REMOTE SENSING AND ENVIRONMENTAL MONITORING

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Contents

Summary

Environmental monitoring and management are activities of global importance. Image data derived from space-borne sensors are widely used to identify spatial and temporal patterns in the properties of the major interrelated global environmental systems (atmosphere, biosphere, cryosphere, and oceans).

Remotely sensed data have two significant characteristics. Firstly, they are available in digital form, which allows them to be manipulated by computer. Secondly, they provide a range of information derived from observations made using electromagnetic radiation (EMR) with wavelengths ranging from those of the visible wavebands (0.4–0.7 μm) to the microwave region (3–30 cm). Modulation of incoming EMR by the atmosphere or land/sea surface provides information about the characteristics of these land, ice, and ocean surfaces and of the atmosphere. For example, observations in the visible and near-infrared regions of the spectrum are used to estimate “colour” (e.g. produced by the presence of phytoplankton in ocean surface waters). Thermal infrared and microwave measurements are used to monitor surface temperature and roughness/soil moisture characteristics, respectively. Overlapping (stereo) images in the visible and microwave wavebands are also used to derive digital datasets showing surface elevation using photogrammetric and interferometric techniques, respectively. Products such as maps of slope angle and aspect can be derived from these datasets.

An overview of methods of digital image processing is provided in Section 2. Image enhancement is required to facilitate the visual interpretation of remotely sensed images, as most sensors are designed to measure a wide range of upwelling radiance values (e.g. very low in the visible wavebands over ocean areas, but high over snow and ice surfaces). Hence, the dynamic range of an image of a specific region will, in general, be small relative to the dynamic range of the instrument and some processing will be

necessary to increase the image contrast. The topics of image filtering and geographical scale are also discussed in this section, which contains a summary of recent developments in the area of pattern recognition techniques, which are primarily used to generate land-use maps for agricultural and forestry management.

1. Introduction

One of the greatest technical achievements of the twentieth century was the U.S. Apollo program. Most people over the age of 40 will recall the day Neil Armstrong became the first human being to set foot on the moon. The impact of the Apollo programme can now be seen to be far wider than the purely technological, for the photographic images of the earth taken by the Apollo astronauts generated an upsurge of interest in the human environment. Geography has been described as the study of "Earth as the home of humankind," and the Apollo photographs provided the first opportunity to view this home from the outside. Figure 1 shows Earth rising above the lunar surface. It is seen as a small, blue planet, which emphasises the important role of water in the maintenance of life. Earth is also seen as a fragile planet floating in space, a view that was emphasised by the images of Earth taken by the Apollo astronauts as they left Earth's orbit. Figure 2 is a photograph taken from Apollo 11 when the spacecraft was about 150 000 km from Earth. At this scale, we can see landmasses, oceans, and clouds. The view from space again emphasises the balance between the different components of the interrelated oceanic, terrestrial, atmospheric, and cryospheric Earth systems.

Figure 1. Earthrise, photographed by the Apollo 11 astronauts, 20 July 1969
(*Source*: NASA photo ID AS11–44–6552)

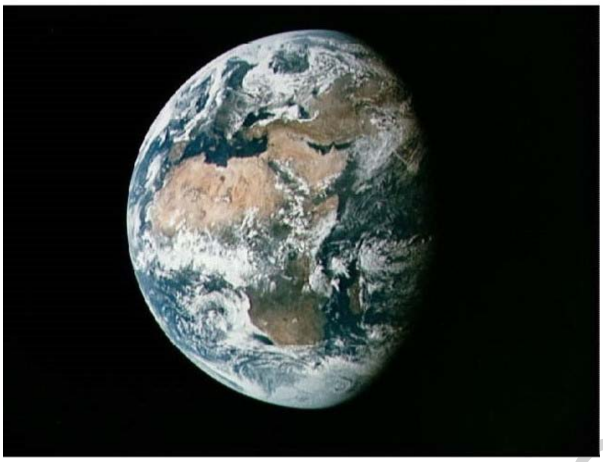

Figure 2. Earth from a distance of 96 000 miles (153 600 km) Apollo 11 mission, 16 July 1969
(*Source*: NASA photo ID AS11–36–5355)

