Remote sensing
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I Introduction

The UNCED 'Earth summit' Conference in Rio De Janeiro identified remote sensing as a source of information to build up a global environmental database (CEOS, 1992). In addition to this role, remote sensing is also needed to monitor environmental pollution at regional and national levels (Oberg and Andersson, 1993). For example, the synthetic aperture radar (SAR) onboard the European satellite ERS-1 can be used to monitor oil slicks (Bern et al. 1993). Techniques using thermal infrared sensors can also be used (Salisbury et al., 1993), and sensors operating in the ultraviolet part of the electromagnetic spectrum can detect even thin sheens of oil (Rogne et al., 1993). The advanced very high resolution radiometer (AVHRR) onboard the NOAA series of meteorological satellites provided an operational system to monitor the environmental effects of the Gulf war, such as burning oil wells (Dech and Glaser, 1992), oil slicks, dust and airplane contrails (Stephens and Matson, 1993). Under certain circumstances, air pollution can be monitored from space (Sifakis and Deschamps, 1992), although it is easier to monitor the effect of pollutants such as SO$_2$ (Gemmell and Colls, 1992) and ozone (Essery and Morse, 1992) on vegetation canopies. Complex phenomena such as urban heat islands (Kim, 1992) and land rehabilitation (Hill and Phinn, 1993) can also be analysed with the help of remote sensing.

Data on biomass burning in tropical forests in becoming increasingly important in the study of the carbon cycle and atmospheric processes in general (Grégoire et al., 1993). A variety of techniques for monitoring forest fires have been developed using coarse resolution geostationary satellite data (Prins and Menzel, 1992) and high spatial resolution data from the Landsat thematic mapper (TM) (Pereira and Setzer, 1993b). However, most techniques employ coarse (1.1 km) spatial resolution AVHRR data (Pereira and Setzer, 1993a). As an alternative to monitoring smoke plumes, AVHRR and ERS-1 SAR data can be used to study resulting wildfire scars (Kasischke et al., 1992; 1993).

II Lithosphere

As visible/shortwave infrared sensor technology has improved, data from earlier sensors have tended to come down in price. Landsat multispectral scanner (MSS) imagery is now

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relatively cheap, even though the sensor is still operational for the benefit of long-term monitoring programmes. If the 79 m spatial resolution is appropriate for the required application, MSS data can provide a cost-effective way of studying the relationship between lithology (El Rakaiby and Shalaby, 1992) and landforms (Dwivedi and Ravi Sankar, 1992; Mitra et al., 1992). The lower cost of MSS data facilitates acquisition of a number of images of different dates to monitor changes in features such as rivers (Nagarajan et al., 1993) and sand dunes (Kumar et al., 1993). The large area coverage of MSS permits mapping megageomorphological features, such as glacial lineations (Clark, 1993).

However, the enhanced spectral information afforded by TM enables applications such as mapping degrees of dynamic metamorphism (Riaza, 1993) and the development of rock coatings and weathering features (White, 1993). TM data have proved effective for monitoring volcanoes (Oppenheimer, 1993), but a number of problems remain, such as sensor overload and infrequent revisit capability (Rothery, et al., 1992). Another problem is that the shortwave infrared signal that is used for much of this work (Oppenheimer et al., 1993) is related to solar input as well as lava temperature. Night-time (Reddy et al., 1993), or thermal infrared (Realmuto et al., 1992) imagery can be used to solve this problem. The 10 m resolution and stereo capability of the French SPOT satellite can be used for detailed analysis of crater morphology (Rowland and Munro, 1992), ashfall and mudflows (Chorowicz et al., 1992). A greater understanding of ash inputs into the atmosphere is needed; ashfall from the June 1991 eruption of Mt Pinatubo in the Philippines is thought to have lowered satellite-measured vegetation values over southern India for the latter half of 1991; despite low values there was a bumper harvest that year (Jeyaseelan and Thiruvengadachari, 1993).

At hyperspectral resolutions, airborne data from NASAs AVIRIS sensor (Vane et al., 1993) enable semi-automated mineral mapping (Kruse et al., 1993; Rubin 1993). In salt-lake areas, evaporite minerals can be mapped to yield information on brine chemistry (Crowley, 1993).

