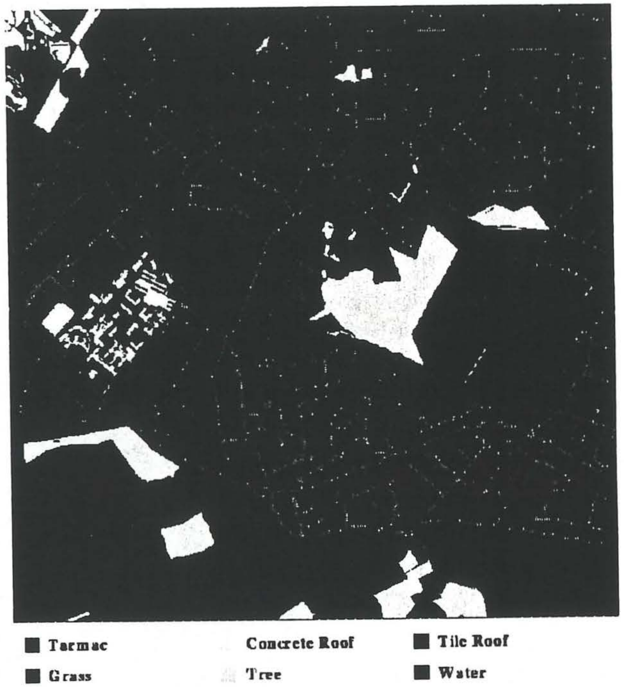


Figure 19: Simulated image covering part of the town of Orpington in the London Borough of Bromley produced from Ordnance Survey 1:1,250-scale digital map data (original in colour). These data can be compared directly with the real image data shown in Figure 16.

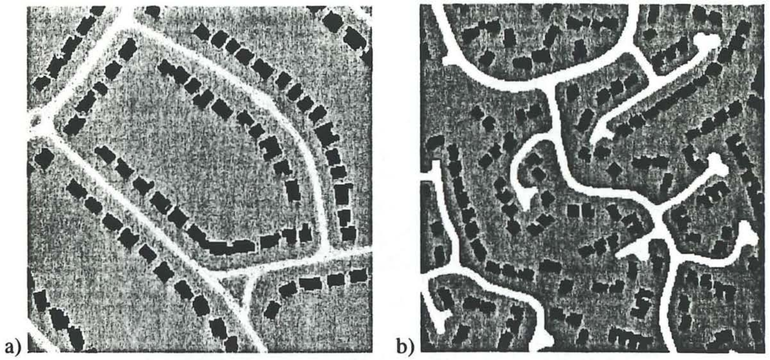


Figure 20: Sample areas extracted from Figure 19 covering a) a 1930s residential district and b) a 1990s housing estate. Source data courtesy of the Ordnance Survey.

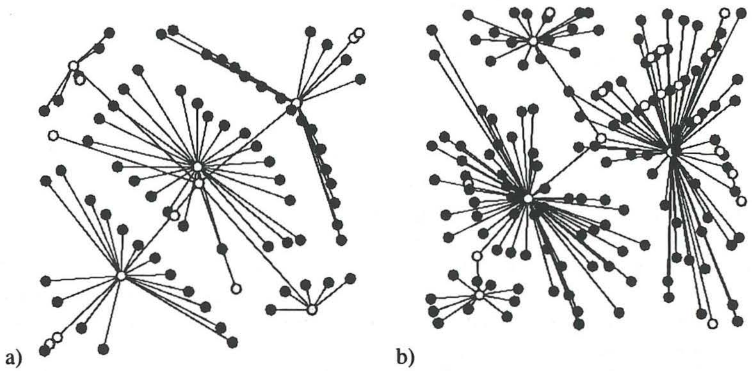


Figure 21: Graph visualizations of the spatial relation adjacency between the land-cover parcels identified in a) the 1930s residential district and b) the 1990s housing estate (Figure 20).

Figure 22: Photograph of part of the coastal dune system in the National Nature Reserve at Kenfig, near Port Talbot, south Wales.

generate maps of urban land use directly from digital remotely-sensed images with the minimum of manual intervention.