Pictures such as those taken by the Apollo astronauts helped to stimulate the growth of the "green" movement and of environmental awareness among the lay public. The state of health of the oceans, the equatorial forests, the polar icecaps, and the atmosphere became political as well as scientific issues. Public concern over what became known as "the environment" led to international agreements as well as national legislation intended to control and reduce pollution of the atmosphere and oceans in an attempt to reduce the impact of global warming. Images from unmanned Earth-orbiting satellites such as the TIROS/NOAA weather satellites also contributed to public concern over the state of the environment. For example, Figure 3 shows the Antarctic ozone hole for the period September–December 1995. These images, together with ground measurements, were instrumental in preparing the way for an international treaty to reduce the amounts of chlorofluorocarbon (CFC) gases released into the atmosphere.

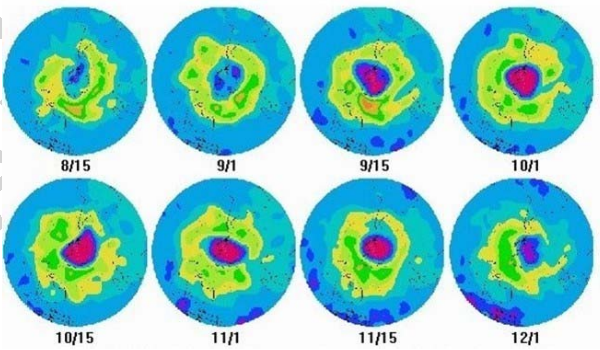

Figure 3. The "ozone hole" over the Antarctic for the period September–December 1995.
Red areas show severe depletion of up to 70% of normal values.
Images are from NOAA TOVS (TIROS operational vertical sounder) instrument.
(*Source*: http://www.epa.gov/ozone/science/hole/holecomp.html)

It is evident that images from space have had a considerable impact on the way human beings perceive our home planet. From the perspective of a sixteenth-century sailor, the earth would probably have seemed a very large and hostile place with limitless resources. As we enter the twenty-first century, our perception is quite different; we see a small and fragile earth that is at risk from the activities of its six billion human inhabitants. It is a planet that needs care and attention. We have also learned that the earth's atmosphere, oceans, land surfaces, and biosphere are all intimately connected. This point of view is developed further in ***NASA Earth Science Enterprise: A New Window on Our World***.

As well as stimulating interest in and concern about planet Earth, the Apollo photographs also had a scientific impact. Pictures taken by astronauts as the Apollo spacecraft were in low Earth orbit demonstrated that valuable scientific information could be derived from space images. Figure 4 shows an area of Angola and present-day Namibia taken by the joint Apollo–Soyuz mission in 1975. The geological structures and drainage pattern are clearly visible for this remote region, covering an area far greater than that shown on a conventional aerial photograph. Figure 5, taken during the same mission, shows the city of Los Angeles. The potential for mapping large areas of the earth's surface was revealed by images such as these. However, it was the potential ability of images from space platforms to track hurricanes (Figure 6) and other weather systems that led to the first operational use of what we now call Earth observation by remote sensing. In 1960, the U.S. National Oceanic and Atmospheric Administration (NOAA) launched the first unmanned civilian satellite specifically to photograph the earth on a regular basis, in order to provide data for weather forecasting. This satellite, called TIROS (Television Infrared Observation Satellite), was the first of the TIROS/NOAA weather satellites that provide daily images of the globe, those that are seen on our daily T.V. weather forecasts. Both polar-orbiting satellites such as NOAA and geostationary satellites such as GOES and METEOSAT (which "hover" above a fixed point on the ground) are used routinely nowadays for weather forecasting.