ASTER (advanced spaceborne thermal emission and reflection radiometer), part of the forthcoming Earth observation system (EOS), will provide global multispectral thermal data with 90 m resolution. In anticipation of this, a concerted effort is under way to improve our understanding of thermal characteristics of natural surfaces and to develop algorithms to differentiate between emissivity and temperature components of radiance measured by thermal satellite sensors. One approach is to compare thermal images taken at different times of the day and assume that the observed change in radiance is due totally to temperature. This assumption is reasonable for rocks and dry soils, but not for vegetation or wet soils, where emissivity will also vary over time (Watson, 1992). Alternatively, emissivity can be calculated from laboratory measurements of spectral reflectance (Salisbury and D’Aria, 1992a). It is possible to retrieve compositional information from thermal data, as mineral spectra mix linearly at these wavelengths, as long as particle size is greater than wavelength (Thomson and Salisbury, 1993). Thus, linear mixture models (Settle and Drake, 1993) can be applied to thermal images (Gillespie, 1992). The above-mentioned control of particle size means that ASTER data have the potential to map soil particle size (Salisbury and D’Aria, 1992b). Other controls on thermal characteristics of surfaces are roughness, aeolian mantle, vegetation (Weitz and Farr, 1992) and rock varnish (Rivard et al., 1993).

Airborne radar data have been used to examine the time-dependent smoothing of lava flows by weathering processes, enabling reconstruction of the eruptive history of volcanic
terrains (Arvidson et al., 1993). Interpretation of backscatter images is likely to be considerably enhanced by the use of radar interferometry. This utilizes the interference pattern produced by two vertically displaced antennas, which can be processed to yield a digital elevation model (DEM) coregistered with the backscatter image. The precision of this technique compares favourably with traditional DEM creation using stereo SPOT images (Tateishi and Akutsu, 1992). These data have been used to study alluvial fans in Death Valley and volcanoes in Iceland (Evans et al., 1992). In addition, multitemporal interferometry can highlight topographic changes, such as those resulting from earthquakes (Massonnet et al., 1993).

III Pedosphere

Hyperspectral data can be used to map different soil types (Mustard, 1993; Roberts et al., 1993) and determine aspects of soil chemistry (Henderson et al., 1992; Joffre et al., 1992; Csillag et al., 1993), but the high variability of soil reflectance, even within a single soil type, remains a significant problem (Major et al., 1992). Interpretation of soil information from these data involves understanding of both spectral and bidirectional reflectance characteristics (Pinty and Verstaete, 1992). Hapke’s model can be adapted to integrate these properties, helping to explain the variability (Jacquemoud et al., 1992) and improve soil mapping techniques (Kimes et al., 1993). Research on soil moisture mapping from radar (Bertuzzi et al., 1992) has suggested that H-H polarization (Schmullins and Furrer, 1992b) and L-band (1GHz) frequency (Schmullins and Furrer, 1992a) is the optimum configuration for this work. Depth of water table can be estimated from passive microwave emissivity (Reutov and Shutko, 1992).

IV Biosphere

Remote sensing techniques are used to analyse vegetation communities from tundra (Hope et al., 1993) to arid rangelands (Pickup et al., 1993). Long time series of images are now available for systems such as AVHRR, and can be used for sophisticated analysis of seasonal/interannual vegetation changes (Eastman and Fulk, 1993). Forest monitoring is routinely undertaken using empirical techniques (Oza et al., 1992; Fiorella and Ripple, 1993), although some canopy reflectance models can be inverted (Rosema et al., 1992). Canopy structure is an important control on vegetation reflectance (Taylor, 1993), particularly for forests (Danson and Curran, 1993). The traditionally employed leaf-area index (Bonan, 1993) is a poor measure of structure, but more appropriate canopy parameters are very difficult to measure. Over some forest types, such as the oak savanna-like ‘dehesa’ of southern Spain, resource inventory is a simple matter, as individual trees can be counted directly using 10 m resolution SPOT data (Joffre and Lacea, 1993). In other situations, a more appropriate technique is to mixture model coarse resolution data to produce vegetation fraction maps (Holben and Shimabukuro, 1993). Hyperspectral data can be used to measure woodland reflectance down to low percentage covers (Elvidge et al., 1993), employing techniques such as second derivative calculation (rate of change of reflectance with wavelength) (Li et al., 1993). SAR data have great potential for forestry work, particularly when used synergistically with multispectral data (Nezry et al., 1993).
The L-band instrument on board JERS-1 (now renamed FUYO-1) should be particularly sensitive to forest canopy roughness (Nishidai, 1993).