5 Mapping Habitat Loss in Coastal Dune Systems

I would now like to turn very briefly to an area of research that I have begun to develop since moving to Swansea in 1995. The work is being carried out in conjunction with my colleague Paul Pan, from the Department of Maritime Studies and International Transport at the University of Wales Cardiff. It concerns the use of remote sensing (in this case from aircraft) and Geographical Information Systems (which are computer-based systems for manipulating map data) to monitor the loss of habitat in coastal dune systems.

To date, our work in this area has focussed on the Kenfig National Nature Reserve (NNR), which lies immediately south-east of Port Talbot (Figure 22). This site hosts a number of nationally and internationally scarce plant species, including the rare and declining fen orchid, *Liparis loeselli* — accounting for approximately 96% of the U.K. population of this species.

Coastal dune systems are normally highly active environments in which the constant transport of mobile sand ensures a wide variety of habitats, ranging from bare sand, through dune slacks, to more established vegetation communities. At Kenfig, however, the dunes have become highly stabilized, so that the area of certain important habitats, notably the dune slacks, has gradually diminished over the last three decades with consequent impacts on floristic biodiversity. We are currently working in close collaboration with staff from the Countryside Council for Wales (CCW) to examine the potential of digital remotely-sensed data to monitor these changes and to provide the basis for effective management of this and other reserves controlled by CCW. To this end we have been making use of remotely-sensed images provided by the Environment Agency from its recent archive, augmenting these with more recent data acquired on our behalf by the Natural Environment Research Council. Figure 23 shows one of the Environment Agency's images of Kenfig recorded in 1995. Areas of photosynthetically active vegetation are shown in red — the deeper the red, the greater the amount of vegetation — areas of bare sand are shown in white, the blue is the beach, while the dark black region in the centre of the image is Kenfig pool.

Figure 23: False-colour composite image of the Kenfig NNR coastal dune system. These data were acquired in 1995 by the Environment Agency using an airborne imaging spectrometer (original in colour).

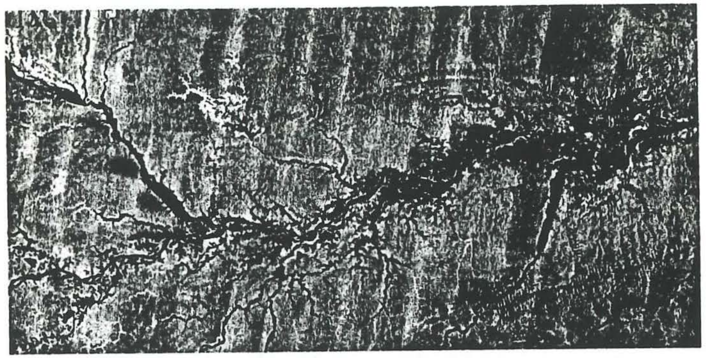


Figure 24: Mosaic of digital images acquired by the Synthetic Aperture Radar (SAR) on board the JERS-1 satellite covering an area of 1000km by 500km of the Brazilian Amazon. Image data courtesy of NASDA.

6 Monitoring Tropical Deforestation

The final area of research that I would like to address tonight is concerned with the use of remote sensing to monitor the present-day loss of tropical forests due to logging and clearance by man. In contrast to the previous three themes that I have covered, each of which made use of data acquired by optical sensor systems, this section examines the use of sensors that operate in the microwave part of the electromagnetic spectrum — specifically, a type of sensor known as a Synthetic Aperture Radar (SAR). This type of sensor offers a number of advantages over optical systems. First, they generate their own pulse of radiation (which is transmitted from the sensor to the ground) before measuring the strength of the signal returned from the ground to the sensor (known as 'backscatter'). This means that they are capable of both day-and-night operation. Second, microwave radiation can penetrate through clouds — which is particularly important when monitoring areas of persistent cloud cover, such as tropical rainforests or, for that matter, Swansea!