Figure 4. An oblique view of unique drainage patterns in south-western Africa in the Rio Cuando area of Angola and Namibia, as photographed from the Apollo spacecraft in Earth orbit during the joint U.S.–USSR Apollo Soyuz Test Project (ASTP) mission (1975)
(*Source*: *http://images.jsc.nasa.gov/images/pao/ASTP/10076558.htm*)

Figure 5. A view of the Los Angeles, California, area, as photographed from the Apollo spacecraft in Earth orbit during the joint U.S.–USSR Apollo Soyuz Test Project (ASTP) mission. Downtown Los Angeles is near the centre of the picture. The photograph was taken at an altitude of 193 kilometres (120 statute miles).
(*Source*: http://images.jsc.nasa.gov/images/pao/ASTP/10076560.htm)

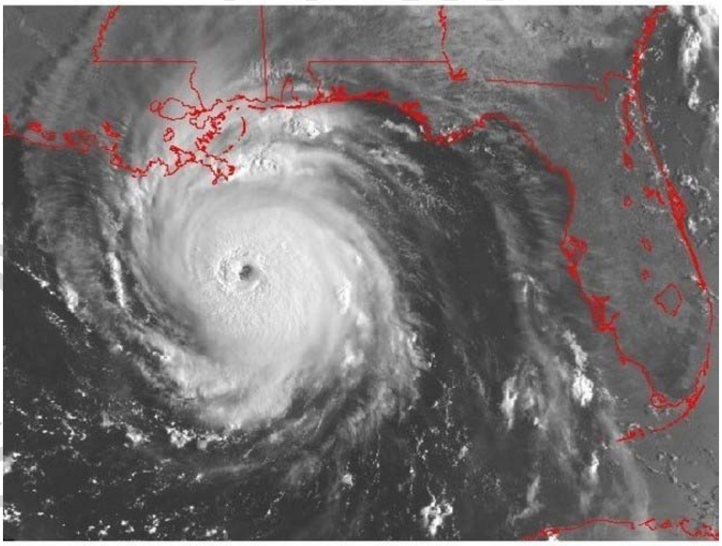

Figure 6. Hurricane Andrew over the Gulf of Mexico (1992). The coastline of the south-eastern USA is superimposed in red.
(*Source*: http://www.geocities.com/deadlockdomain/hurricanes/Andrew3.jpg)

The wide area of view obtained from orbital altitudes is one of the main reasons images obtained from instruments carried by satellite platforms have been so readily adopted as mapping and monitoring tools in disciplines such as oceanography, meteorology, ecology, geography, and geology. Figures 4 and 5 illustrate this aspect of space imaging. A second important feature of polar-orbiting satellites is that they can be configured in such a way as to pass over the equator at the same local time each day, providing repetitive coverage of the earth's surface. The U.S. Landsat programme, for example, was initially designed as a monitoring system for crops and vegetation. In order to observe the status of growing crops, frequent coverage is necessary (Landsat's revisit time is 16 days).

One of the most important steps forward in imaging from space was the development of instruments that provided data (a) in digital form and (b) in several bands of the electromagnetic spectrum. Digital data are required if computers are to be used in the storage and manipulation of images collected by sensors on board orbiting platforms, while multi-channel data provide more information about the nature of the targets observed on such images. For a detailed description of the physical basis of remote sensing, including the nature of remote sensing, the use of electromagnetic radiation to "sense" the characteristics of the target, and the interactions between electromagnetic radiation and the atmosphere, **see *Physical Basis of Remote Sensing***. Remote sensing is possible only in certain regions of the electromagnetic spectrum, in those regions known as atmospheric windows. Figure 7 of ***Physical Basis of Remote Sensing*** illustrates that, in the visible and short-wave infrared (SWIR) regions of the electromagnetic spectrum, it is possible to discriminate between soil, water, and healthy vegetation. These graphs of reflectance versus wavelength are called spectral reflectance curves.

The constraints imposed by the effects of the atmosphere and the shapes of the spectral reflectance curves of targets of interest mean that remote sensing instruments for Earth surface monitoring use wavebands in the visible, SWIR, and thermal infrared wavebands (plus the microwave bands), and that multiple measurements are made in order to discriminate between different spectral reflectance curves. The first Landsat satellite, launched in 1972, carried a sensor called the multi-spectral scanning system (MSS). This instrument acquired four channels of data—two located in the visible region of the spectrum (green and red) and two in the SWIR band. Reference to Figure 7 of ***Physical Basis of Remote Sensing*** shows why this choice was made. Water is easily separated from soil and water at wavelengths above 0.75 micrometers (μm), so that either of the SWIR bands could be used for this purpose. The spectral reflectance curve for vegetation, shown in more detail in Figure 8 of ***Physical Basis of Remote Sensing***, shows a characteristic peak at a wavelength of around 0.55 μm and an absorption feature at or near 0.7 μm, due to chlorophyll absorption. The Landsat MSS sensor uses the green and red wavebands to pick up these features. Instruments designed for other purposes, such as the coastal zone colour scanner (CZCS), use wavebands that differ from Landsat's because their targets are different. For a detailed account of remote sensing systems, including Landsat and CZCS, **see *Satellite Remote Sensing***.