V Cryosphere

The frozen regions of the Earth are difficult to study in situ, so scientists working in this environment have frequent recourse to satellite imagery for a variety of tasks, from measuring velocity (Scambos et al., 1992) and radiation budgets (Gratton et al., 1993) of glaciers, to estimating snow grain size (Nolin and Dozier, 1993). The response of the cryosphere to climatic change can be studied by monitoring the date of breakup of lake ice (Wynne and Lillesand, 1993), or by monitoring the equilibrium line between firn and superimposed ice (Parrot et al., 1993). Remotely sensed data on ground cover can significantly improve mapping of the depth of the active permafrost layer (Peddle and Franklin, 1993).

VI Hydrosphere

For effective monitoring of inland water quality, a comprehensive database of lake and river conditions is needed (Dekker and Peters, 1993). Work has begun on such large-scale monitoring (Gitelson et al., 1993), but problems already identified include a lack of understanding of the mechanisms involved, particularly those associated with the atmosphere (Tassan and D'Alcalá, 1993), and technical limitations of the instruments (van Stokkom et al., 1993). Nevertheless, thermal sensors can be used to study diurnal and seasonal lake temperature changes (Xin and Shih, 1993), highlighting features such as thermal bars, which can isolate nearshore waters and cause pollution problems (Malm and Jönsson, 1993). Work with the airborne thematic mapper sensor (ATM) has shown that temperature is directly related to water quality parameters such as suspended sediment content in cooling water reservoirs of power stations (Ramsey et al., 1992; Davies and Mofor, 1993). A variety of techniques are available to estimate suspended sediment using visible/near-infrared data, including chromaticity analysis (Gallie and Murtha, 1993), high resolution derivative spectra (Goodin et al., 1993) and mixture modelling (Mertes et al., 1993). In coastal waters, both empirical techniques (Sunar, 1992; Froidefond et al., 1993) and physical models (Estep and Armone, 1993; Nanu and Robertson, 1993) are used to retrieve suspended sediment information, though equations derived from both approaches are similar (Tassan, 1993a). Imaging spectrometer data (Sun and Anderson, 1993) can be used to study the relationship between turbidity and salinity (Carder et al., 1993). Chlorophyll concentrations in water can be estimated from remotely sensed data (Gitelson, 1992), but can easily be confused with coloured dissolved organic matter, or 'yellow substance' (Hamilton et al., 1993), often concentrated around pollution sources (Ferrari and Tassan, 1992; Nichol, 1993). Coastal zone colour scanner (CZCS) data are particularly suitable for phytoplankton estimation, an important aspect of ocean ecology (Prasad and Haedrich, 1993), enabling study of upwelling systems (Hernández-Guerra et al., 1993), and prediction of good sites for aquaculture (Cusidó et al., 1992). TM data enable algae, a major pollutant problem in coastal waters, to be mapped in terms of depth (Tassan, 1992). Although different algal species are spectrally very similar, they have different scattering properties, and may be distinguished using remote sensing (Quibell,
AVHRR, though of low spatial resolution, can be useful in monitoring algae due to its high temporal resolution (Tassan, 1993b).

Larger freshwater plants provide another indicator of water quality that can be remotely sensed (Jensen et al., 1993), and similar techniques can be applied to coastal submerged vegetation canopies (Armstrong, 1993). Sea-bottom cover can be mapped using multispectral band ratios (Luczkovich et al., 1993) and mixture modelling, where good bathymetry information is available (Bierwirth et al., 1993). Such data can be used for detecting change (Michalek et al., 1993; Zainal et al., 1993), or analysing the relationships between coral reef construction and wave action (Courboules and Maniere, 1992).

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