The work in this area is being led by a recent appointment to the Department of Geography, Dr. Adrian Luckman, who has been appointed to one of only two Lectureships in the U.K. part-funded by the NERC under its recent Earth Observation Science Initiative scheme. The following figures illustrate some of Adrian's recent research, in which he has used Synthetic Aperture Radar images from the Japanese Earth Resources Satellite (JERS-1) to map the extent of deforestation in Amazonia. Figure 24 illustrates the potential of radar remote sensing for monitoring very large areas — in this case a 1000km by 500km region of the Brazilian Amazon. If we focus in on a section of this image (Figure 25), it just possible to see the dark 'herring bone' pattern of deforestation that follows the route of the Trans-Amazonian highway and along logging roads at right angles to this (lower right quadrant of the image). Radar devices are sensitive to the roughness of the observed surface, so that we are able to distinguish the relatively rough surface of the virgin forest which scatters much of the pulse of microwave radiation transmitted by the radar back towards the sensor and, hence, produces the lighter grey tones. By comparison, the relatively smooth surfaces of the areas cleared for ranching scatter much less radiation back towards the radar and, hence, appear as much darker areas in the image. To the north, you can also see the flooded areas along the Amazon river.

Figure 25: SAR image extract showing the 'herring bone' pattern of deforestation in the Brazilian Amazon that follows the trans-Amazon highway and along logging roads at right angles to this highway. Image data courtesy of NASDA.

Finally, one area of exciting, new research into microwave remote sensing, known as radar interferometry, exploits the change in 'phase' of the signal returned to the satellite sensor before and after deforestation to provide an even clearer picture of the extent and rate of deforestation (Figure 26). Thus, the areas shown in Figure 26 represent virgin forest, while those in red represent ranch land. We can therefore use this science and technology to monitor both the areal extent and rate of deforestation — not only for environmental 'policing', but also to understand better the contribution of deforestation, burning, ranching and forest regrowth to the global circulation of carbon, in the search for the Gigatonnes of carbon that are 'missing' from the equation based on our current levels of understanding.

7 Concluding Remarks

Having whisked you extremely rapidly through some areas of research into Earth Observation that we are currently undertaking here at Swansea, I would now like to make a few concluding remarks:

- It should be evident that Earth Observation is an important source of data on both the natural and built environments. At the global scale, it is perhaps the only viable means of acquiring these data.

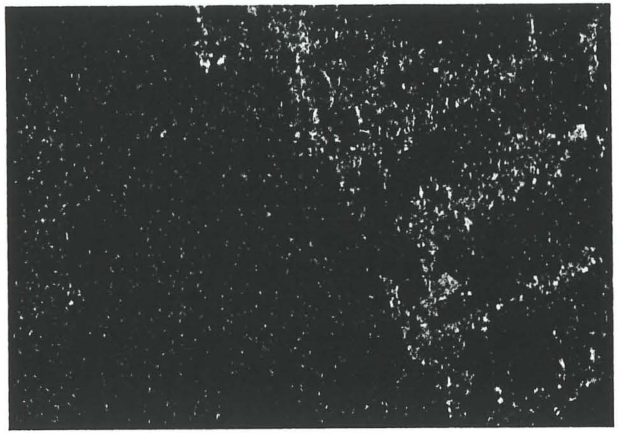


Figure 26: Interferometric SAR image covering a small part of the Brazilian Amazon, showing areas of virgin forest (green) and deforestation (red) (original in colour). Image data courtesy of NASDA.

- It should also be clear that Earth Observation is a highly interdisciplinary subject — one that brings geographers together with physicists, engineers, computer scientists, mathematicians, and many others. I am certain that each group benefits from this interaction and the resultant exchange of ideas and methods. There is, however, some evidence that geographers may be foregoing their role in this demanding subject for want of the necessary quantitative and scientific skills. We must ensure that this trend is arrested and, if possible, reversed by providing future generations of undergraduate and postgraduate *geography* students with the appropriate training. This is vital. Geographers can (and do) provide an important link between the technological developments in remote sensing technology and the eventual users of the data that this technology produces.
- The financial investment in Earth Observation has been, and continues to be, very large — measured in many billions of dollars at the international level — which is a reflection of the importance attached by both the public and elected politicians to address many of the most significant environmental problems of the day. However, this investment is highly skewed towards the space segment (notably sensor and platform development) and away from the applications of the resulting data. This imbalance must be addressed if we are to derive maximum benefit from the technology.
- Finally, although the potential 'returns' are immense — in terms of improving our ability to monitor, understand and possibly manage the environment — current levels of investment in Earth Observation place considerable pressure on its practitioners to 'deliver the goods', and soon. The next decade will therefore be a critical one in the development and uptake of remote sensing. In this context, 'success' will be dependent on continuing high-quality academic research — by geographers amongst others — and the transfer of the resultant knowledge and skills to industry.