The selection of the number and location of the wavebands to be used in remote sensing is partly a function of the objectives of the program of work. Thus, a system designed for oceanographic purposes would acquire data in wavebands that differed from those used in remote sensing of terrestrial vegetation or in atmospheric monitoring. It is also likely that these systems would differ in their spatial resolution, which can be regarded as the size of the smallest object for which a data value is obtained. This smallest object in a digital image is known as a pixel. Both weather satellites and ocean-monitoring satellites carry instruments that view much of the earth’s surface in a single day, for the oceans and the atmosphere are dynamic (meaning that their characteristics change rapidly over time). The Amazonian forests are, in that sense, not very dynamic and thus do not need to be monitored every day. In order to collect images of the earth’s surface in a single day, the size of the image pixel is of the order of 1 km. If we are prepared to accept a lower temporal frequency of revisits, such as the 16-day revisit period of Landsat compared to one day for the NOAA satellites, then the size of the image pixel can be reduced. Landsat’s MSS had a pixel size of 80 m, compared with 1 km for the advanced very high resolution radiometer (AVHRR) carried by the NOAA satellite. The pixel size in an image is related to the spatial resolution of the sensor. As noted above, a daily global view is feasible only with a coarse spatial resolution (of the order of 1 km), whereas agricultural crop monitoring can be accomplished using a revisit period of around 14 days and a spatial resolution of the order of 30 m. Higher spatial resolutions are needed for mapping applications. The Ikonos satellite, launched in 1999, provides images with a spatial resolution as fine as 1 m.

So far, discussion has focused on the sensing of relatively easily differentiated targets such as soil, vegetation, and water. These targets can be characterised in terms of relatively few wavebands (Landsat’s MSS used four bands; the SPOT HRV system uses just three, while Landsat’s new ETM+ instrument produces seven bands of data). If we look at Figure 10 of ***Physical Basis of Remote Sensing***, we see complex curves representing the emittence spectra of various minerals in the thermal infrared region of the spectrum. Other examples, not restricted to the thermal infrared, can be found in ***Imaging Spectrometry***. Curves such as these cannot be characterised by measurements in a small number of bands. Instead, a hyperspectral instrument is used to extract measurements at a large number of points **(see *Imaging Spectrometry*)**. For example, the German Space Agency’s DAIS hyperspectral instrument uses 32 bands with a bandwidth of 15–30 nanometres (nm) to cover the 0.4–1.0 μm region, a further 8 bands (45 nm bandwidth) for the 1.5–1.8 μm band, and 32 bands (20 nm bandwidth) for the 2.0–2.5 μm region, giving a total of 72 bands. The AVIRIS instrument developed in the United States uses 220 bands (with a 9.7 nm bandwidth) to measure spectra in the 0.4–2.5 μm (optical) region of the spectrum. The number of bands contained in a hyperspectral dataset is a problem in its use, because many of the bands are inter-correlated, and so there is a degree of redundancy. Techniques such as principal components analysis (PCA) and minimum noise fraction (MNF) have been developed to reduce the degree of redundancy in large datasets. These methods are described in **Section 2.2. Filters, Noise, and Scale**.

Flight navigators during World War II reported that they were able to see crude radar images of the ground below and to the side of their aircraft. Since then, the instruments capable of generating, transmitting, and receiving microwave radiation have found wide application in remote sensing. Multi-spectral and hyperspectral instruments such as those discussed in the preceding paragraphs record ground-leaving radiance in the visible and infrared spectral bands. Such instruments are described as “passive sensors,” as they rely on the sun or the earth for the energy they record. Radar is an active sensor and can therefore operate during both day and night. Furthermore, at the centimetre wavelengths used by radar, energy is able to penetrate clouds, thus overcoming one of the disadvantages of optical (visible and infrared) radiation. The first radar satellite, Seasat, was launched in 1978 and, during the 100 days of its operation it produced images of both land and sea that proved to be of great value to Earth scientists. Since that date, a number of space radar systems have been placed in orbit, including the European ERS-1 and 2, the Japanese JERS-1, and the Canadian Radarsat. All of these systems use a synthetic rather than a physical antenna and are thus known as SAR (synthetic aperture radar) systems. They operate using a single antenna and a fixed wavelength. Experimental radar systems have been carried by NASA's space shuttle to investigate the simultaneous use of multiple wavelengths and of different directions of polarisations. The results of these experiments will be incorporated in instrument systems to be flown in the early years of the twenty-first century.

One of the many applications of SAR data is the development of measuring the elevation of the earth's surface from space, using the technique of interferometry. Two SAR images of the same area of the earth's surface, acquired from different but close positions, are required. Surface elevation can then be computed from the difference in phase of the two signals and the distance apart in orbit of the two sensing systems. A Shuttle mission during February 2000 (the Shuttle Radar Topography Mission, SRTM) was the first to carry two SAR antennae on the same spacecraft and so was able to acquire simultaneous SAR "image pairs" of around 90% of the earth's surface. Figure 7 shows a 3-D rendition of surface elevation for a part of the Kamchakta Peninsula, Russia, derived from SRTM data. ***Radar Remote Sensing*** presents a survey of radar systems and sensing, while ***Landform and Earth Surface*** (Section 4.1.2) describes the use of interferometry in the building of digital elevation models.

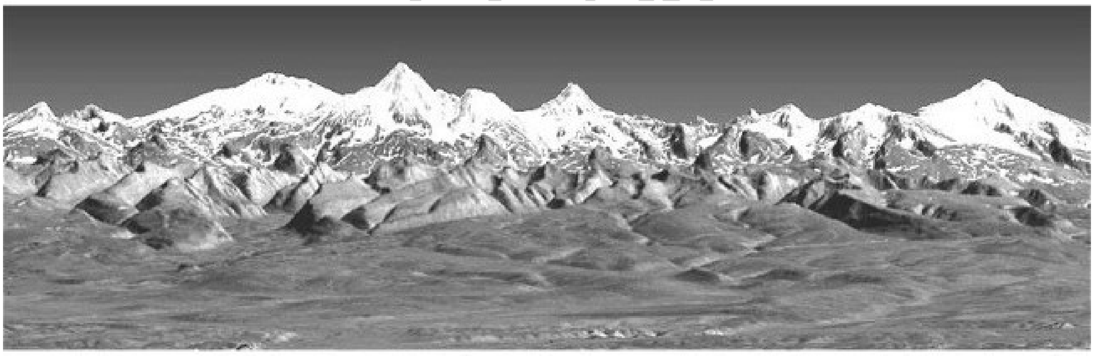

Figure 7. 3-D perspective view, Kamchatka Peninsula, Russia, generated from interferometric SAR data acquired during the Shuttle Radar Topography Mission, February 11–22, 2000
(*Source*: www.jpl.nasa.gov/srtm/russia.html)

SAR data is not the only source of remotely sensed data available for mapping surface elevation. The use of lasers mounted on aircraft to generate high spatial resolution surface models, though still in its early stages, appears to be a cost-effective method for detailed surveys. One characteristic of light detection and ranging (lidar) data is that a profile of measurements can be obtained from the point where the laser light first reaches an object on the earth's surface to the point where it reaches the ground. These two points are termed the "first bounce" and "last bounce," respectively, and analysis of the lidar return between these two points can provide information about the structure of the target, as well as its elevation. For example, the first-bounce point may be the top of a forest canopy, while the last bounce is the ground surface. The lidar profile between these two points may be able to provide information about the height of the forest trees as well as the structure of the forest. Section 4.3 of ***Landform and Earth Surface*** provides a summary of laser-based systems of elevation measurement.

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Biographical Sketch

Paul Mather is professor of geographical information science in the School of Geography, The University of Nottingham. His research interests include multivariate statistical analysis, digital image processing, and pattern recognition applied to remotely sensed data.