8 Acknowledgements

I would like to express my thanks to the Natural Environment Research Council, the Economic and Social Research Council, the Leverhulme Trust and the Research Corporation Trust for a series of research grants that has enabled me to undertake the work described above. My thanks also go to various colleagues with whom I have worked over the last thirteen or so years, most notably Prof. Peter Muller and Dr. Philip Lewis (University College London), Prof. Alan Strahler and Dr. Wolfgang Lucht (Boston University, USA), Paul Pan (University of Wales Cardiff), and Dr. Adrian Luckman (University of Wales Swansea). Finally, I am very grateful to my postgraduate students and research assistants — both past (Dr. Simon Kay (CEC-JRC Ispra, Italy), Dr. Tin-Seong Kam (Singapore), Dr. Kevin Morris (currently at the NERC Plymouth Marine Laboratory), Richard Morris (EOS Ltd), Martin Sutherland (BT Ltd)) and present (Stuart Barr (University of Wales Swansea), Trevor Tsang (UCL), Peter Blamire, Zoltan Hesley, Paul Hobson, Sanjeevi Shanmugam,Kate Evans-Jones, Graham Thackrah and Tristan Quaife (all Swansea)) — who have not only humoured me by pursuing some of the outlandish research projects that I have come up with, but who have also contributed their own sound and original ideas.

9 Selected Bibliography

1. Barnsley, M.J., 1994, Environmental monitoring using multiple view angle (MVA) remotely-sensed images, In Curran, P.J., and Foody, G., (eds.), *Global environmental monitoring using remote sensing*, (Chichester: John Wiley), 181-201.
2. Barnsley, M.J., Allison, D.A., and Lewis, P., 1997, On the information content of multiple-view-angle (MVA) images, *International Journal of Remote Sensing*, **18**, 1937-1960.
3. Barnsley, M.J., and Barr, S.L., 1996, Inferring urban land use from satellite sensor images using kernel-based spatial reclassification, *Photogrammetric Engineering and Remote Sensing*, **62**, 949-958.
4. Barnsley, M.J., Barr, S.L., Hamid, A., Muller, J-P., Sadler, G.J., and Shepherd, J.W., 1993, Spatial analytical tools to monitor the urban environment, In Mather, P., (ed.), *Geographical information handling - research and applications*, (London: Taylor and Francis), 147-184.
5. Barnsley, M.J., Lewis, P., Sutherland, M., and Muller, J-P., 1987, Estimating land surface albedo in the HAPEX-Sahel southern super-site: inversion of two BRDF models against multiple angle ASAS images, *Journal of Hydrology*, **188-189**, 749-778.

6. Barnsley, M.J., Strahler, A.N., Morris, K.P., and Muller, J-P., 1994, Sampling the surface Bidirectional Reflectance Distribution Function (BRDF): 1. Evaluation of current and future satellite sensors, *Remote Sensing Reviews*, **8**, 271-311.

7. Barr, S.L., and Barnsley, M.J., 1995, A spatial modelling system to process, analyse and interpret multi-class thematic maps derived from satellite sensor images, In P.Fisher (ed.), *Innovations in GIS 2*, (Taylor and Francis: London), 1995, 53-65.

8. Barr, S.L., and Barnsley, M.J., 1997, A region-based, graph-theoretic data model for the inference of second-order thematic information from remotely-sensed images, *International Journal of Geographical Information Science*, **11**, 555-576.

9. Hyman, A.H., and Barnsley, M.J., 1997, On the potential for land-cover mapping from multiple-view-angle (MVA) remotely-sensed images, *International Journal of Remote Sensing*, **18**, 2471-2475.

10. Strahler, A H, Wanner, W, Li, X, Muller, J-P, Barnsley, M J, and Lewis, P, 1995. *MODIS BRDF/Albedo product: Algorithm Technical Basis Document (ATBD), Version 3.1*, NASA Publication, 50pp.

11. Wanner, W., Strahler, A.H., Hu, B., Lewis, P., Muller, J-P., Li, X., Barker-Schaaf, C.L., and Barnsley, M.J., 1997, Global retrieval of bidirectional reflectance and albedo over land from EOS MODIS and MISR data: theory and algorithm, *Journal of Geophysical Research*, **102**, 17143-17161.